Edrolo

VCE CHEMISTRY

Units 3 & 4

3RD EDITION

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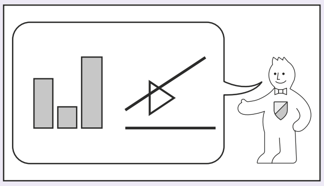
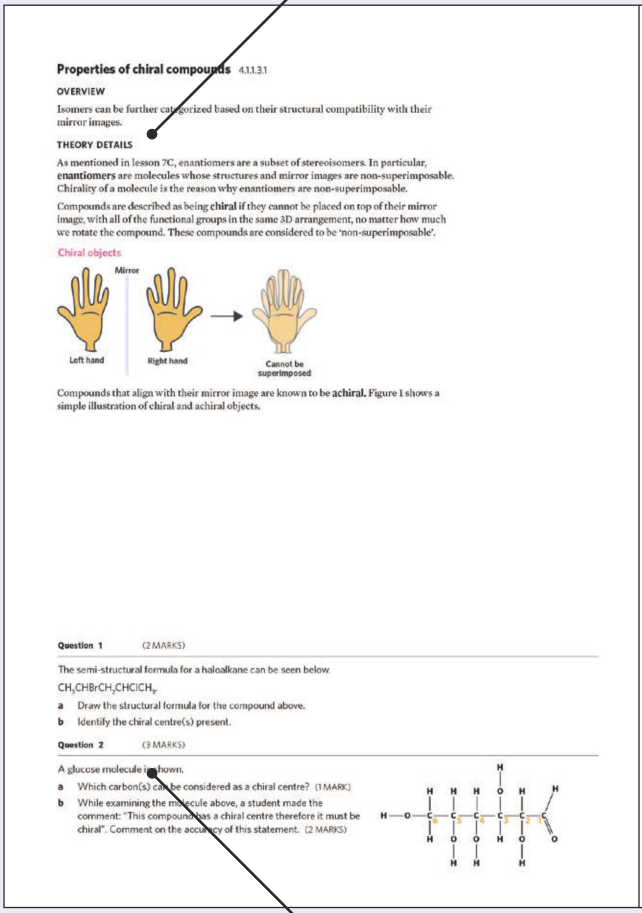




Properties of chiral compounds 4.1.1.3.1

OVERVIEW

Isomers can be further categorized based on their structural compatibility with their mirror images.

THEORY DETAILS

As mentioned in lesson 7C, enantiomers are a subset of stereoisomers. In particular, **enantiomers** are molecules whose structures and mirror images are non-superimposable. Chirality of a molecule is the reason why enantiomers are non-superimposable.

Compounds are described as being **chiral** if they cannot be placed on top of their mirror image, with all of the functional groups in the same 3D arrangement, no matter how much we rotate the compound. These compounds are considered to be 'non-superimposable'.

Chiral objects

Compounds that align with their mirror image are known to be **achiral.** Figure 1 shows a simple illustration of chiral and achiral objects.

Question 1 (2 MARKS)

The semi-structural formula for a haloalkane can be seen below.

$CH_3CHBrCH_2CHClCH_3$.

a Draw the structural formula for the compound above.

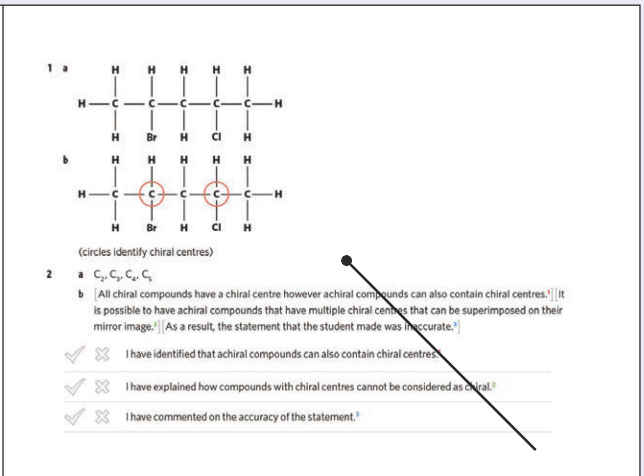
b Identify the chiral centre(s) present.

Question 2 (3 MARKS)

A glucose molecule is shown.

a Which carbon(s) can be considered as a chiral centre? (1 MARK)

b While examining the molecule above, a student made the comment: "This compound has a chiral centre therefore it must be chiral". Comment on the accuracy of this statement. (2 MARKS)



1 a

b

(circles identify chiral centres)

2 a C_2, C_3, C_4, C_5

b [All chiral compounds have a chiral centre however achiral compounds can also contain chiral centres.[1]] [It is possible to have achiral compounds that have multiple chiral centres that can be superimposed on their mirror image.[2]] [As a result, the statement that the student made was inaccurate.[3]]

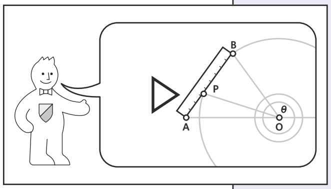
✓ ☒ I have identified that achiral compounds can also contain chiral centres.[1]

✓ ☒ I have explained how compounds with chiral centres cannot be considered as chiral.[2]

✓ ☒ I have commented on the accuracy of the statement.[3]

ANSWERS

Every exam style question in this book has an even more detailed solution video, that shows you how to break down the question, and learn all the steps required to solve it. There are also online static worked solutions and interactive checklists.



QUESTIONS

There are hundreds of questions in this book, and these questions can also be found and completed online. Answering your textbook questions online will enable you to better track your progress, and will enable your teacher to engage with your responses – so they support you even further.

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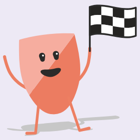
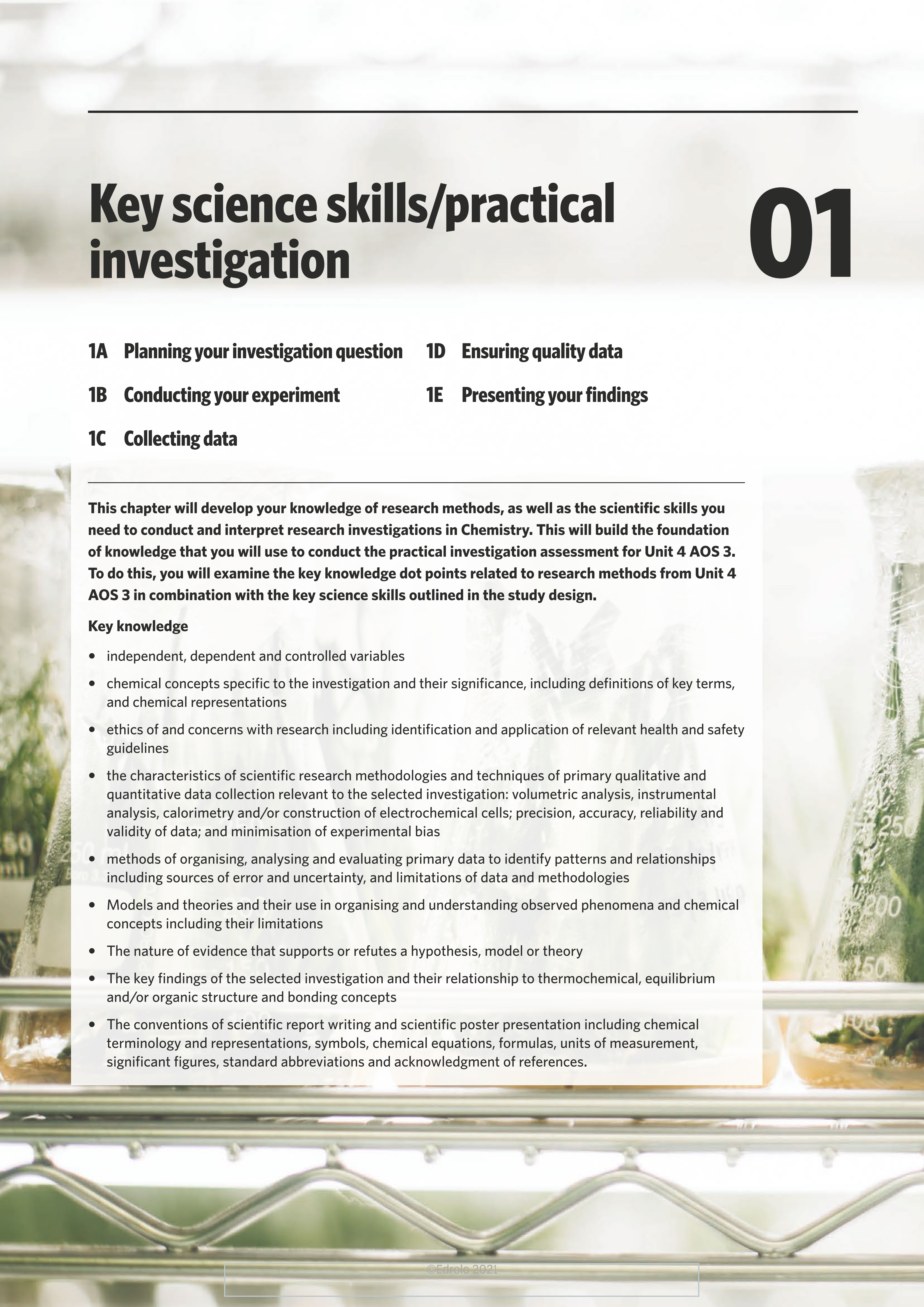




Key science skills/practical investigation

01

This chapter will develop your knowledge of research methods, as well as the scientific skills you need to conduct and interpret research investigations in Chemistry. This will build the foundation of knowledge that you will use to conduct the practical investigation assessment for Unit 4 AOS 3. To do this, you will examine the key knowledge dot points related to research methods from Unit 4 AOS 3 in combination with the key science skills outlined in the study design.

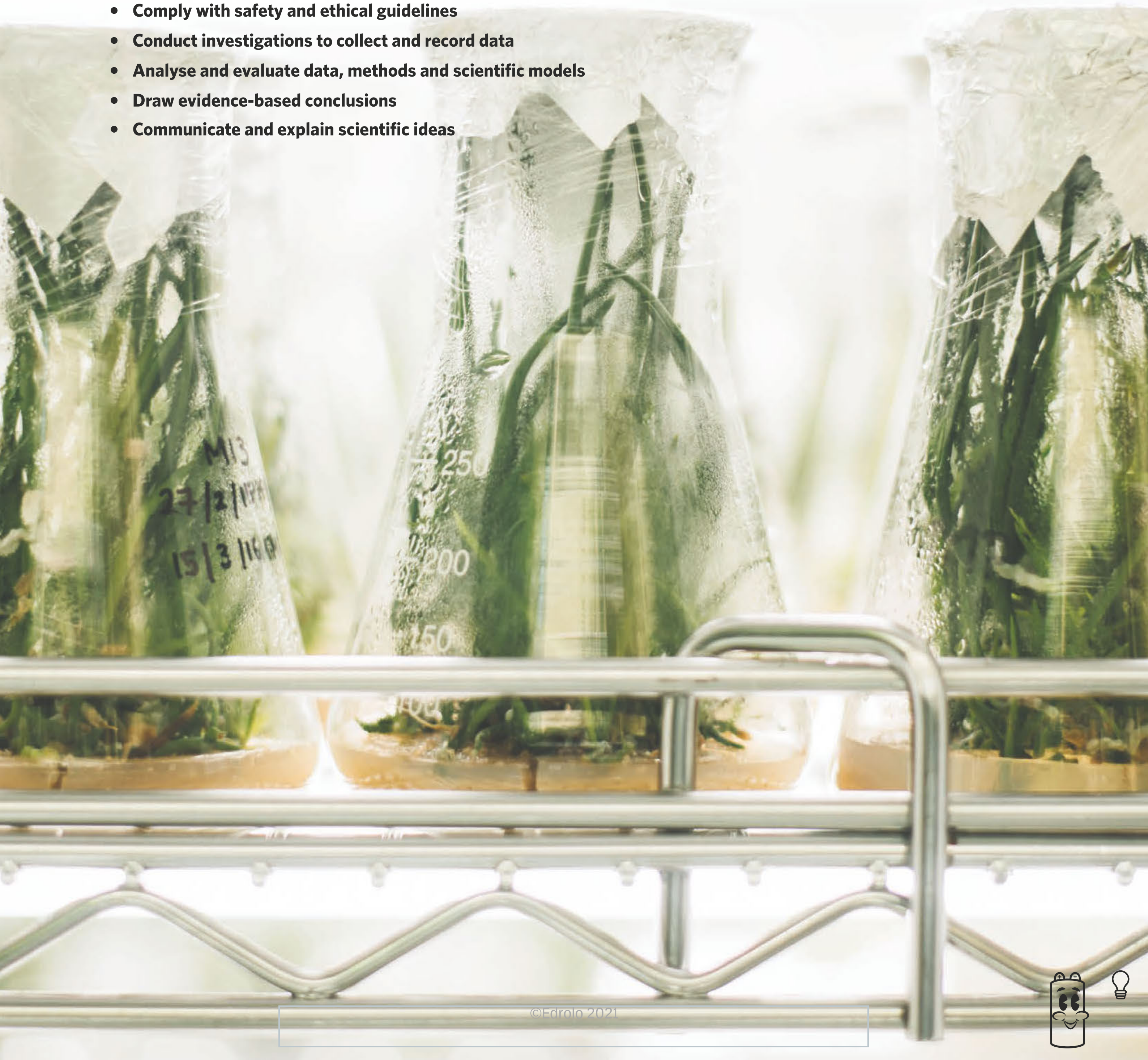
Key knowledge

- independent, dependent and controlled variables
- chemical concepts specific to the investigation and their significance, including definitions of key terms, and chemical representations
- ethics of and concerns with research including identification and application of relevant health and safety guidelines
- the characteristics of scientific research methodologies and techniques of primary qualitative and quantitative data collection relevant to the selected investigation: volumetric analysis, instrumental analysis, calorimetry and/or construction of electrochemical cells; precision, accuracy, reliability and validity of data; and minimisation of experimental bias
- methods of organising, analysing and evaluating primary data to identify patterns and relationships including sources of error and uncertainty, and limitations of data and methodologies
- Models and theories and their use in organising and understanding observed phenomena and chemical concepts including their limitations
- The nature of evidence that supports or refutes a hypothesis, model or theory
- The key findings of the selected investigation and their relationship to thermochemical, equilibrium and/or organic structure and bonding concepts
- The conventions of scientific report writing and scientific poster presentation including chemical terminology and representations, symbols, chemical equations, formulas, units of measurement, significant figures, standard abbreviations and acknowledgment of references.

The development of a set of key science skills is a core component of the study of VCE Chemistry and applies across Units 1 to 4 in all areas of study. In designing teaching and learning programs and in assessing student learning for each unit, teachers should ensure that students are given the opportunity to develop, use and demonstrate these skills in a variety of contexts when undertaking their own investigations and when evaluating the research of others. As the complexity of key knowledge increases from Units 1 to 4 and as opportunities are provided to undertake investigations, students should aim to demonstrate the key science skills at a progressively higher level.

Key science skills

- Develop aims and questions, formulate hypotheses and make predictions
- Plan and undertake investigations
- Comply with safety and ethical guidelines
- Conduct investigations to collect and record data
- Analyse and evaluate data, methods and scientific models
- Draw evidence-based conclusions
- Communicate and explain scientific ideas



1A PLANNING YOUR INVESTIGATION QUESTION

In this lesson, we will unravel the processes involved in planning an investigation.

1A Planning your investigation question	1B Conducting your experiment	1C Collecting data	1D Ensuring quality data	1E Presenting your findings

Study design dot points

- independent, dependent and controlled variables
- chemical concepts specific to the investigation and their significance, including definitions of key terms, and chemical representations
- ethics of and concerns with research including identification and application of relevant health and safety guidelines

Key knowledge units

Deciding what to investigate	4.3.2.1
Identifying your variables	4.3.1.1
Ethical and health considerations	4.3.4.1

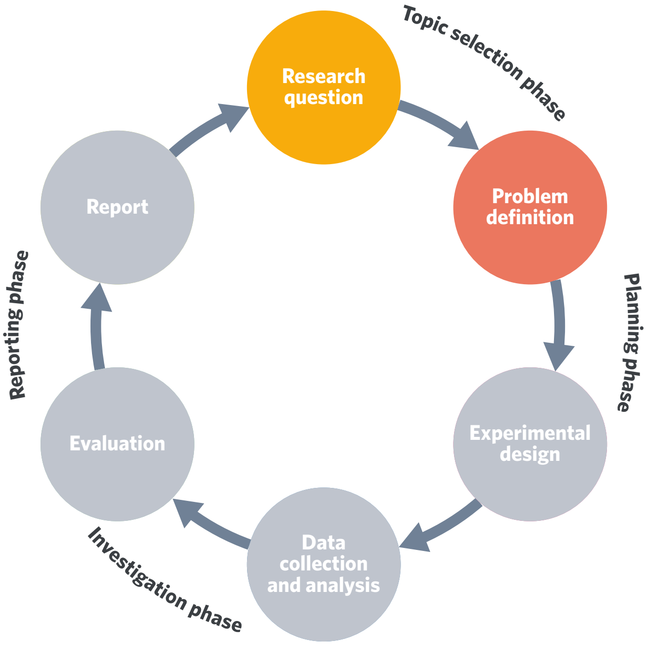


Figure 1 The scientific investigation process

Key terms and definitions of this lesson

- **Aim** purpose/objective of an experiment
- **Independent variable** variable that is deliberately manipulated (or changed) by the experimenter
- **Dependent variable** variable that is measured by the experimenter
- **Controlled variable(s)** variable(s) held constant throughout the experiment
- **Hypothesis** testable statement which predicts the outcome of an experiment/investigation

Deciding what to investigate 4.3.2.1

OVERVIEW

Once an investigation question is devised, it is important to research the ideas associated with the theory being investigated.

THEORY DETAILS

Scientific investigations are multi-step processes. As shown in figure 1, there are a few processes involved in conducting an experiment. The cyclic nature of the research process indicates that science is a systematic and progressive discipline whereby findings give rise to new areas for study.

Although each process is essential in the overall success of the experiment, the initial planning phase is important as it sets the direction for the whole experiment. During this stage, as the experimenter, we would need to determine the kind of investigation that needs to take place in order to answer the question.

Before the research question can be established, we would need to choose a topic that we wish to investigate. This decision can be derived from a number of different factors, including:

- Personal interest
- Extension of what has already been done
- Analysis of available data

From here, we would be able to define a particular question that we wish to investigate. It may be helpful during this stage to seek advice from a teacher to help develop an appropriate research question. An example of this process can be seen in figure 2.

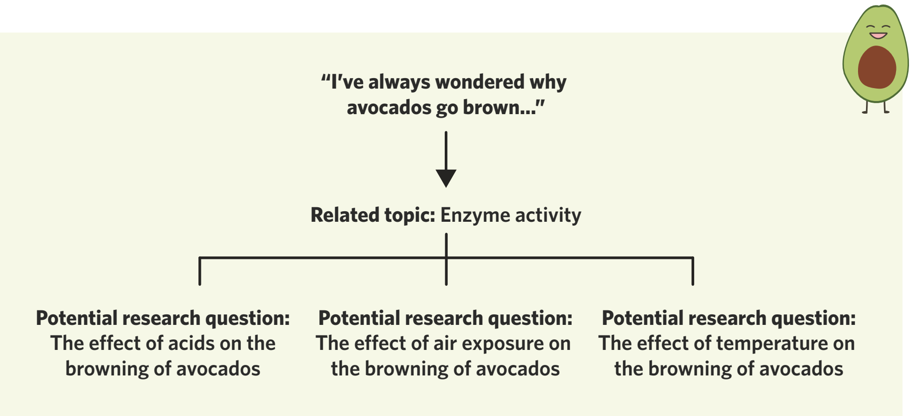


Figure 2 Example of the planning process involved in identifying a research question

Once the topic and question has been defined, we are able to conduct research to see what is known about this area. This may include reviewing the literature to develop a general understanding of the topic of interest. Through this process, we would be able to improve our understanding of:

- The particular theory(ies) relevant to the phenomenon under analysis
- The experimental methods that can be employed to investigate the research question
- The ideas that we can build upon to improve our understanding of this phenomenon
- Current gaps in knowledge in the area of research

The information gathered here will help us to define the important chemical concepts and definitions that need to be addressed during the investigation, and in particular, in the write up.

The purpose of the investigation is not to reinvent the wheel; we are not being expected to develop something completely new from the experiment. Put simply, we are attempting to add to the current state of knowledge on a particular topic, thereby contributing to the scientific communities' understanding of the world.

Identifying your variables 4.3.1.1

OVERVIEW

Once the research question has been determined, we are able to define the variables in the investigation.

THEORY DETAILS

The **aim** of an experiment can be derived from the research question and highlights the purpose of the research. Once this has been identified, we are then able to define the **independent** and **dependent variables** in the experiment. When thinking about the independent and dependent variable, it's useful to ask ourselves the following questions:

- What is being manipulated/changed by the experimenter? This becomes the independent variable.
- What is being affected by the variable that is being changed? This becomes the dependent variable.

The purpose of the experiment is to determine the relationship between the independent and dependent variables. In an experiment, only the independent and dependent variables should experience any changes; either as a result of the experimenter or in response to the independent variable respectively. Any fluctuations in the other variables involved in the experiment can affect the results collected in that it cannot be assessed by the experimenter whether the independent variable caused a change in the dependent variable or whether another variable was responsible for this change. This in turn could mean that no conclusion could be drawn from the experiment. The variables in the experiment that are kept constant throughout are known as the **controlled variables**. Figure 3 shows an example of how the variables can be identified from the research question.

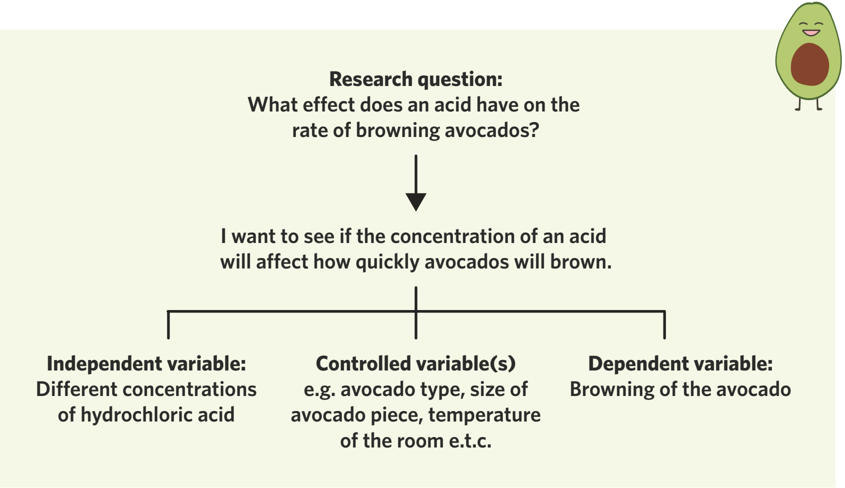


Figure 3 Identifying the variables involved in an experiment

Defining the variables not only helps to convey the idea to the reader, it also gives us an idea as to how to decide on the methods and materials required for the investigation. From there, we will be able to develop a **hypothesis** for the experiment. The easiest way to develop a hypothesis is to use the following framework.

Table 1 Framework to developing a hypothesis. IV stands for independent variable and DV stands for dependent variable.

	Phrase outlining relationship between DV and IV		**trend indicating effect on the DV**		**trend indicating action by the IV**
If... the DV...	...depends on... ...results from... ...is affected by... ...is directly related to...	...then...	...show an increase/ decrease ... ...be greater than/ less than... ...be larger/smaller...	...when...	...increased/ decreased... ...greater/less... ...large/small...

Adapted from VCAA advice for teachers – Controlled experiments and hypothesis formulation

In relation to our experiment on avocado browning, a hypothesis could be:

If browning of an avocado is due to enzyme activity, then the use of increasing concentrations of hydrochloric acid will result in a decrease in the rate of avocado browning.

Ethical and health considerations 4.3.4.1

OVERVIEW

Different investigations require certain ethical and health considerations depending on the experimental technique employed.

THEORY DETAILS

Research questions can be investigated using a variety of different experimental techniques. Depending on the objective of the investigation, experiments can generate different types of data. This is partly why the planning phase is so important as it allows us to determine the best type of experimental method to use to answer our particular research question.

Details about the method that is to be used during the investigation phase give important information about the potential ethical and health concerns that need to be taken into consideration prior to conducting the research.

Ethical considerations

Ideas developed in the field of chemistry can potentially have significant effects on our whole society. As a result, when conducting research, we need to be aware of the potential impact of our research on the greater community.

For example, we need to be aware of factors such as:

- The sourcing of the material
- The type of research being conducted
- Falsification of data
- Acknowledging prior work

Not only do we need to consider following proper scientific conduct, it’s also important to consider the more indirect consequences of our research and how it can be used by the community.

Health and safety considerations

As there may be many potential hazards when working with a variety of different chemicals, it’s important that all precautions are taken to ensure the safety of everyone involved. Apart from researching the experimental method involved in an investigation, we also need to have a thorough understanding of the potential safety risks involved so that measures can be taken to prevent any harm.

Besides wearing personal protective equipment (PPE) such as gloves, goggles, lab coats, etc., it is crucial to take specific precautionary measures based on the chemicals and materials used in the experiment. A way in which we can ensure this is to refer to the Material Safety Data Sheet (MSDS) of each chemical used in the experiment. The MSDS is a document that includes all of the information relating to the potential health effects of chemical substances.

Another aspect to remember is identifying potential dangers in the equipment and method, to ensure that a plan of action is in place should anything go wrong.

Theory summary

- The research question can be developed from personal interest, an extension of current research and available information.
- The purpose of research is to contribute to the pool of scientific knowledge.
- Developing the research question can help to identify the aim and various variables of the experiment.
- It’s important to control all variables outside the independent and dependent variable to make sure that a solid conclusion can be made from the results.
- The independent variable is manipulated by the experimenter and the dependent variable is the variable affected by the independent variable.
- A hypothesis provides a possible explanation for the results in the experiment based on the relationship between the independent and dependent variables.
- Findings in chemical research have wider implications on the community, therefore ethics is an important factor to consider when conducting an investigation.
- It is our responsibility to ensure the safety of ourselves and everybody involved in the research investigation.

1A QUESTIONS

Theory review questions

Question 1

The independent variable in an experiment

A will never change throughout the experiment.

B is the variable that is measured.

C has two different subtypes.

D is the variable manipulated by the experimenter.

Question 2

It is important to have a controlled variable(s) as

A the conditions of the experiment will always change, therefore the variables need to change with it.

B it helps to ensure that we can confidently draw a conclusion from our results.

C it helps to define the independent variable.

D it makes the experiment less expensive.

Question 3

An experiment aims to

A investigate the relationship between the controlled variable and independent variable.

B investigate the relationship between the controlled variable and dependent variable.

C investigate the relationship between the measured variable and independent variable.

D investigate the relationship between the dependent variable and independent variable.

Exam-style questions

Within lesson

Question 4 (1 MARK)

Lennard wanted to test whether or not chunks in an ice cream can affect the rate at which the ice cream can melt. In his experiment, Lennard measured how long it took for 20 g of different ice cream types to melt in 26 degrees.

The dependent variable in this experiment is

A temperature.

B ice cream type.

C the rate at which ice creams melt.

D the stopwatch used.

Question 5 (4 MARKS)

Meg wishes to investigate the effect of salt on the time it takes for water to boil. To do this she has three beakers of water with different amounts of salt in each. She then times how long it takes for each beaker of water to boil.

a What types of variables are the amount of salt and time, respectively? Explain your answer. (3 MARKS)

b Why is it important for the amount of water to be the same in each beaker? (1 MARK)

Question 6 (4 MARKS)

Proteins present in milk coagulate and form clumps when an acid such as hydrochloric acid is added. Vera wanted to test the protein content of different milks using this method.

a Identify the independent variable. (1 MARK)

b Write a suitable hypothesis for this experiment. (2 MARKS)

c The volume of milk and hydrochloric acid used in the experiment were kept constant. What kind of variable does this represent? (1 MARK)

Question 7 (4 MARKS)

The time taken to bake cookies can depend on different factors. In a rush to make something for his friend's birthday party, Barukh decided to bake two separate batches of cookies at two different temperatures, one at 180 °C and one at 220 °C. As he was in a rush, the amount of dough in each cookie varied.

a Identify the dependent variable. (1 MARK)

b The independent variable cannot be clearly defined. Explain why this is the case. (2 MARKS)

c Write an aim for the intended experiment. (1 MARK)

Question 8 (4 MARKS)

Students conducted some research on how to extract iron ions from a sample of iron ore. An excerpt from their research is shown below.

> As the iron ore sample contains iron in the form of iron (III) oxide, we conducted some internet research into the properties of iron (III) oxide. We found that:
>
> iron (III) oxide is an insoluble basic oxide
>
> iron (III) oxide should dissolve in hot concentrated hydrochloric acid to produce Fe^{3+} ions

a Identify the controlled variable(s) in the experiment if they wanted to test the internet's results. (1 MARK)

b The iron ions extracted can be used to produce solid iron. Given that iron is used in many different materials, explain why it would be important for scientists to investigate such a process. (3 MARKS)

Question 9 (6 MARKS)

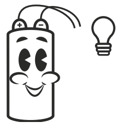
Mohini enjoys eating extremely hot food. In search of the hottest chilli, she developed an experiment to identify the type of chilli that produces the most 'heat' as measured in Scoville Heat Units.

a Write an aim for this experiment. (1 MARK)

b To make sure that her experiment was well setup, she made sure that she consumed the same amount of each chilli with the same food. Why is it important for Mohini to do this? (2 MARKS)

c Considering hot chillies can cause skin irritations and a burning sensation when coming into contact with eyes, list two main safety precautions that need to be taken during this experiment. (2 MARKS)

d If a researcher wished to conduct this study, identify a possible ethical concern. (1 MARK)



1B CONDUCTING YOUR EXPERIMENT

In this lesson we will learn about the different types of research methods specific to our study design and how they can be classified.

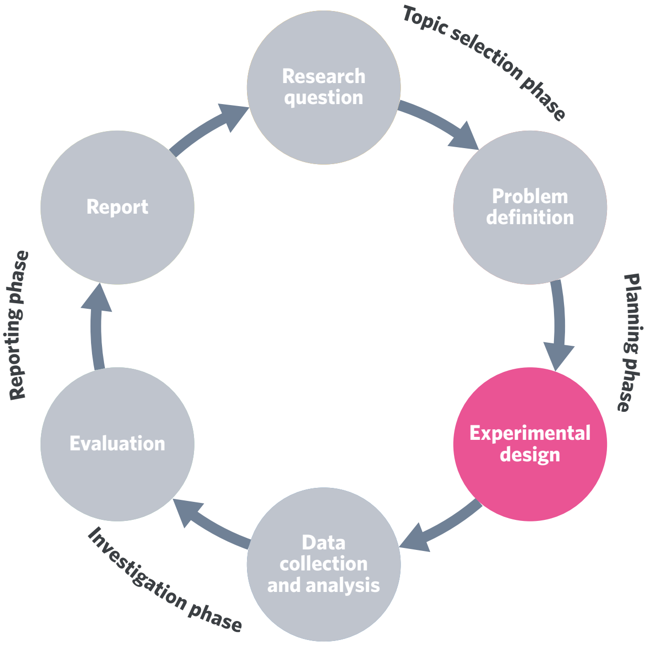
1A Planing your investigation question	1B Conducting your experiment	1C Collecting data	1D Ensuring quality data	1E Presenting your findings

Study design dot point

- the characteristics of scientific research methodologies and techniques of primary qualitative and quantitative data collection relevant to the selected investigation: volumetric analysis, instrumental analysis, calorimetry and/or construction of electrochemical cells; precision, accuracy, reliability and validity of data; and minimisation of experimental bias

Key knowledge units

Quantitative research methods	4.3.3.1
Qualitative research methods	4.3.3.2



Key terms and definitions

- **Quantitative analysis** technique that identifies the amount of a substance present
- **Quantitative data** data which provides a numerical value
- **Qualitative analysis** technique that determines the composition of a sample – i.e. what's 'in' it
- **Qualitative data** non-numerical (descriptive) data collected based on observations taken during the experiment

Quantitative research methods 4.3.3.1

OVERVIEW

Quantitative research methods are used when the purpose of the analysis is to determine the quantity of a substance(s).

THEORY DETAILS

The purpose of an experimental design is to allow us to produce valid, accurate and reliable results that can help to gain insight into the research question. Depending on the question under investigation, there are often preferred methodologies that have been shown, through previous investigations, to give valid, accurate and reliable results specific to the aim of the experiment. We will go into further detail about the importance of validity, accuracy and reliability in the following lessons.

Similar to those seen in cooking recipes, the section of an experiment where the method is outlined gives detailed step-by-step instructions on how to conduct the experiment. The specificity of the method section not only gives the experimenter direction, but it also allows for the experiment to be replicated by other scientists so that we are able to build upon the knowledge gained by the experiment.

Experiments whose method allow for the collection of data that can help us identify how much of a substance is present are referred to as **quantitative analysis** techniques. The **quantitative data** we can gain from these types of experiments give us numerical data that can be used to determine the amount of a substance present/produced. This type of analysis is important as it allows us to predict our yield and identify how much reactant is required to produce a desired amount of product. This application is particularly important in industry as it maximises efficiency and minimises waste and production costs.

Examples of quantitative analytical techniques that we will study in Units 3 & 4 can be seen in table 1.

Table 1 An outline of the quantitative techniques that will be studied during the course of the current study design

Technique	**Example of quantitative data derived from this technique**	**Purpose**
Electrolytic cells	The time, voltage and/or current at which electricity is passed through the cell	To predict the amount of reactant used or mass of product formed
HPLC (high performance liquid chromatography)	The retention time of different components in a sample	To identify properties and the identity of the components in a sample
Volumetric analysis (i.e. titrations)	The volume of titrant used in the experiment	To determine the concentration/amount of an unknown compound
Calorimetry	The temperature change as a result of a reaction	To determine the ΔH of a reaction

It's important to note that the table above shows a sample of the information that can be collected within the context of our study design. There are other pieces of data that can also be collected as a result of these techniques.

Building on the example research question from lesson 1A, the aim of the research is to determine the effect of acids, and in particular, acid concentration on the rate of browning of avocados. With this in mind, we need to think about what kind of data we want to collect. As we are dealing with rate, we need to collect data relating to a change over time. For the purpose of our example, let's collect data on percentage of browning of an avocado sample over time which would be quantitative in nature.

Qualitative research methods 4.3.3.2

OVERVIEW

Qualitative research methods are used to determine the composition of different substances and compounds.

THEORY DETAILS

Unlike quantitative research, **qualitative analysis** gives us information about what is contained in a substance. The **qualitative data** collected as a result of the research is generally based around the observations taken during the experiment such as sensory descriptions (what you see, hear, smell, etc.). Examples of this include:

- Colour changes
- Temperature changes (based on touch)
- Bubbling
- State changes

This type of research is often not as in depth as quantitative techniques; however, it is still useful as it allows us to make sure we know what substances we are working with, which is especially important when we are dealing with potentially hazardous substances. Qualitative analysis techniques also help with quality assurance in industry.

Examples of qualitative analytical techniques that we will study in Units 3 & 4 can be seen in table 2.

Table 2 An outline of the qualitative techniques that will be studied during the course of the current study design

Technique	**Example of qualitative data derived from this technique**	**Purpose**
Galvanic cells	The temperature change (measured by touch)/bubbling during the reaction	To determine if a spontaneous redox reaction has occurred
Mass spectroscopy (can be quantitative with the use of a calibration curve)	The *m/z* ratio of the fragments of a molecule	To determine the structure of the fragments and therefore overall structure of a molecule
Infrared spectroscopy (can be quantitative with the use of a calibration curve)	The shape of and wavenumber of peaks	To determine the functional groups and thereby the overall structure of an organic compound
Nuclear magnetic resonance spectroscopy (can be quantitative with the use of a calibration curve)	The chemical shift and splitting pattern of different environments in an organic molecule	To determine the nature of different environments in an organic compound to identify its overall structure

As we can appreciate, both types of techniques can give us slightly different information and therefore have their own advantages and disadvantages. Table 3 illustrates some of the advantages and disadvantages of both.

Table 3 Examples of the advantages and disadvantages of quantitative and qualitative research methods

	Advantage	**Disadvantage**
Quantitative research methods	• Data obtained can be assessed for reliability, validity and accuracy • Data obtained can be easily represented through graphs	• The data is only accurate for very specific conditions • Apparatus used can introduce error
Qualitative research methods	• Can give descriptive data and provide more 'humanised' information • Gives a quick snapshot of what is going on	• More subjective and therefore hard to assess for reliability and accuracy • Human error can compromise accuracy of data

Theory summary

Table 4 summarises the main differences between qualitative and quantitative techniques.

Table 4 Key differences between qualitative and quantitative analysis techniques

Quantitative analysis	**Qualitative analysis**
Tells us 'how much'	Tells us 'what is present'
Collects predominantly quantitative data	Collects predominantly qualitative data
Can help to calculate unknown values	Can help to identify the structure of compounds

1B QUESTIONS

Theory review questions

Question 1

Quantitative analysis would be most suitable for which of the following scenarios?

I Determining the concentration of an unknown substance
II Determining the structure of a compound
III Determining the amount of carbon dioxide released as a result of a reaction

A I only
B I and II only
C II and III only
D I and III only

Question 2

Which of the following would indicate that the experiment conducted was a form of quantitative analysis?

A A substance changes colour

B An odour is given off during the experiment

C 2.04 g of a substance is produced

D The beaker in which the reaction was occurring decreased in temperature

Exam-style questions

Within lesson

Question 3 (2 MARKS)

The diagrams represent equipment used in an investigation to determine the chloride ion concentration in a water sample.

a What type of analysis, quantitative or qualitative, was conducted during this experiment? (1 MARK)

b The filtrate was analysed by titration. During the titration, there was a colour change occurring in the beaker. What type of data was observed? (1 MARK)

Adapted from NESA 2007 Exam Section I Part B Q27

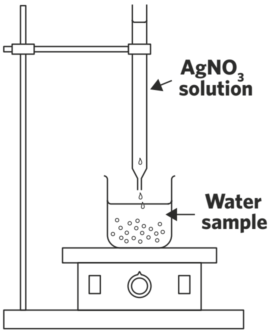


Figure 1

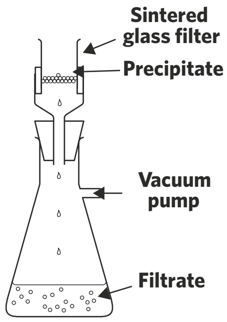


Figure 2

Question 4 (2 MARKS)

Electrolysis is a technique that can be used to plate objects with a protective metal layer.

a In the experiment shown, identify the qualitative data that can be collected. (1 MARK)

b The student conducting this experiment wanted to collect quantitative data to determine how much metal was deposited on rod *P*. Suggest a technique that would allow the student to do so. (1 MARK)

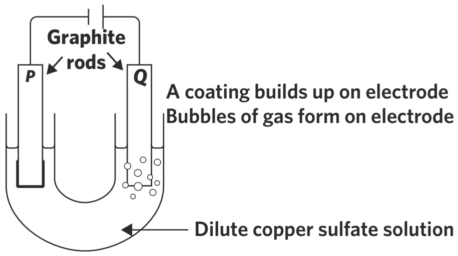


Image: NESA 2007 Exam Section II Q29a

Multiple lessons

Question 5 (5 MARKS)

Sheldon was curious to see the colour changes of different indicators at different pHs. The results from the experiment are provided.

a Write an aim for this experiment. (1 MARK)

b In reference to collecting information pertaining to the colour change of different indicators, what type of data can this be classified as? (1 MARK)

c Identify the independent and dependent variables for this experiment. Explain. (3 MARKS)

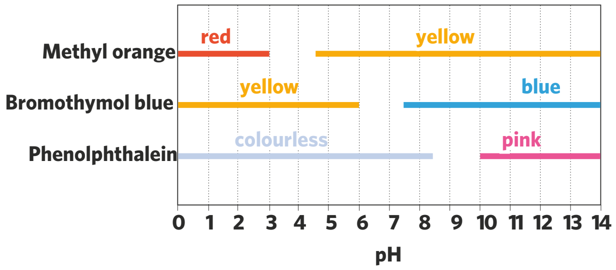


Image: NESA 2012 Exam Section I Q7

Question 6 (3 MARKS)

Maryam wanted to see how different liquids could affect the growth of copper sulfate crystals. The experimental setup is provided.

a Identify the independent variable in the experiment. (1 MARK)

b It was seen that the mass of the crystal depended on the amount of liquid used. What type of analysis was conducted? Explain. (2 MARKS)

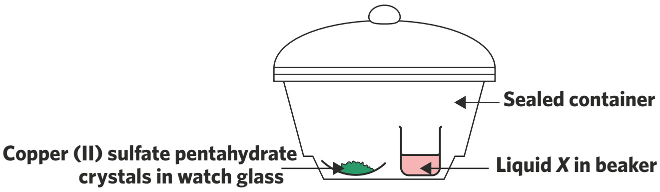
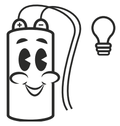


Image: NESA 2011 Exam Section II Q33



1C COLLECTING DATA

In this lesson, we will learn how to represent and analyse data that is collected from experiments.

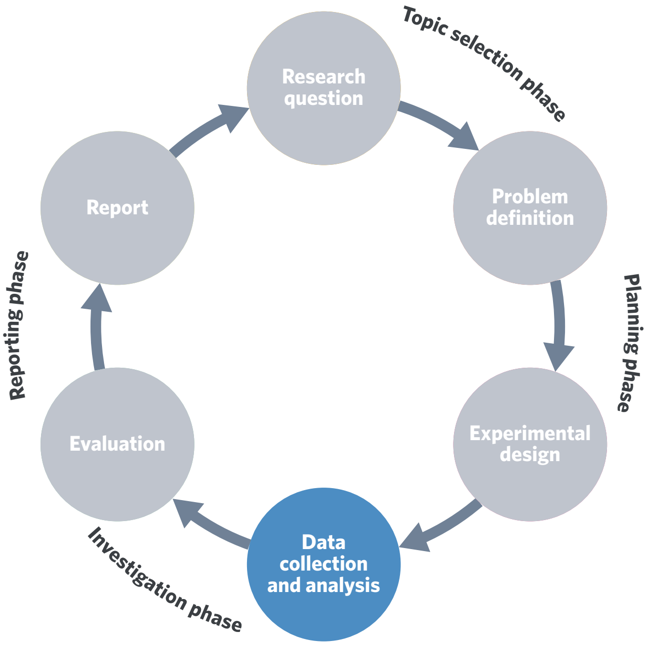
1A Planning your investigation question	1B Conducting your experiment	1C Collecting data	1D Ensuring quality data	1E Presenting your findings

Study design dot point

- methods of organising, analysing and evaluating primary data to identify patterns and relationships including sources of error and uncertainty, and limitations of data and methodologies

Key knowledge units

Organising your data	4.3.5.1
Analysing data	4.3.5.2.1



Key terms and definitions

- **Primary data** data collected first-hand by the experimenter

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Organising your data 4.3.5.1

OVERVIEW

The type of data collected during an experiment can help to indicate the way in which the data should be presented.

THEORY DETAILS

The purpose of conducting research is to gain a better understanding of our world. By conducting experiments, we are able to obtain data that can help us to develop a better understanding of the idea being investigated.

After experimental results are recorded, there are many different ways in which the data can be presented and organised. The representation of data we choose needs to make any trends/relationships between our variables visible. When deciding how to present our data, it's useful to consider the type of data that's being collected (i.e. qualitative or quantitative data). For simplicity, we will refrain from going deeper into the subcategories of qualitative and quantitative data. Table 1 outlines the key features of different types of data representation that you may have come across before.

Table 1 Characteristics of common data representation formats

Type of data representation	Type of data being represented	Advantage
Line graph	Quantitative	Good for displaying trends over time; also helpful when predicting trends over time
Bar graph	Both qualitative and quantitative	Easy to visualise and compare different categories of data
Pie chart	Both qualitative and quantitative	Used to show proportions (e.g. percentage)
Table	Both qualitative and quantitative	Helps to organise and compare multiple sets of values

Tip When drawing line graphs, the data does not need to go through 0.

What we are trying to identify is the relationship between the independent and dependent variable. Through analysing our data, we are able to identify any trends that exist between these two variables. The data we collect from experiments is known as **primary data**.

Using the example experiment involving avocados, the data that is collected as a result of our experiment can be seen in table 2.

Table 2 Data collected from our avocado experiment

	Concentration		
Time	**0.50 M HCl**	**1.0 M HCl**	**No HCl**
2 hrs	10%	5%	12%
4 hrs	21%	13%	30%
6 hrs	36%	24%	50%
8 hrs	50%	40%	73%

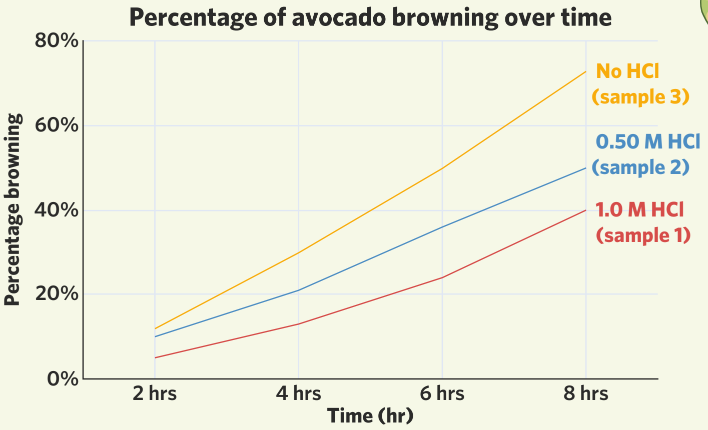


Figure 1 Graph representing the percentage of avocado browning when treated with different acid concentrations over time

When drawing graphs that have an *x* and *y* axis, the *x* axis represents the independent variable and the *y* axis represents the dependent variable as shown in figure 2.

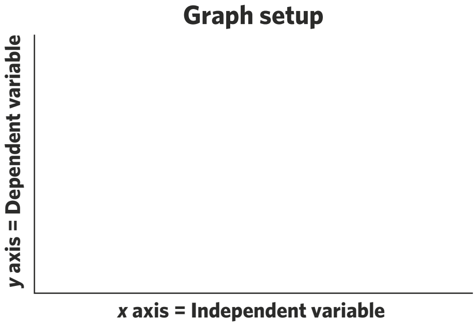


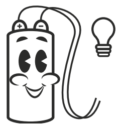
Figure 2 Format used to represent data in a graphical form

Analysing data 4.3.5.2.1

The data collected from an experiment usually shows a relationship between the independent and dependent variable. The relationship that is indicated can help us answer the research question and provide further information about the theory being tested. It may also give us insight into connections between different theories.

When analysing data, there are a few questions we need to ask ourselves:

- What trend can we see from the data collected?
- In the context of the theory underlying the research project, what is the connection between the trend identified and what we know now?
- What concepts can explain the trend that has been identified by the data?



Let's apply this thought process to the research question that we have been addressing throughout this chapter. Assume that the graph represented in figure 1 is based on primary data that was collected from an experiment. Based on the information presented, we can see that there is a relationship between the rate at which the avocado browns and the concentration of hydrochloric acid used. Comparing the three samples in the experiment, we can see that sample 3 experiences the most browning within a given amount of time, followed by sample 2, then sample 1. If we look at the conditions of each sample, assuming that the only difference was the change in the independent variable, we can make a conclusion that an increase in acid concentration decreases the rate at which avocados brown. This conclusion is likely a valid one since the control (no HCl) and experimental groups (two different HCl conditions) differed only in the concentration of HCl present – all other variables were controlled, meaning this can be the only explanation for results.

The next question we need to ask is – why? More specifically, what is the underlying theory(ies) that can explain why this occurred? This may be answered by the information obtained when we conducted the initial literature review to formulate the research question. Here, we can draw from previous research to both inform and support our analysis of the data and how it answers the research question, and subsequently how it addresses the hypothesis.

The one point to remember is that correlation does not equal causality. Causality means that a change in the dependent variable is attributable/caused by a change in the independent variable. However, for correlation, a change in one variable is associated with a change in the other but other variables may be responsible for this change.
Also, there may be factors that impact on the validity and reliability of our conclusion; an idea that we will explore in the next lesson.

Theory summary

- The representation of the data collected from the experiment depends on the type of data that is being collected.
- During data analysis, we are trying to figure out if there's a relationship between the independent variable and dependent variable.
- The correlation between the independent variable and the dependent variable isn't always causal (i.e. the independent variable may not cause the changes in the dependent variable).

1C QUESTIONS

Theory review questions

Question 1

When deciding how to represent the data collected in an experiment, the **most** important thing to consider is

A the reader.

B the amount of data we have collected.

C the type of experiment conducted.

D the type of data being collected.

Question 2

When analysing data

A we are trying to identify a relationship between the independent and controlled variable.

B we are trying to identify trends in the data between the dependent and independent variable.

C the trend identified shows a causal relationship between the variables.

D there will always be a correlation between the dependent and controlled variables.

Exam-style questions

Within lesson

Question 3 (1 MARK)

A bar graph is most appropriate to represent that data relating to

A the number of coffees bought every day.

B the height of a baby over time.

C the composition of petroleum.

D the speed of a car during a road trip.

Question 4 (3 MARKS)

Humans depend on enzymes to stay alive. Enzymes can be quite temperamental, and will only function properly if they are in the right environment.

Sebastian obtained an enzyme that is normally found in the body and experimented with it to see the ideal pH for the particular enzyme. A graph of his experimental result is provided.

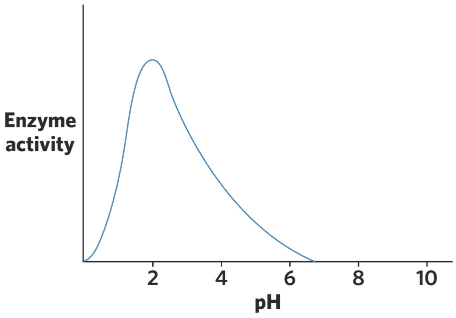


Image: NESA 2017 Exam Section I Part B Q33ai

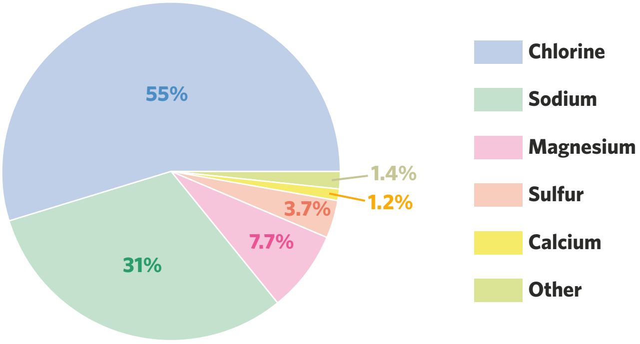
a Based on the graph, at what pH does the enzyme perform the best? (1 MARK)

b What trend can be seen from the graph? (2 MARKS)

Question 5 (2 MARKS)

Supplements contain a variety of different substances. The composition of ingredients is developed to provide the body with appropriate nutrients to maintain a healthy lifestyle.

Dimitri wanted to identify the ingredients found in a supplement that was sold at a chemist. The data obtained is represented in the graph shown.



a In a 5.0 g sample that he tested, there was 0.385 g of element *L* present. Identify element *L*. (1 MARK)

b What analysis can be made from the data presented? (1 MARK)

Question 6 (3 MARKS)

Metal ions are able to absorb electromagnetic radiation. This property is used by scientists for quantitative analysis. An example of the type of result obtained by this method is shown.

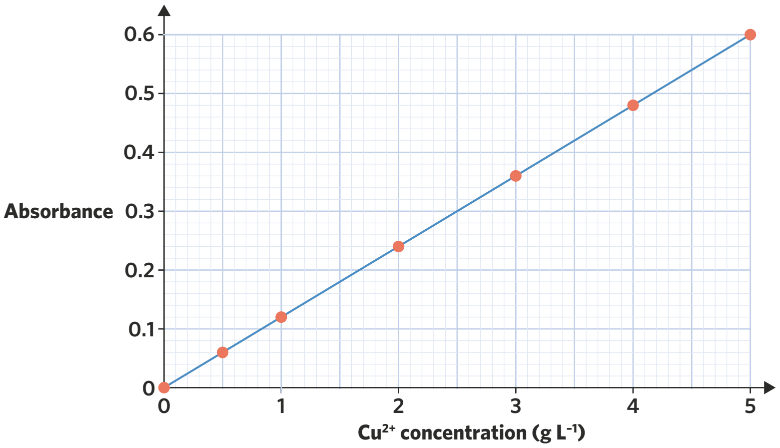


Image: VCAA 2016 Exam Section B Q6

a What is the general trend shown by this graph? (1 MARK)

b The experimenter accidentally forgot to label one of their test tubes containing copper ions. To identify the concentration of copper ion in the sample, the experimenter decided to measure the absorbance of the unlabelled test tube. Given that the absorbance was measured at 0.36, what was the concentration of the unknown sample? (2 MARKS)

Question 7 (4 MARKS)

Rosalind conducted an experiment to see the change in pH of a reaction at different temperatures.

a At what temperature does the reaction have the most H^+ ions? (1 MARK)

b What trend is shown by this graph? (1 MARK)

c Looking at her results, Rosalind concluded that temperature is the only factor that can cause the decrease in pH of the reacting species. Comment on the accuracy of this statement. (2 MARKS)

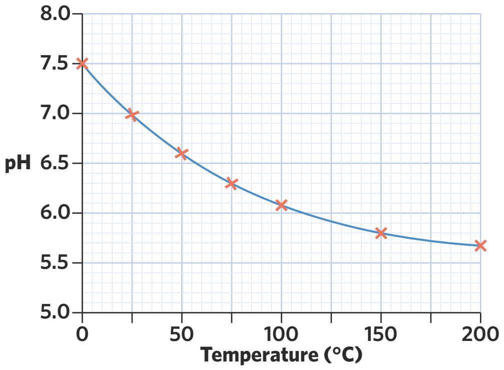


Image: NESA 2014 Exam Section I Part A Q8

Multiple lessons

Question 8 (4 MARKS)

In his quest to find a new molecule, Planck was able to discover molecule *Z* when reacting elements *T* and *Y*. Under certain conditions, the amount of *Z* produced during the reaction (yield) could be increased. The results of his experiment are provided.

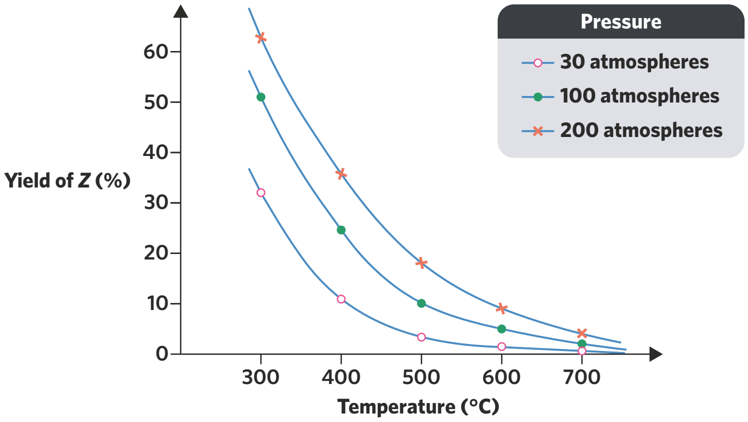


Image: NESA 2014 Exam Section I Part A Q20

a Overall, what pressure resulted in the highest yield of *Z*? (1 MARK)

b What type of data is being collected in this experiment? Explain. (1 MARK)

c What is the relationship between pressure and yield as shown by the graph? (2 MARKS)

Question 9 (5 MARKS)

Val conducted an experiment that resulted in the production of sulfur trioxide. As part of this experiment, she wanted to test the effect of different temperatures on the concentration of sulfur trioxide produced over a certain period of time.

The graph provided shows the result she obtained.

a Identify the independent and dependent variables. (2 MARKS)

b Identify the axis labels for the vertical (*y*) and horizontal (*x*) axis. (1 MARK)

c Describe the result obtained from the graph. (2 MARK)

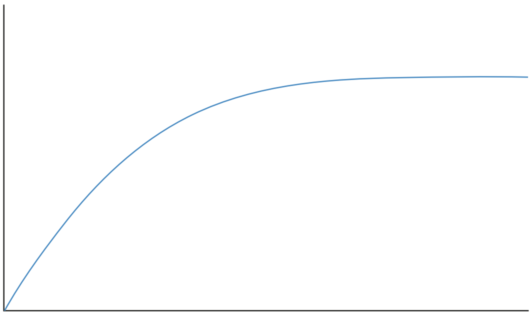


Image: NESA 2017 Exam Section I Part B Q31b

1D ENSURING QUALITY DATA

In this lesson we will learn about the factors that can affect the quality of data obtained during experiments and consequently, the findings of research investigations.

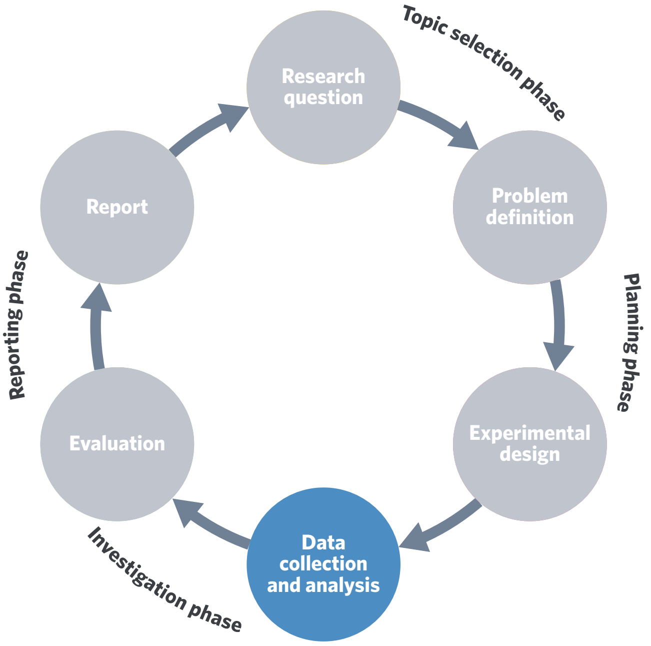
1A Planning your investigation question	**1B Conducting your experiment**	**1C Collecting data**	**1D Ensuring quality data**	**1E Presenting your findings**

Study design dot points

- methods of organising, analysing and evaluating primary data to identify patterns and relationships including sources of error and uncertainty, and limitations of data and methodologies
- the characteristics of scientific research methodologies and techniques of primary qualitative and quantitative data collection relevant to the selected investigation: volumetric analysis, instrumental analysis, calorimetry and/or construction of electrochemical cells; precision, accuracy, reliability and validity of data; and minimisation of experimental bias

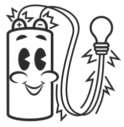
Key knowledge units

Sources of error	4.3.5.2.2
Ensuring accuracy and precision of your experiment	4.3.3.3
Limitations	4.3.5.2.3



Key terms and definitions of this lesson

- **Accuracy** how close measured values are to their true value
- **Errors** difference between true value and measured value
- **Precision** how close measured values are to each other
- **Personal error** result of mistakes or misinterpretations of methods and/or readings by the experimenter
- **Systematic error** error in measurement by the same amount / proportion in the same direction every time which also includes errors that are inherent in the experiment.
- **Random error** error in measurement that differs in amount / proportion each time experiment is conducted and is usually a 'one-off' error
- **Uncertainty** level of doubt around the data measured (for VCE purposes, we are only looking at this from a qualitative perspective)
- **Bias** difference between the average of a large set of measurements and the true value
- **Significant figures** number of digits required to express a number to a certain level of accuracy
- **Validity** whether or not the experiment (and its components) is suitable to address the aim and hypothesis of the research



- **Reproducibility** closeness of results from repeated experiments using the same method under different conditions
- **Repeatability** closeness of results obtained using the same method, materials and under the same conditions
- **Reliability** experiment is able to produce consistent results even in varying conditions
- **Outliers** results that fall outside the expected range

Sources of error 4.3.5.2.2

OVERVIEW

During experiments, there are various sources of error that can affect the measurement of data.

THEORY DETAILS

As much as we try to carefully control the conditions of an experiment, there's always a possibility that errors could occur that would affect the measurement of results. As a result, there may be a level of uncertainty with the data collected during the experiment. There are two main sources of **uncertainty**; systematic errors and random errors. For the scope of the study design, we will only need to understand the qualitative nature of uncertainties, that is non-numerical variables. In the context of scientific measurements, **errors** are the difference between the value that is measured and the true value of what is being measured.

Systematic errors

Systematic errors are errors which affect the **accuracy** of a measurement in a consistent manner. These types of errors cause measured values to be skewed by a consistent amount every time. Systematic errors can be inherent in the apparatus used or the method employed in the experiment and therefore can often be identified and compensated for. For example, a mass balance may be calibrated 0.05 g higher than the true value, therefore any measurements taken using this apparatus will be consistently higher than the true value by 0.05 g. Another example of a systematic error occurs when reading the volume of a liquid in a beaker or graduated cylinder using the meniscus line, as shown in figure 1. The meniscus is the curve of the surface of a liquid in a container. If the experimenter reads the instrument at an angle that is consistently too high or too low, the measurement taken will be inaccurate due to a perceived shift in the level of the liquid – this is known specifically as a parallax error. For the measurement to be accurate, the level of the liquid must be read at a straight line of sight. It is important to note that these types of errors cannot be rectified by repeating an experiment. However, a careful analysis of the apparatus and method employed may enable the experimenter to identify possible sources of systematic error and make relevant changes to eliminate them.

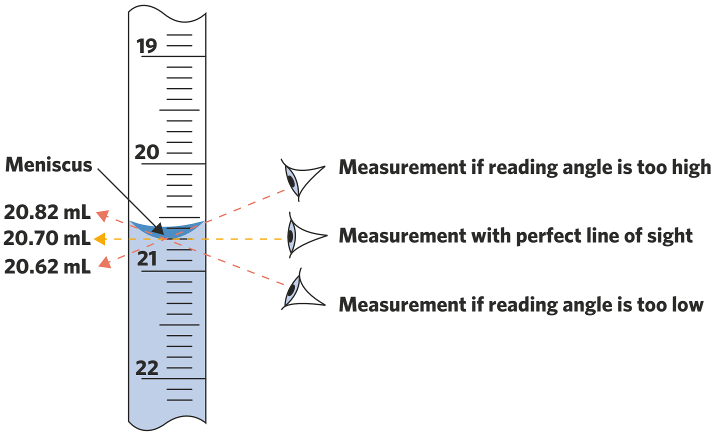


Figure 1 Systematic error in misreading the meniscus line

In order to reduce the impact of systematic errors on the measured values, measuring apparatus used should be calibrated prior to conducting the experiment. Another effective method in reducing the effect of systematic errors is to change the experiment. For example, including a step in the method that explicitly outlines the steps required to calibrate the apparatus used in the experiment.

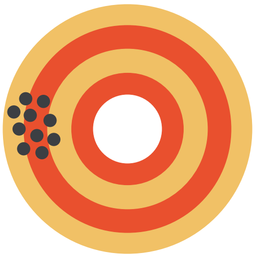
Referring back to the avocado experiment, an error would be the point at which we consider the avocado to have 'browned'. Is it when it starts browning, is evenly brown or when it is completely brown? This kind of measurement is subjective and is built into the experimental methodology, as such, we would consider this as a systematic error. This error can also affect the precision of the measurements as different experimenters could have a different understanding of 'browning', consequently affecting the repeatability and reproducibility of the experimental results. A way in which we can rectify this is to introduce a step that would allow for quantitative analysis of the amount of browning, using techniques such as UV Vis, and develop an understanding of the point at which the flesh can be considered as 'browning' based on a numerical value.

Random errors

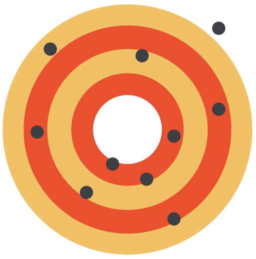
Random errors are unpredictable errors resulting in a spread of measurements. These are always present during measurement. This type of error includes instances where subjective judgements need to be made often quickly about occurrences in an experiment such as the formation of a substance. Random errors can also occur when the experimenter needs to estimate a measurement that falls between the lines in a measuring instrument. An example of this would be the varying titre volumes obtained during a titration – some are too high and some too low due to the subjective determination as to when the end point is reached. This concept will be explored further in lesson 8F. The effect of these errors can be minimized by repeating measurements multiple times and calculating the average of the results obtained.

A random error relevant to our avocado experiment may be slight fluctuations in air temperature resulting in faster or slower browning of the avocados.

Both types of errors affect results in a different way. Figure 2 and 3 highlight the main difference between the two.



Systematic error



Random error

Figure 2 Distinctions between systematic and random errors

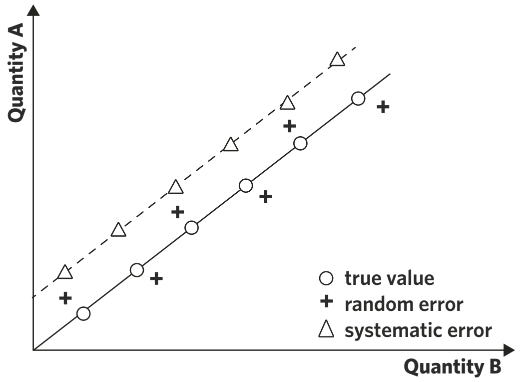


Figure 3 A graphical representation of the effect of random and systematic errors

The gap that exists between the average of repeated experiments and the data including systematic errors is known as the **bias**. Taking steps to minimize the systematic and random errors as mentioned above reduces bias in an experiment.

Personal errors

Another type of error that exists is **personal errors**. These types of errors are generally mistakes made by the experimenter that stem from misinterpretation of information or method. Examples of this type of error include miscalculations, taking measurements that don't relate to the purpose of the experiment and misreading scales of measuring apparatus. Personal errors can be eliminated by repeating the experiment in the correct manner.

Returning to our avocado experiment, an example of a personal error may be the experimenter misreading the scales when weighing the various avocado pieces for use in the study. In turn, this would lead to an uncontrolled variable (different mass of avocado pieces) and may undermine the validity of the experiment due to the introduction of an uncontrolled variable.

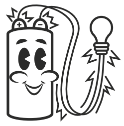
It's important to note that personal errors are different from uncertainties in that personal errors are avoidable errors made by the experimenter whereas uncertainties refer to the extent of doubt associated with data.

Errors and the three R's

The presence of errors can affect the **reproducibility, reliability** and **repeatability** of results.

Reproducibility describes the closeness of values measured from repeated experiments under different conditions, where changes in equipment, environmental conditions and experimenters can all be considered as different conditions. The more the conditions vary, the greater the chances of introducing random errors into the experiment. The use of precise apparatus and increasing the number of measures taken can improve the reproducibility of results.

Repeatability gives information about how close measured values are from repeated experiments conducted using the same method, under the same conditions by the same experimenter. For example, concordant values measured during a titration experiment are said to be repeatable if they are obtained by the same experimenter using the same equipment and experimental method in the same lab on that day. The repeatability of an experiment can also be improved by the use of precise equipment and increasing the number of measurements taken.



Reliability refers to whether or not consistent results can be achieved when conducting the same experiment under varying conditions. For example, an electrolytic experiment conducted by different experimenters yielding consistent results would be considered as reliable. Repeating an experiment and averaging results can increase reliability. At times, results are obtained that are outside the expected range. These are known as **outliers** and should be further investigated rather than disregarded.

Ensuring accuracy and precision of your experiment 4.3.3.3

OVERVIEW

When collecting data from experiments, we want to ensure that the results are as accurate and precise as possible.

THEORY DETAILS

Experiments do not always yield data that is accurate and precise. Depending on the type of research and the data collected, measurements can be accurate but not precise, and vice versa. Where **accuracy** talks about how close the measurements are to the true value, **precision** describes how 'close' the measured values are to each other. The model in figure 4 highlights the differences between the two ideas.

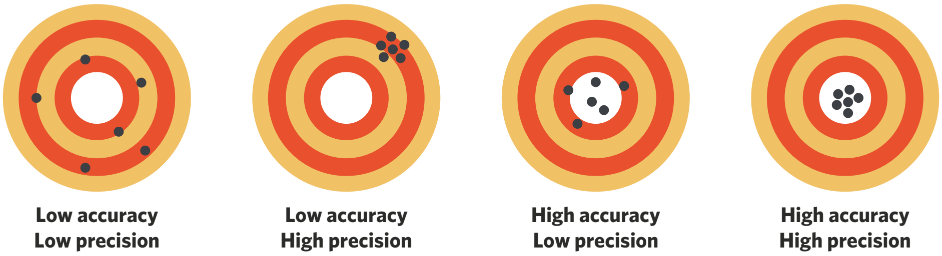


Figure 4 Illustration depicting the key differences between the levels of accuracy and precision

The accuracy of an experiment is greatly affected by systematic errors in the experimental design. Elements of an experiment that can affect the accuracy of an experiment include:

- Purity of substances
- Methods that are vague
- Apparatus that are not cleaned or calibrated appropriately before use

Removing systematic errors in an experiment can greatly increase the accuracy of the measured values. A way in which we can test the accuracy is to determine the measurement error of the results, which can be done by finding the difference between the measured value and the true value.

Unlike the accuracy, precision is more affected by random errors. In experiments where results require a level of estimation, precision is compromised. This can occur when we use measuring apparatus with large graduations for experiments that require small measurements. For example the use of a kitchen scale that measures to the nearest whole number is used to measure precipitates that vary by 0.01 g. Using appropriate apparatus and repeating experiments will improve precision.

It is important to be able to collect data that is both accurate and precise as it affects the results of the experiment and therefore the overall conclusion that can be made about an experiment. Both of these can affect the **validity** of an experiment – whether or not the results obtained by the experimental design are able to answer the aim or hypothesis. There are two subcategories of validity; internal and external. Internal validity indicates whether or not the experimenter followed the correct procedures, for example using equipment that allowed the collection of accurate and precise data. External validity identifies any confounding factors that may impact the results, for example if there were any other variables apart from the independent and dependent variables that could have led to the results obtained. To ensure the validity of results, it is important to make sure that:

- Controlled variables are constant
- Appropriate apparatus is used that collects accurate results
- The data is collected under appropriate environmental conditions
- The method actually tests the hypothesis

Significant figures

The number of digits we use to express measurements suggest the error in the measurement itself. It's important to not confuse **significant figures** with the number of decimal places.

When counting significant figures, the general rules are:

- Start counting significant figures starting with the first non-zero digit, and read from left to right.
- Every zero after we start counting our significant figures is considered insignificant unless followed by a non-zero digit or a decimal place.

This is important when it comes to the number of digits used to express answers. Depending on the number of significant figures of the data presented in the question and the type of calculation being performed, there are slightly different rules as to the total number of digits or significant figures expressed in answers.

During addition/subtraction, express the answer with as many digits on the right of the decimal place as there are for the number with the fewest digits to the right of the number involved in the calculation.

During multiplication/division, express the answer to the same number of significant figures as the value with the least number of significant figures involved in the calculation.

Consider the following calculations:

$2.113 + 1.98$	5.34×8.6
Answer is expressed to 2 decimal places	Answer is expressed to 2 significant figures
(based on the number 1.98)	(based on the number 8.6)

It is important that we don't round off too much and too soon in multi-step calculations as this will lead to inaccurate answers.

Also, when recording experimental data in a table, numbers within the same column should be written to the same number of decimal places.

1 Worked example

Calculate the amount of carbon dioxide present in a 4.11 g sample of carbon dioxide. Express your answer to the correct number of significant figures.

What information is presented in the question?

The mass of carbon dioxide.

What is the question asking us to do?

Calculate the amount, in mol, of CO_2 in 4.11 g.

What strategy(ies) do we need in order to answer the question?

1. Determine the molar mass of carbon dioxide.
2. Calculate the amount of carbon dioxide present.
3. Check that answer is expressed in the right number of significant figures.

Answer

$M(CO_2) = 12.0 + 16.0 \times 2 = 44.0 \text{ g mol}^{-1}$

$n(CO_2) = \frac{4.11}{44.0}$

$= 0.09341$

$= 0.0934$ correct to 3 sig figs

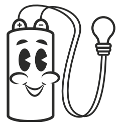
Limitations 4.3.5.2.3

OVERVIEW

Although we have measures in place to ensure the quality of the research method, there are still limitations that affect the overall research.

THEORY DETAILS

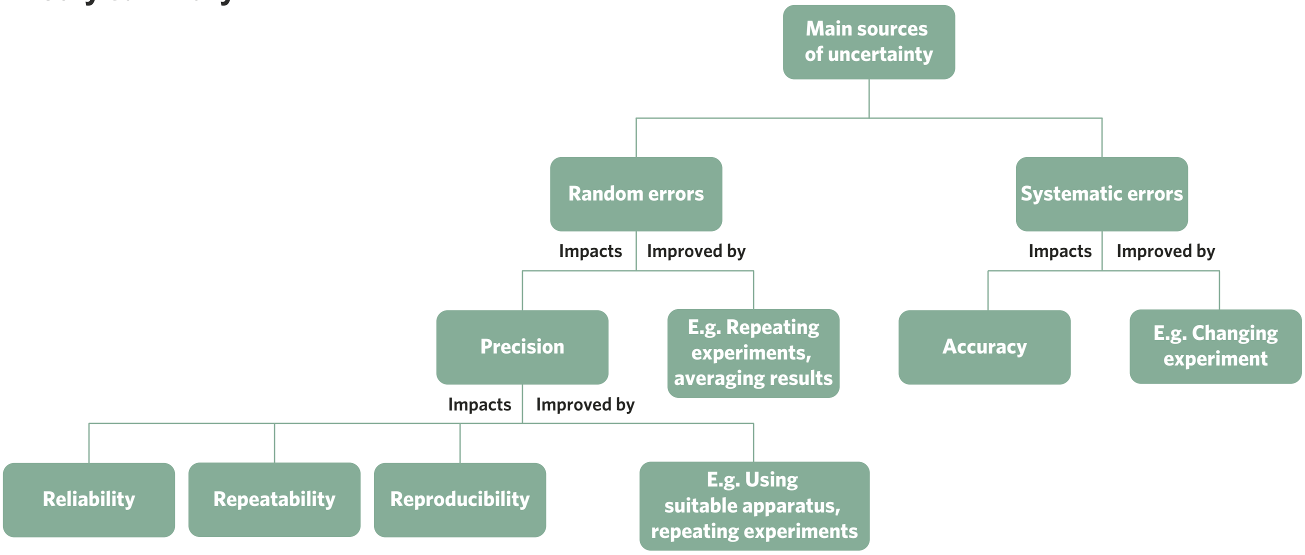
The scientific method is a very useful tool that can allow us to investigate ideas to gain a better understanding of our world. There are many different factors taken into account when designing and conducting an experiment to make sure that the conclusions made are sound.



However, there will always be uncontrolled variables making it difficult to identify a relationship between independent and dependent variables thereby limiting the accuracy and validity of conclusions drawn. These limitations can arise from the design and methodology of the experiment itself, or even the environment in which the experiment is conducted.

The experiments that contributed to the development of our current understanding of science were conducted under certain conditions, and therefore the data and conclusions made are accurate for those particular conditions. For example, the information presented in the data book is true under SLC conditions as stated in the data book. However, when we conduct experiments that fall outside of those conditions, the values we use in our calculations may not be 100% accurate, which in turn affects the quality of our data.

Theory summary



- Measurements can be precise but not accurate.
- Experimenters aim to collect valid, precise, accurate, repeatable, reliable and reproducible data.
- There are many types of errors: systematic, personal and random.
- Depending on the calculation performed, the rules that dictate the number of significant figures an answer needs to be expressed to changes.
- There are limitations to the data we collect and the method we use to investigate a research question, all of which can affect the validity of our results.

1D QUESTIONS

Theory review questions

Question 1

Which of the following statements is true?

A Uncertainties are the same as errors.

B Personal errors cannot be eliminated by repeating an experiment.

C As long as measurements are precise, they can also be considered as accurate.

D Systematic errors have a significant impact on the accuracy of data collected.

Question 2

With reference to significant figures,

A zeros are never counted.

B rounding off during a calculation can affect the accuracy of results.

C we must use the number with the greatest number of significant figures as a reference for our final answer.

D the rules used when adding and dividing are the same.

Question 3

A measurement is considered valid if

A all variables are different.

B it measures what it is supposed to.

C it has been checked by other experimenters.

D it is measured multiple times.

Question 4

Experiments are **most** limited by

A the methods used during the experiment.

B another experimenter performing the experiment.

C having very precise measuring tools.

D the controlled variable(s).

Exam-style questions

Within lesson

Question 5 (3 MARKS)

Curie conducted an experiment to measure the amount of sodium found in a food substance. The data has been provided.

	Test 1	Test 2	Test 3
Mass of sodium (mg)	100	122	82

According to the company, there is 99 mg of sodium found in every 100 g.

a Comment on the precision of these results. (2 MARKS)

b Based on the results obtained, what type of error is most likely to have occurred? (1 MARK)

Question 6 (4 MARKS)

Dorothy was making a cup of tea and was intrigued by the way water can be heated. To investigate heat transfer, she conducted an experiment to figure out the amount of energy absorbed by some water.

The data she recorded is provided.

Mass of the beaker and water	330.1 g
Initial temperature	22.5 °C
Final temperature	71.0 °C
Energy absorbed	66.9 kJ
Mass of fuel used	1.22 g

Comments:

I calculated the amount of energy absorbed by the water using 330.1 g because that was the mass of the water used. All of the energy from the fuel source was transferred into the water and caused the water to increase in temperature.

1.22 g of this fuel contains 66.9 kJ of energy.

a Based on the information provided, identify the type of error that occurred in this experiment. (1 MARK)

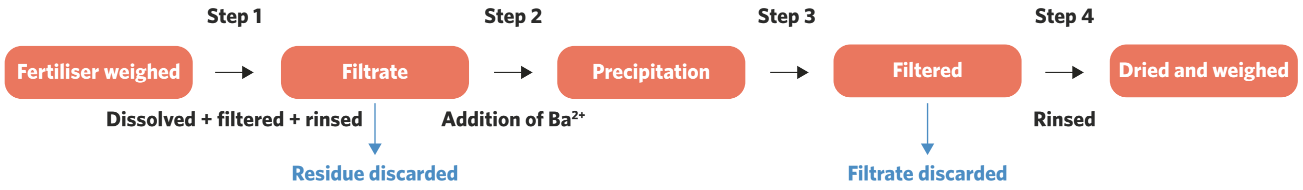
b Comment on Dorothy's calculation of the energy absorbed by the water. (2 MARKS)

c What assumption did Dorothy make when claiming that 1.22 g of her fuel contains 66.9 kJ? (1 MARK)

Question 7 (10 MARKS)

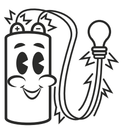
Sulfur is important for photosynthesis in plants. As a result, companies add sulfate into fertilisers to improve crop growth.

This flowchart shows the process involved in determining the amount of sulfate present in lawn fertilisers.



Adapted from NESA 2010 Exam Section II Q29

a A student conducting this experiment accidentally used a piece of filter paper with a slight tear in it in step 1. Identify the type of error that occurred during this step. (1 MARK)



b During step 4, the student was asked to leave the filtered sample in an incubator to allow the sample to dry. The student periodically weighed the sample until they were satisfied that the sample was completely dry. The student decided that after 3 measurements, the sample would be completely dry. The results are provided.

	Measurement 1	**Measurement 2**	**Measurement 3**
Mass (g)	14.01	13.55	10.89

i Comment on whether or not it was appropriate for the student to have stopped weighing the sample after three measurements. (3 MARKS)

ii Given that the fertiliser sample analysed was 1.445 g, determine the total number of significant figures that would be required in the answer if the student were to calculate the % of sulfur present in the sample. (1 MARK)

c Identify one way that the student could increase the precision of their measurements in part b. (2 MARKS)

d Outline a possible systematic error relevant to this experiment and explain how it could have impacted upon results. (3 MARKS)

Multiple lessons

Question 8 (3 MARKS)

All enzymes are proteins. Polyphenoloxidase (PPO) is an enzyme that catalyses the browning of fruit and vegetables. This catalytic reaction can be studied in the laboratory by monitoring the oxidation of a phenol to a quinone, a red compound. The intensity of the red colour indicates the extent of the reaction. A student studied the enzyme activity of PPO in relation to a number of biological factors, using quinone colour as a measure of activity. The following table summarises the results of one set of these experiments.

pH at 37 °C	3.0	4.0	5.0	6.0	7.0	8.0
Colour	colourless	light red	medium red	dark red	dark red	colourless

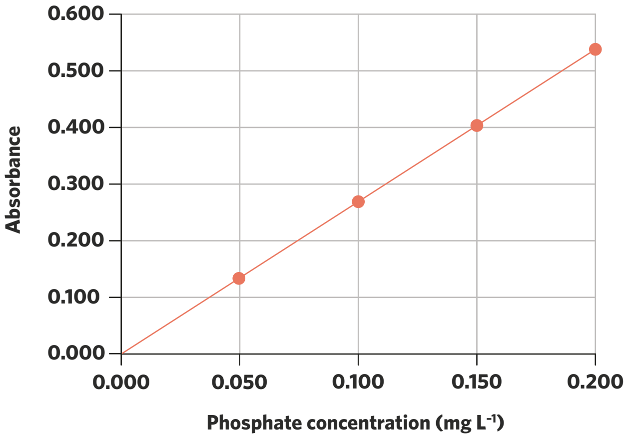
Adapted from NESA 2009 Exam Section II Q29b

a What type of data is being collected in this experiment? (1 MARK)

b If this experiment was repeated by another experimenter, do you expect the results to be identical? Explain. (2 MARKS)

Question 9 (5 MARKS)

An analytical chemist determined the phosphate concentration of water samples from three local streams. The graph provided is a calibration curve developed for this experiment.



Adapted from NESA 2009 Exam Section II Q25a

The results for the streams are as follows.

Stream	**Absorbances measured**
1	0.090, 0.092, 0.088
2	0.513, 0.511, 0.514
3	0.234, 0.237, 0.234

a Which of the set of results is the most precise? (2 MARKS)

b Order the streams from greatest to smallest in terms of the concentration of phosphate. (1 MARK)

c After the experiment was conducted, the experimenter realised that the instrument used to measure the absorbance of the sample was consistently giving data that was 0.002 units higher than the true value. What type of error is this? (2 MARKS)

1E PRESENTING YOUR FINDINGS

In this lesson we will learn about the conventions of scientific writing, and how we use these to present findings to the scientific community.

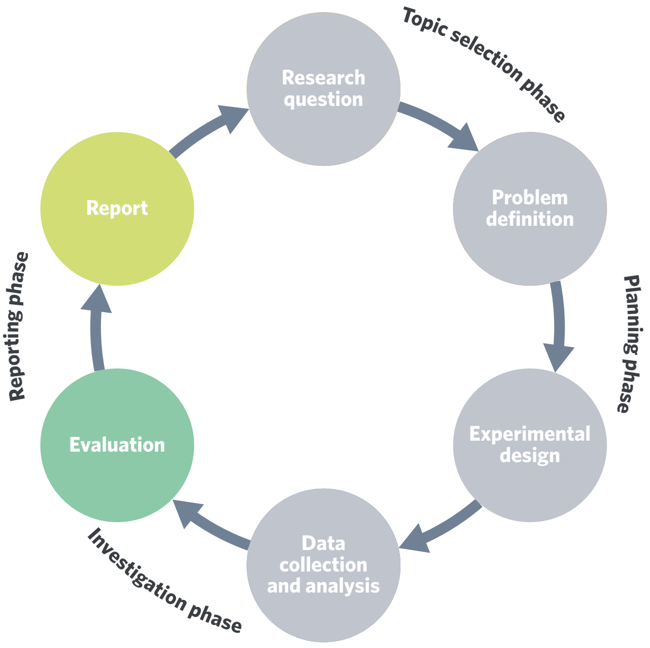
1A Planing your investigation question	1B Conducting your experiment	1C Collecting data	1D Ensuring quality data	1E Presenting your findings

Study design dot points

- models and theories and their use in organising and understanding observed phenomena and chemical concepts including their limitations
- the nature of evidence that supports or refutes a hypothesis, model or theory
- the key findings of the selected investigation and their relationship to thermochemical, equilibrium and/or organic structure and bonding concepts
- the conventions of scientific report writing and scientific poster presentation including chemical terminology and representations, symbols, chemical equations, formulas, units of measurement, significant figures, standard abbreviations and acknowledgment of references.

Key knowledge units

Supporting your evaluation	4.3.6.1 & 4.3.7.1 & 4.3.8.1
Scientific writing	4.3.9.1



Supporting your evaluation 4.3.6.1 & 4.3.7.1 & 4.3.8.1

OVERVIEW

Analysis of experimental data indicates key findings of the research, which can be explained using current scientific theories and models.

THEORY DETAILS

Our understanding of scientific concepts and models have been developed from the findings of countless experiments that have been conducted previously. As a result, all of the research conducted from this point forward, including our own, can help to further develop this understanding.

The foundation of present-day research is the models and theories that are currently available and accepted by the scientific community. We use these concepts to not only justify the direction of our research but to also explain the key findings identified by the experimental data. Although our evaluations are founded in experimental and theoretical perspectives, this does not necessarily mean that the hypothesis will always be supported. Irrespective of whether data obtained supports or rejects the hypothesis, it is important that we use related models and theories to help understand and explain the experimental results and provide areas for future research.

It is important to note that even if the data from our experiment supports or rejects our hypothesis or a certain theory or model, this does not mean that the hypothesis, theory or model has been proven. No scientific theory, model or hypothesis even if there is extremely compelling evidence to support or reject it can be proven as new data is constantly being collected through experimentation requiring constant revision of our current understanding of scientific phenomena.

Let's apply this idea to the ongoing investigation throughout this chapter.

The literature search during the planning stages of the investigations would have identified that avocado browning occurs due to chemical processes that result in the polymerisation of compounds known as quinones into polymers called polyphenols. These chemical reactions only occur when the avocado flesh is exposed to oxygen in the air and are aided by a specific enzyme known as polyphenol oxidase. Therefore, to reduce browning of avocados, we can either minimize oxygen exposure or reduce the activity of the enzyme involved in the process. Further investigation into the function of enzymes, an idea that we will further investigate in our book, will show that enzymes are active under specific conditions. This is the theoretical premise behind our investigation and is what we use to unpack and evaluate the experimental results illustrated in lesson 1C.

If we refer back to the results of the experiment in figure 1, we can see that the increase in acid concentration decreases the rate at which an avocados brown. From a theoretical perspective, we can explain this using our understanding of the function and structure of enzymes and the impact of changes in pH on enzyme activity. Depending on this information, we may even be able to relate the degree of browning to the capacity of the enzyme to function at the pH of HCl used in this experiment. To be even more precise, we can relate this specifically to polyphenol oxidase using evidence from previous research that is specific to this enzyme.

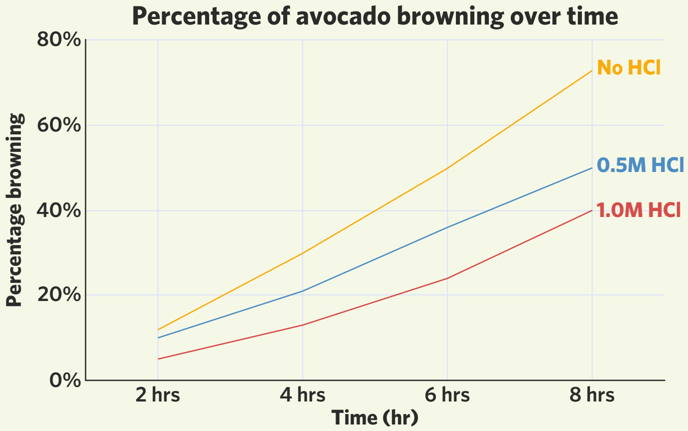
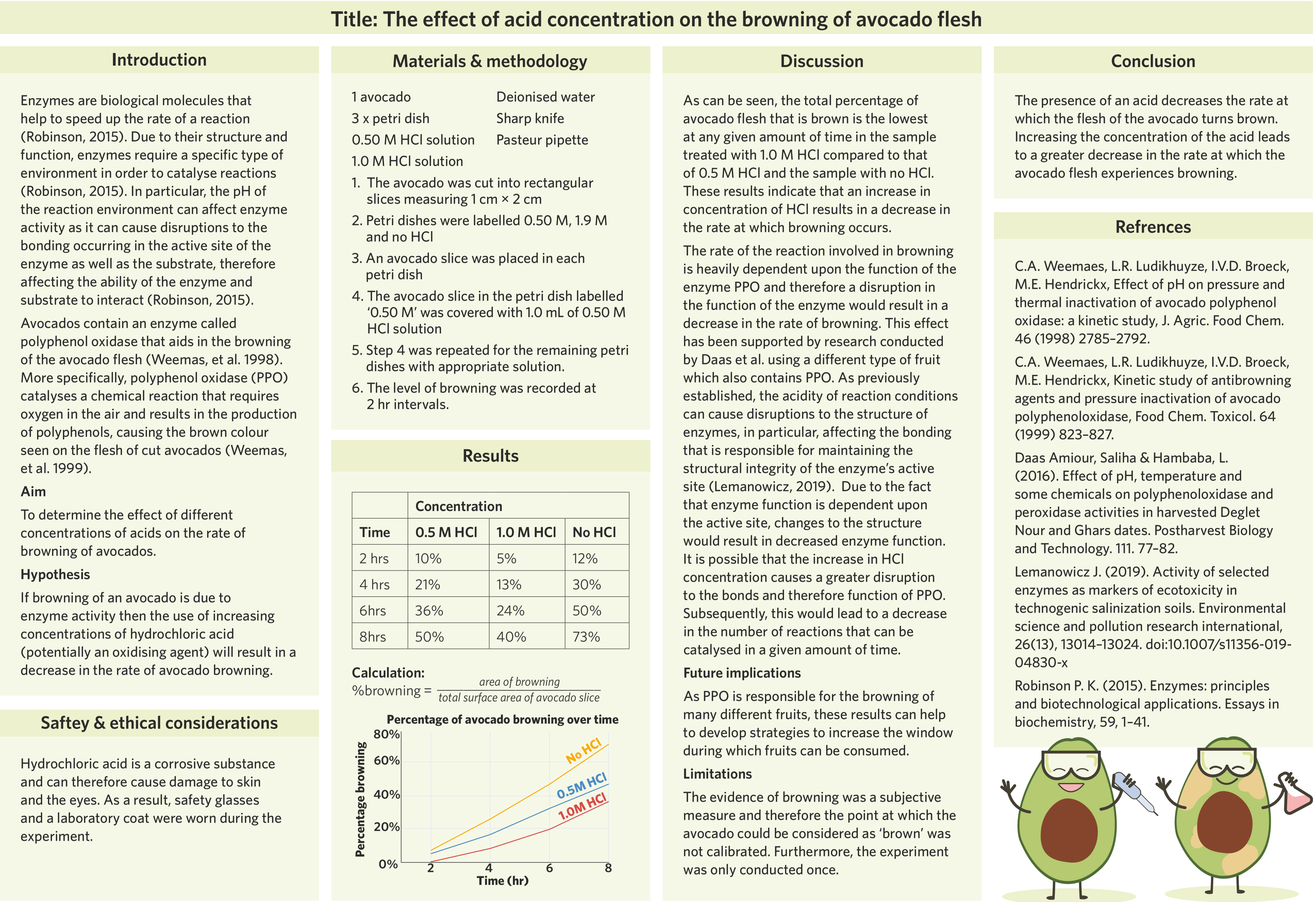


Figure 1 Graph representing the percentage of avocado browning when treated with different acid concentrations over time

The hypothesis formulated for this experiment was:

If browning of an avocado is due to enzyme activity then the use of increasing concentrations of hydrochloric acid will result in a decrease in the rate of avocado browning.

Based on the raw data presented, it is implied that the hypothesis is supported. However, we need to remember that in order to be confident that our conclusion is accurate, valid and precise, we need to ensure that errors that may have occurred during the experiment are acknowledged and accounted for (as best we can). For this particular experiment, due to the fact that it was conducted only once, and that the judgement of 'browning' is quite subjective, we cannot guarantee that the data is accurate, valid and precise. As a result, although there is a correlation that is evident between our independent and dependent variables, we aren't able to conclude there is a causal relationship.



Title: The effect of acid concentration on the browning of avocado flesh

Introduction

Enzymes are biological molecules that help to speed up the rate of a reaction (Robinson, 2015). Due to their structure and function, enzymes require a specific type of environment in order to catalyse reactions (Robinson, 2015). In particular, the pH of the reaction environment can affect enzyme activity as it can cause disruptions to the bonding occurring in the active site of the enzyme as well as the substrate, therefore affecting the ability of the enzyme and substrate to interact (Robinson, 2015).

Avocados contain an enzyme called polyphenol oxidase that aids in the browning of the avocado flesh (Weemas, et al. 1998). More specifically, polyphenol oxidase (PPO) catalyses a chemical reaction that requires oxygen in the air and results in the production of polyphenols, causing the brown colour seen on the flesh of cut avocados (Weemas, et al. 1999).

Aim

To determine the effect of different concentrations of acids on the rate of browning of avocados.

Hypothesis

If browning of an avocado is due to enzyme activity then the use of increasing concentrations of hydrochloric acid (potentially an oxidising agent) will result in a decrease in the rate of avocado browning.

Saftey & ethical considerations

Hydrochloric acid is a corrosive substance and can therefore cause damage to skin and the eyes. As a result, safety glasses and a laboratory coat were worn during the experiment.

Materials & methodology

1 avocado	Deionised water
3 x petri dish	Sharp knife
0.50 M HCl solution	Pasteur pipette
1.0 M HCl solution	

1. The avocado was cut into rectangular slices measuring 1 cm × 2 cm
2. Petri dishes were labelled 0.50 M, 1.9 M and no HCl
3. An avocado slice was placed in each petri dish
4. The avocado slice in the petri dish labelled '0.50 M' was covered with 1.0 mL of 0.50 M HCl solution
5. Step 4 was repeated for the remaining petri dishes with appropriate solution.
6. The level of browning was recorded at 2 hr intervals.

Results

	Concentration		
Time	0.5 M HCl	1.0 M HCl	No HCl
2 hrs	10%	5%	12%
4 hrs	21%	13%	30%
6hrs	36%	24%	50%
8hrs	50%	40%	73%

Calculation:

$$\%\text{browning} = \frac{\textit{area of browning}}{\textit{total surface area of avocado slice}}$$

Percentage of avocado browning over time

Discussion

As can be seen, the total percentage of avocado flesh that is brown is the lowest at any given amount of time in the sample treated with 1.0 M HCl compared to that of 0.5 M HCl and the sample with no HCl. These results indicate that an increase in concentration of HCl results in a decrease in the rate at which browning occurs.

The rate of the reaction involved in browning is heavily dependent upon the function of the enzyme PPO and therefore a disruption in the function of the enzyme would result in a decrease in the rate of browning. This effect has been supported by research conducted by Daas et al. using a different type of fruit which also contains PPO. As previously established, the acidity of reaction conditions can cause disruptions to the structure of enzymes, in particular, affecting the bonding that is responsible for maintaining the structural integrity of the enzyme's active site (Lemanowicz, 2019). Due to the fact that enzyme function is dependent upon the active site, changes to the structure would result in decreased enzyme function. It is possible that the increase in HCl concentration causes a greater disruption to the bonds and therefore function of PPO. Subsequently, this would lead to a decrease in the number of reactions that can be catalysed in a given amount of time.

Future implications

As PPO is responsible for the browning of many different fruits, these results can help to develop strategies to increase the window during which fruits can be consumed.

Limitations

The evidence of browning was a subjective measure and therefore the point at which the avocado could be considered as 'brown' was not calibrated. Furthermore, the experiment was only conducted once.

Conclusion

The presence of an acid decreases the rate at which the flesh of the avocado turns brown. Increasing the concentration of the acid leads to a greater decrease in the rate at which the avocado flesh experiences browning.

Refrences

C.A. Weemaes, L.R. Ludikhuyze, I.V.D. Broeck, M.E. Hendrickx, Effect of pH on pressure and thermal inactivation of avocado polyphenol oxidase: a kinetic study, J. Agric. Food Chem. 46 (1998) 2785–2792.

C.A. Weemaes, L.R. Ludikhuyze, I.V.D. Broeck, M.E. Hendrickx, Kinetic study of antibrowning agents and pressure inactivation of avocado polyphenoloxidase, Food Chem. Toxicol. 64 (1999) 823–827.

Daas Amiour, Saliha & Hambaba, L. (2016). Effect of pH, temperature and some chemicals on polyphenoloxidase and peroxidase activities in harvested Deglet Nour and Ghars dates. Postharvest Biology and Technology. 111. 77–82.

Lemanowicz J. (2019). Activity of selected enzymes as markers of ecotoxicity in technogenic salinization soils. Environmental science and pollution research international, 26(13), 13014–13024. doi:10.1007/s11356-019-04830-x

Robinson P. K. (2015). Enzymes: principles and biotechnological applications. Essays in biochemistry, 59, 1–41.

Figure 2 Scientific poster representing research on the effect of acid concentration on the browning of avocados

Scientific writing 4.3.9.1

OVERVIEW

When presenting scientific research, there is a particular format in which the information needs to be presented.

THEORY DETAILS

When communicating ideas, scientists follow a particular framework. Whether it is a journal article or a poster, the format is generally the same. In fact, the format may seem quite familiar as it is something that all students who study science, regardless of year level, would have encountered previously.

To make this more contextual, we will further explore the idea of scientific writing through an analysis of a scientific poster presented in figure 2 that was developed for the research question identified early in the chapter. Although this is presented in a poster format, the ideas explored also apply when writing scientific reports and/or articles.

The general flow of the way in which the information is presented is can be seen in figure 3.

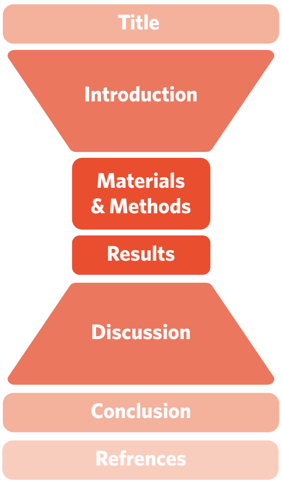


Figure 3 General outline of a scientific write up

Different sections require slightly different types of information, and to a particular depth. Figure 4 gives an overview of the key concepts covered in each major section.

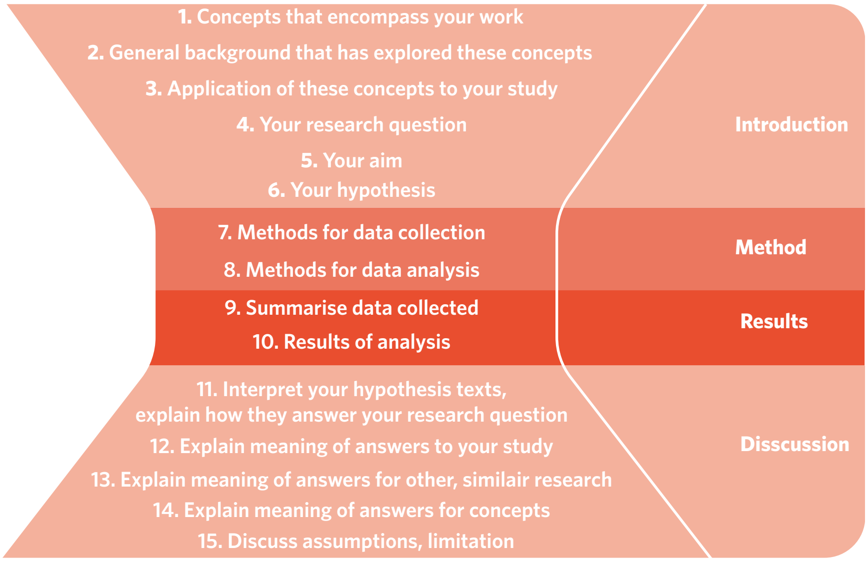


Figure 4 Main ideas covered in each section of a scientific write up

As illustrated in figure 4, both the introduction and discussion sections require a substantial level of depth. The purpose of the introduction is to give the reader the context of the investigation by providing a background of the relevant concepts that are to be explored as part of the research. The discussion section is where the experimental results are interpreted and analysed, and is the place where connections are made to current theories, as well as highlighting the implications of the results to the wider community.

In comparison, the conclusion and reference section are relatively small, where the conclusion gives a summary of the key finding(s) and the references identify the sources used to develop and/or support the experimental ideas. There are many different formats in which the references can be presented, and this can vary depending on the requirement of the subject, journal, etc.

Different scientific disciplines have different concepts, theories and ways in which they represent ideas. For Chemistry, the language used to convey ideas needs to align with the way in which chemical ideas are represented, including the use of symbols, equations, appropriate units etc. Also, personal language is not used when writing the research report/poster, therefore words such as ‘I, we, us’ are generally not included. Instead, third person language and usually the past tense is employed in scientific writing.

Theory summary

- There is a particular way in which scientific research is presented and communicated to the wider community.
- Different sections of a scientific write up require different information.
- Experimental results need to be analysed and connected to past and potential future research.
- Personal language is not used in scientific writing.
- Scientific writing usually uses the past tense.

1E QUESTIONS

Theory review questions

Question 1

When presenting experimental findings

A there is no need to reference theoretical concepts.
B the experimenter is able to choose the sequence in which the information is presented.
C there is no need to include units of measurement.
D we need to use appropriate chemical representations, including symbols and formulas.

Question 2

The conclusion of an experiment

A can refute the hypothesis.
B will always support the hypothesis.
C does not have to be supported by theories and models.
D does not have to align with the experimental data collected.

Question 3

When developing a scientific poster, the discussion section

A occurs last.
B acts to restate the data collected.
C expands on the implications of the experimental data collected.
D is not always required.

Exam-style questions

Within lesson

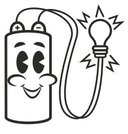
Question 4 (1 MARK)

Collision theory states that chemical reactions will only occur if the following criteria are met:

1 Particles collide
2 Particles collide with a sufficient amount of energy
3 Particles collide at the correct orientation

This criteria will vary slightly for different reactions as different reactions require slightly different conditions. Which of the following statements would support this theory?

A Reactants will always be completely consumed in a reaction.
B All chemical reactions will always have a 100% yield.
C HCl and NaOH will always react at any temperature.
D There is a chance that, at a temperature of 50 °C, magnesium ribbon will react with the atmosphere.



Question 5 (3 MARKS)

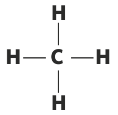
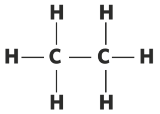
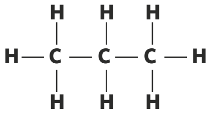
The following is an excerpt from a chemistry resource:

> Dispersion forces are created by spontaneous dipole-dipole moments that occur due to the random movement of electrons. These forces are very weak but can become significant when the number of electrons in a molecule increases and thus the size of the molecule, or the molecules are closely spaced to each other.

Based on this, a student decided to conduct an experiment. The results from the experiment are shown.

a Identify the trend that can be seen from the data. (1 MARK)

b Determine whether or not the results from the experiment support the theoretical concept stated in the excerpt. (2 MARKS)

Alkane	Boiling point (°C)	Structure
Methane	-164	
Ethane	-89	
Propane	-42	

Question 6 (3 MARKS)

This question relates to the scientific poster illustrated in figure 2.

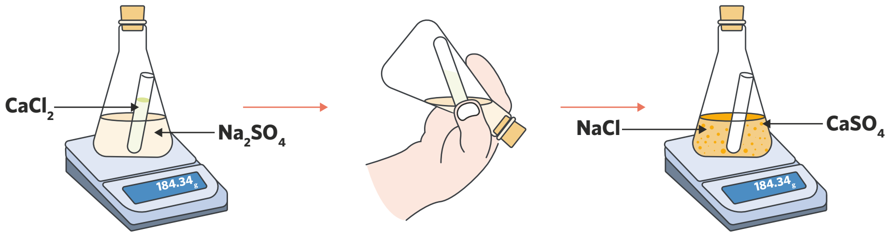
a Identify the main reason for the decrease in the rate of browning as highlighted by the discussion section of the poster. (2 MARKS)

b Outline whether only conducting the study once is relevant to the repeatability, accuracy or precision of results in each experiment. Assume that subsequent experiments are under the same conditions. (1 MARK)

Multiple lessons

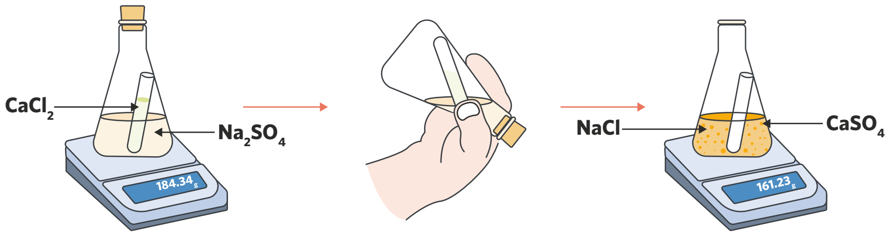
Question 7 (7 MARKS)

Lavoisier conducted an experiment that led to the discovery of the law of conservation of mass. A similar experiment is shown.



a Based on the experiment conducted, what conclusion can be made about the law of conservation of mass? (1 MARK)

b He conducted a subsequent experiment to identify the parameters at which this law is true. The second experiment is shown.



  i How does the result in this experiment further develop the initial concept identified in part a? (2 MARKS)

  ii Lavoisier conducted further experiments, in which the results allowed him to make the following statement about the law of conservation of mass:

  "Mass is neither created nor destroyed in chemical reactions."

  What implication does this have on the results in experiment 2, and subsequently the conclusion developed in question b.i? (2 MARKS) iii In this experiment, what type of data is being collected? (1 MARK)

c A student is conducting an experiment with the following aim.

To determine the change in mass of a reaction involving hydrochloric acid and sodium bicarbonate in a closed system.

Write an appropriate hypothesis. (1 MARK)

Question 8 (7 MARKS)

The solubility of a substance can be affected by the polarity of the solvent in which it is dissolved, as well as the temperature and pressure in which the experiment is conducted.

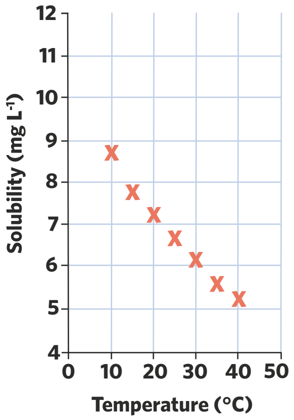


Image: NESA Exam 2013 Section II Q 33c

a Predict the temperature at which the solubility of oxygen would be 5 mg L^{-1}. (1 MARK)

b Identify the independent and dependent variables in the experiment. (2 MARKS)

c Prior to conducting the experiment, the experimenter developed the following hypothesis: "If solubility of a substance depends on the temperature of the reaction, then an increase in temperature would result in an increase in solubility". Using the results obtained, identify whether this hypothesis would be supported or refuted. (2 MARKS)

d Given the results obtained in the experiment, describe the implications this would have on deep sea divers when descending. (2 MARKS)

CHAPTER 1 QUESTIONS

MULTIPLE CHOICE (10 MARKS)

Question 1 (1 MARK)

Claudia conducted an experiment by adding 50 mL of 0.10 M hydrochloric acid to four different beakers, three of which contained 50 mL of different types of household cleaners and the remaining beaker contained water only.

In this experiment, the household cleaner used is referred to as the

A control.

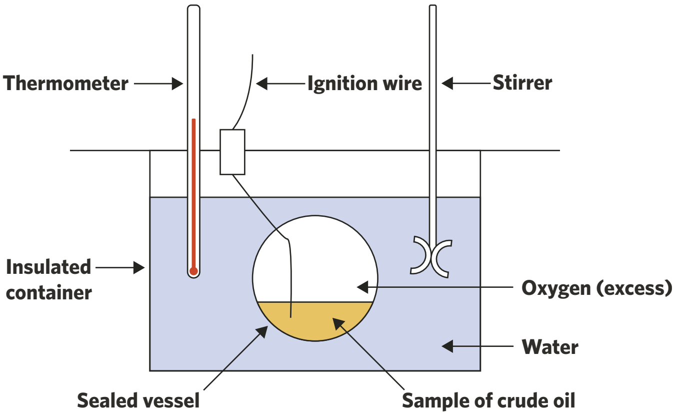
B dependent variable.

C controlled variable.

D independent variable.

Question 2 (1 MARK)

Crude oil is made of a mixture of different organic molecules. Ethan wanted to know how much heat can be released if the crude oil mixture is ignited in a sealed vessel. He was taught that the change in temperature of the surrounding water is an indicator of the amount of heat that's been released as a result of the reaction.



In this experiment, Ethan could maximise

A the validity of his results by calculating the number of moles of crude oil.

B accuracy by using crude oil from two different places.

C uncertainty by following a different method to his peers.

D precision by using a thermometer ±0.3 °C rather than a thermometer ±1.0 °C .

Question 3 (1 MARK)

Acetone is a commonly used solvent in many cleaning products with a boiling point of 56 °C. According to the MSDS (material safety data sheet), acetone comes with the following risks:

- Highly flammable
- Harmful by inhalation and if swallowed
- Repeated exposure may cause skin dryness and cracking
- Vapours may cause drowsiness and dizziness
- Irritant to eyes and respiratory system

If acetone were to be used in an experiment, it would be best to be carried out

A on the lab bench.

B close to a bunsen burner in a fume cupboard.

C in a fume cupboard.

D next to an operating fan with safety glasses on.

Question 4 (1 MARK)

Deb wrote a scientific poster for the experiment she conducted for her SAC. Below is an excerpt from her poster:

Question under investigation: Is there a relationship between the rate of the reaction between magnesium, Mg, and different concentrations of hydrochloric acid, HCl?

Equation for the reaction: $Mg_{(s)} + 2H^{+}_{(aq)} \rightarrow Mg^{2+}_{(aq)} + H_{2(g)}$

Experimental design: Four different concentrations of HCl were tested. The rate of each reaction was investigated by measuring the volume of hydrogen, H_2, gas produced at 60–second intervals.

Hypothesis: The greater the concentration of the acid, the faster the reaction will be. I expect this beacuse, for a reaction to occur, H^+ ions must collide with Mg atoms. The greater the concentration of the acid, the more frequently the H^+ ions will collide with the surface of the Mg and so the greater the amount of H_2 gas that wil be produced.

In the control, you would expect that

A the highest concentration of hydrochloric acid is used.

B no magnesium is added into the reaction.

C water is used instead of hydrochloric acid.

D there is a smaller volume of hydrochloric acid used compared to the other reactions.

Question 5 (1 MARK)

When performing a titration, it's important that the instrument used is rinsed appropriately so that the concentration of the reagent is not affected during the experiment. Usually, the burette is rinsed with the substance that will be used in it. If a student continually rinses the burette with water, this would affect the

A accuracy. **B** reliability. **C** uncertainty. **D** validity.

Question 6 (1 MARK)

A food company knows that there is only 100–102 mg of sodium chloride per packet of chips. Pumba conducted an experiment to confirm the company's claims.

Which set of results would be described as having a high level of precision but relatively low accuracy?

A 103 mg, 106 mg, 108 mg, 99 mg

B 82 mg, 92 mg, 88 mg, 105 mg

C 91 mg, 89 mg, 88 mg, 92 mg

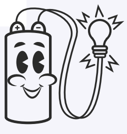
D 110 mg, 100 mg, 107 mg, 115 mg

Question 7 (1 MARK)

Tia wanted to conduct an experiment to measure how much acid was required to neutralise a particular base. While waiting for her partner to prepare the acid, Tia left the base on the lab bench. Unfortunately, the base she selected for her experiment also reacts with carbon dioxide in the air. In this case, the carbon dioxide acts as an acid and therefore reacts with her base. Forgetting this bit of information, she ran out of the lab quickly to get a drink of water.

Classify the type of error that has occurred and how this would affect the amount of acid used in the reaction.

	Type of error	Effect on the amount of acid used
A	Systematic	Lower than if the base was not contaminated
B	Systematic	Higher than if the base was not contaminated
C	Random	Lower than if the base was not contaminated
D	Random	Higher than if the base was not contaminated



Question 8 (1 MARK)

Jessie wanted to test whether or not different sweeteners have a different level of 'sweetness'. The table below was taken from her lab report.

Test tube	**1**	**2**	**3**	**4**
Contents	Sweetener A + 30 mL of water	Sweetener B + 30 mL of cola	Sweetener C + 30 mL of water	Sweetener D + 30 mL of cola

Notes:

- I added 1 tablet of each sweetener in each test tube.
- The sizes of each sweetener was different.

Which of the following components of the experiment would be **most** affected?

A Accuracy

B Reliability

C Validity

D Uncertainty

Question 9 (1 MARK)

Ariana was asked to submit a laboratory report for her class. However, due to time constraints, she was not able to conduct the experiment herself. To make sure she had data to work with, she searched online and read an article about an experiment very close to her own. Happy that the experiments were quite similar, she used the data (measured in mass) from this experiment to inform her discussion.

The data she used could be described as

A quantitative, primary data.

B quantitative, secondary data.

C qualitative, primary data.

D qualitative, secondary data.

Question 10 (1 MARK)

Florey wanted to conduct a test to see how using a catalyst can speed up the breakdown of hydrogen peroxide (H_2O_2). The table below shows the results from his experiment.

	Trial 1	**Trial 2**
Volume H_2O_2	100 mL	200 mL
Concentration H_2O_2	2.0 M	4.0 M
Catalyst	0.5 g MnO_2	50 mL 0.1 M $Fe(NO_3)_3$
Volume of oxygen produced	3.0	10.1

Which of the following statements is true regarding this experiment?

A The results are not accurate as the mass of the catalyst was measured in both grams and milliliters.

B The results are not precise as they were measured using different instruments.

C The results are not valid as many variables were changed.

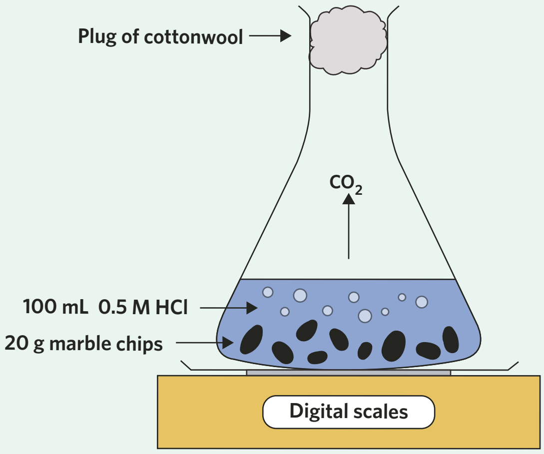
D The results are not consistent as they are not measured to the right significant figures.

SHORT ANSWER (20 MARKS)

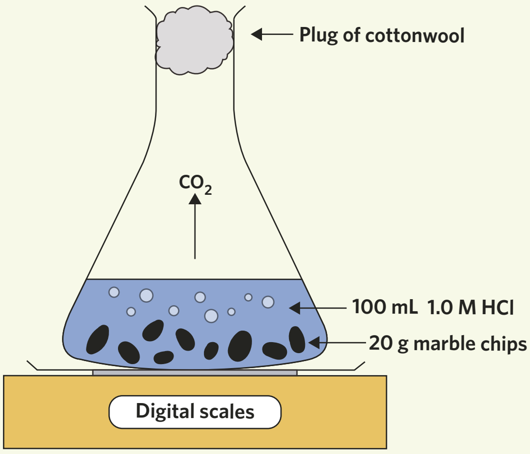
Question 11 (5 MARKS)

Ahmed decided to do a quick experiment as shown below. The experiment was set up to test the effect of different factors on the rate and extent of the reaction between a strong acid and marble chips (calcium carbonate). In each trial, the mass of the flask and its contents was measured every 30 seconds, from the instant the reactants were mixed.

Trial 1
The strong acid used was hydrochloric acid, HCl.
The equation for the reaction is as follows.
$2HCl_{(aq)} + CaCO_{3(s)} \rightarrow CaCl_{2(aq)} + CO_{2(g)} + H_2O_{(l)}$



Trial 2
One change to the reaction conditions was made and the experiment was repeated.



Adapted from VCAA 2016 Exam Ssection A Q27

a Identify the independent variable. (1 MARK)

b What would be the difference between trial 1 & 2 and a control setup? (1 MARK)

c According to the MSDS, strong hydrochloric acid could result in severe irritation if it comes into contact with the skin. Identify two main safety precautions that need to be taken. (2 MARKS)

d The scale used in the experiment was not recently calibrated. Identify the type of error that would occur as a result of this. (1 MARK)

Question 12 (4 MARKS)

Diana Prince was packing for her camping trip and came across two different bottles of fuel; butan-1-ol and propan-1-ol. Each bottle was marked to contain 100 g of fuel. Curious, she decided to set up an experiment to figure out which fuel would be able to give her more energy.

After some searching, she found that the best way to figure out the amount of energy available in each fuel bottle was to use the fuels to heat a beaker of water and then measure the temperature change as a result of using the fuel. The results can be seen below.

	Propan-1-ol	**Butan-1-ol**
Mass of fuel used	50 g	50 g
Temperature change (°C)	14.12	17.11
Volume of water heated during the experiment (mL)	100 mL	100 mL

a Write an aim for this experiment. (1 MARK)

b What can be concluded from this experiment? (1 MARK)

c Diana used a mercury thermometer to measure the temperature change. She noticed that some of the marks on the thermometer scale were rubbed off and so she had to make the best estimate of the temperature at the time she took the readings.

- **i** What kind of error does this represent? (1 MARK)
- **ii** Given that she only had the mercury thermometer available, what could she do to minimise the error identified in part i? (1 MARK)

Question 13 (5 MARKS)

Sulfur dioxide is often used as a preservative in food and drink. The sulfur dioxide content in dried apricots was determined by gravimetric analysis as follows:

- The dried apricots were powderised in a blender.
- A sample of the apricot powder weighing 50.00 g was put into a conical flask containing 100 mL of de-ionised water.
- A 3% solution of hydrogen peroxide was added to convert the dissolved sulfur dioxide to sulfate ions.
- An excess of barium chloride solution was then added. The barium sulfate precipitate was filtered off, dried and weighed to constant mass.

The equation for the precipitation of barium sulfate is $Ba^{2+}_{(aq)} + SO_4^{2-}{}_{(aq)} \rightarrow BaSO_{4(s)}$.

The following results were recorded.

Mass of dry filter paper	0.864 g
Mass of dry filter paper and $BaSO_4$ sample	1.338 g

$M(BaSO_4) = 233.4 \text{ g mol}^{-1}$ $M(SO_2) = 64.1 \text{ g mol}^{-1}$

Adapted from VCAA 2014 Exam 2 Section B Q 8b

a Identify the dependent variable in the experiment. (1 MARK)

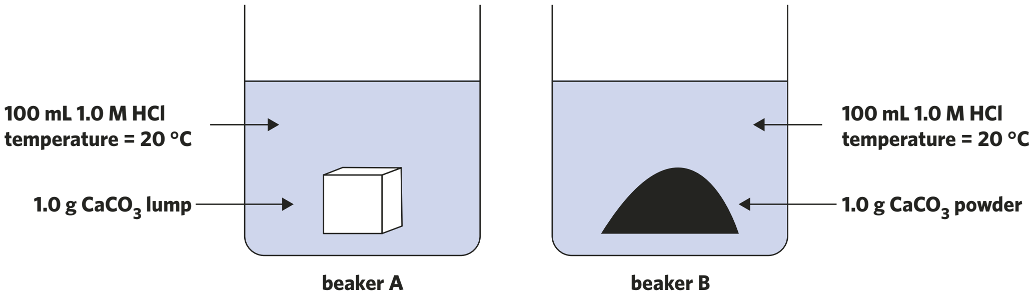
b The content of sulfur dioxide in the apricot sample is calculated by determining the amount of barium sulfate precipitate formed, using the mol ratio between barium and sulfate, and then using this value to calculate the mass of sulfur dioxide.

  i Explain the effect on the final value if the precipitate was not completely dry when weighed. (2 MARKS)

  ii The scientist conducting the experiment ordered a scale that could measure up to three decimal places as he believed that this would increase the precision of the results. Comment on the scientist's justification, evaluating whether the precision or accuracy is affected. (2 MARKS)

Question 14 (6 MARKS)

Albert wanted to determine whether or not chemical reactions involving a solution and a solid substance would occur quicker if he were to crush the solid material rather than leave it whole. To test his idea, he conducted the experiment below:



a From the setup, identify the controlled variables in the experiment. (2 MARKS)

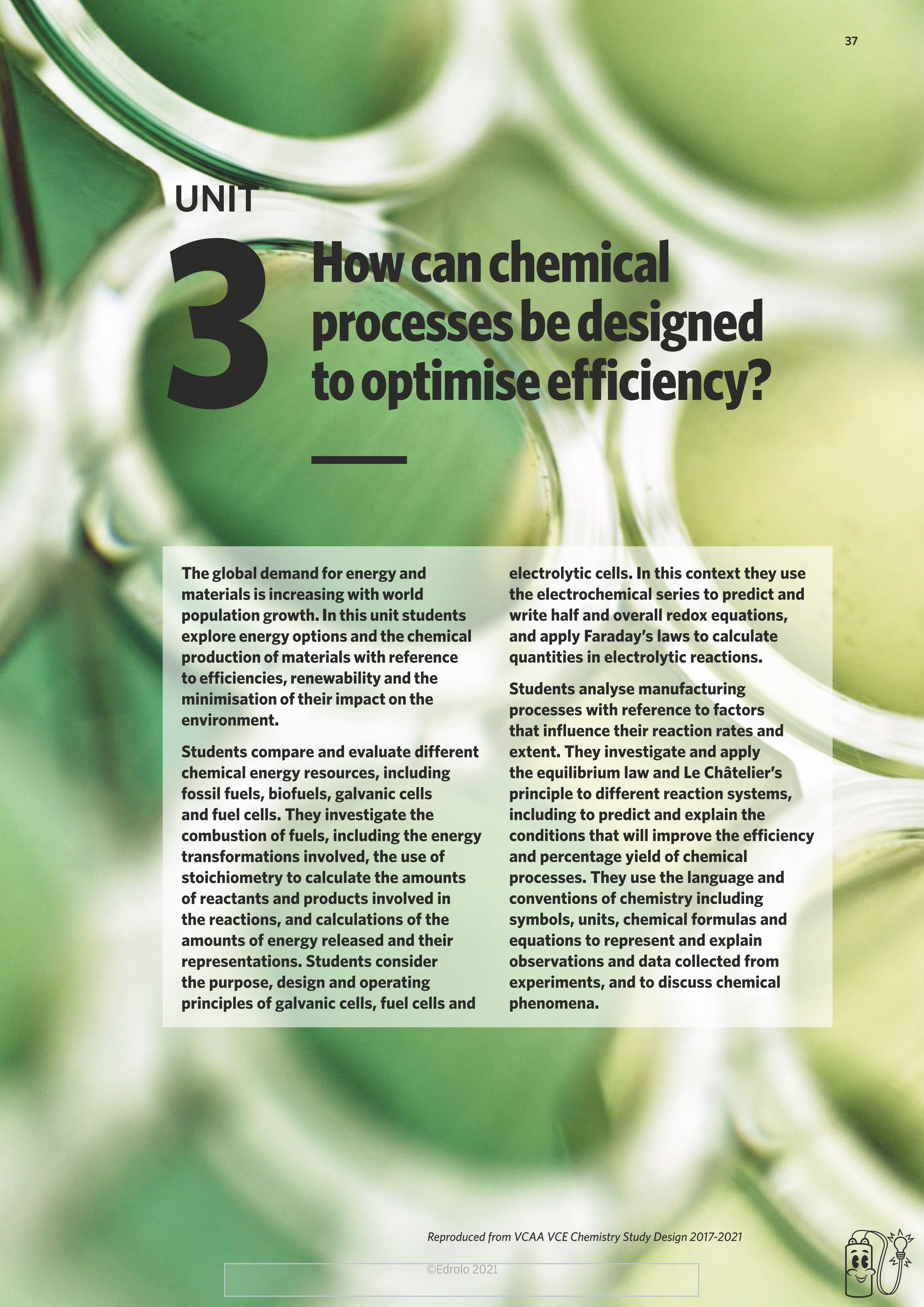
b Write a balanced chemical equation for this reaction. (1 MARK)

c Below is a table that Albert used to collect the results from his experiment:

	Beaker A	**Beaker B**
Before the experiment		
After the experiment		

  i The experiment was allowed to occur for 1 minute. What data would Albert need to collect during this experiment? (1 MARK)

  ii Explain your answer. (2 MARKS)



UNIT 3

How can chemical processes be designed to optimise efficiency?

The global demand for energy and materials is increasing with world population growth. In this unit students explore energy options and the chemical production of materials with reference to efficiencies, renewability and the minimisation of their impact on the environment.

Students compare and evaluate different chemical energy resources, including fossil fuels, biofuels, galvanic cells and fuel cells. They investigate the combustion of fuels, including the energy transformations involved, the use of stoichiometry to calculate the amounts of reactants and products involved in the reactions, and calculations of the amounts of energy released and their representations. Students consider the purpose, design and operating principles of galvanic cells, fuel cells and electrolytic cells. In this context they use the electrochemical series to predict and write half and overall redox equations, and apply Faraday's laws to calculate quantities in electrolytic reactions.

Students analyse manufacturing processes with reference to factors that influence their reaction rates and extent. They investigate and apply the equilibrium law and Le Châtelier's principle to different reaction systems, including to predict and explain the conditions that will improve the efficiency and percentage yield of chemical processes. They use the language and conventions of chemistry including symbols, units, chemical formulas and equations to represent and explain observations and data collected from experiments, and to discuss chemical phenomena.

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UNIT 3

AOS1

What are the options for energy production?

In this area of study students focus on analysing and comparing a range of energy resources and technologies, including fossil fuels, biofuels, galvanic cells and fuel cells, with reference to the energy transformations and chemical reactions involved, energy efficiencies, environmental impacts and potential applications. Students use the specific heat capacity of water and thermochemical equations to determine the enthalpy changes and quantities of reactants and products involved in the combustion reactions of a range of renewable and non-renewable fuels.

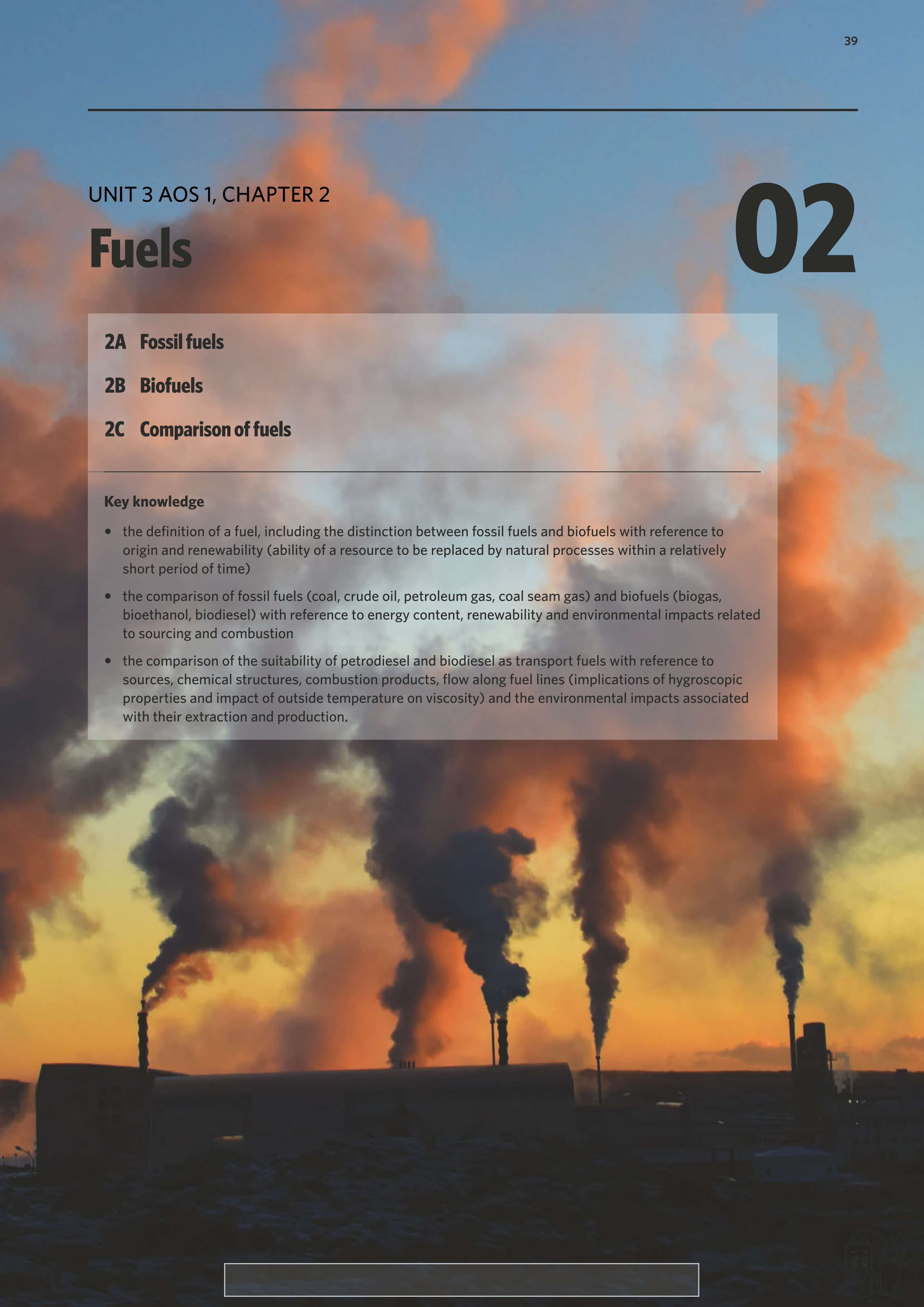
Students conduct practical investigations involving redox reactions, including the design, construction and testing of galvanic cells, and account for differences between experimental findings and predictions made by using the electrochemical series.

They compare the design features, operating principles and uses of galvanic cells and fuel cells, and summarise cell processes by writing balanced equations for half and overall cell processes.

Outcome 1

On completion of this unit the student should be able to compare fuels quantitatively with reference to combustion products and energy outputs, apply knowledge of the electrochemical series to design, construct and test galvanic cells, and evaluate energy resources based on energy efficiency, renewability and environmental impact.

solar cell design in which the metals and transport materials are solution-processed by either ink jet or spray coating.



UNIT 3 AOS 1, CHAPTER 2

Fuels

02

Key knowledge

- the definition of a fuel, including the distinction between fossil fuels and biofuels with reference to origin and renewability (ability of a resource to be replaced by natural processes within a relatively short period of time)
- the comparison of fossil fuels (coal, crude oil, petroleum gas, coal seam gas) and biofuels (biogas, bioethanol, biodiesel) with reference to energy content, renewability and environmental impacts related to sourcing and combustion
- the comparison of the suitability of petrodiesel and biodiesel as transport fuels with reference to sources, chemical structures, combustion products, flow along fuel lines (implications of hygroscopic properties and impact of outside temperature on viscosity) and the environmental impacts associated with their extraction and production.

2A FOSSIL FUELS

In this lesson we will learn about the different types of fossil fuels and why they are considered non-renewable.

2A Fossil fuels | **2B Biofuels** | **2C Comparison of fuels**

Study design dot point

- the definition of a fuel, including the distinction between fossil fuels and biofuels with reference to origin and renewability (ability of a resource to be replaced by natural processes within a relatively short period of time)

Key knowledge units

Definition and origin of fossil fuels	3.1.1.1.1
Non-renewability of fossil fuels	3.1.1.1.2

Key terms and definitions

- **Fuel** substance that is used, usually combusted, that has energy stored in its bonds
- **Fossil fuel** natural fuel that is formed in the earth from plant or animal remains
- **Coal** combustible fossil fuel formed by the partial decay of plant matter
- **Petrodiesel** liquid hydrocarbon fossil fuel obtained from crude oil
- **Natural gas** fossil fuel consisting largely of hydrocarbons
- **Coal seam gas** natural gas sourced from coal deposits
- **Greenhouse effect** process of the warming of the Earth's lower atmosphere due to the increased quantities of gases, like carbon dioxide, water vapour and methane, in the air
- **Non-renewable resource** resource that cannot be replenished as quickly as it is being consumed

---

Definition and origin of fossil fuels 3.1.1.1.1

OVERVIEW

Fossil fuels are substances that have been formed by the fossilisation of organic matter over millions of years, and contain chemical energy that can be converted to electrical, heat or kinetic energy.

THEORY DETAILS

Fuels are incredibly useful substances that contain chemical energy, which can be readily released through combustion reactions (i.e. burning) to produce heat or power. Energy is measured in the SI unit of the joule, given the symbol J. A single joule is a relatively small amount of energy, so table 1 shows some common units of energy that we will use.

Table 1 List of common units of energy

kilojoules	1 kJ = 10^3 J
megajoules	1 MJ = 10^6 J
gigajoules	1 GJ = 10^9 J
terajoules	1 TJ = 10^{12} J

Tip the prefixes kilo-, mega- and giga- can be found in your data booklet.

A **fossil fuel** is a specific type of fuel that is given its name due to the way it is formed from the remains of living organisms. Fossil fuels are currently the world's primary energy source – without them we wouldn't be able to power our cars, homes or businesses.

Common fossil fuels include **coal**, **petrodiesel** and **coal seam gas** (**natural gas**), each derived from the decomposition of plants and animals over a very long period of time. All of these named fossil fuels have a high carbon content, making them excellent substances to burn. The amount of energy that is produced from the combustion reactions of fuels is dependent on the type of fuel that is being burned.

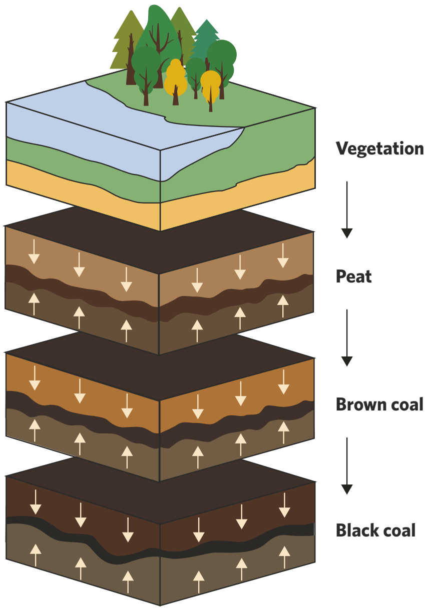


Image: Kolonko/Shutterstock.com

Figure 1 Diagram of how coal is formed by natural processes

As shown in figure 1, coal is formed from the natural breakdown of vegetation. Vegetation dies to form peat, peat is compressed between sediment to form brown coal, which is further compressed to form black coal (the most pure form of coal). Afterwards, it is mined from the ground where it is then processed in power plants for electricity. Coal-fired power plants produce electricity by burning coal in a boiler to produce steam that propels a turbine, generating electricity, as shown in figure 2.

Coal is a mixture of molecules including carbon, hydrogen, sulfur and nitrogen, the proportions of which depend on the stage of decay the coal is at. Peat, the earliest stage of decay, contains roughly 60% carbon, brown coal contains 70% carbon, and black coal contains 90% carbon. As we go down the layers of coal, the water content decreases which results in the increasing energy content of the coal. This is because with less water needing to be vaporised, the amount of heat released is greater than if the water content in the coal was greater. The higher the carbon content of the coal, the more heat is released when it is burned. Therefore, the energy content of the fuel increases with increasing carbon content.

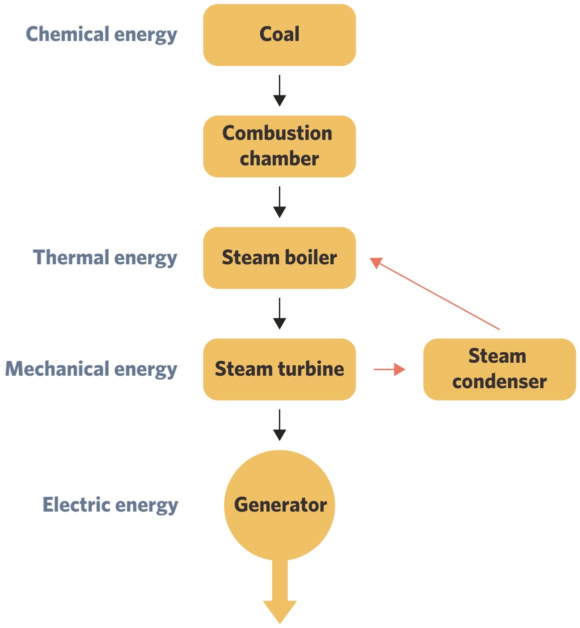


Figure 2 Flowchart of energy transformations in a coal-powered energy plant

Petroleum, also known as crude oil, is a mixture of hydrocarbons that needs to be separated, in a process known as fractional distillation. The separated fractions can then be used as a fuel or can be treated to produce desired products, as shown in figure 3. For the context of this study design, you will not need to know this process in detail.

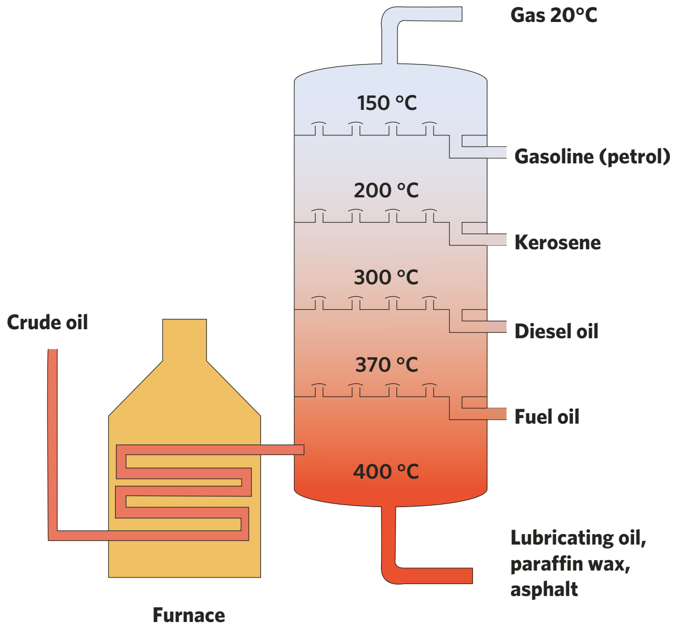


Figure 3 Stages of fractional distillation of crude oil, with the common uses of each fraction

A useful by-product of the fractional distillation of crude oil is petrodiesel. Petrodiesel contains a mixture of hydrocarbon molecules, an example of which is shown in figure 4, that range in length from 8 to 21 carbon atoms. Whilst petrodiesel itself consists purely of hydrocarbons, meaning burning it should only release carbon dioxide and water, petroleum deposits are often contaminated by hydrogen sulfide (H_2S) and other sulfur and nitrogen compounds. When petrodiesel contaminated with sulfur is burned, it produces sulfuric acid and nitric oxide, making it less desirable as a fuel due to negative effects on the environment.

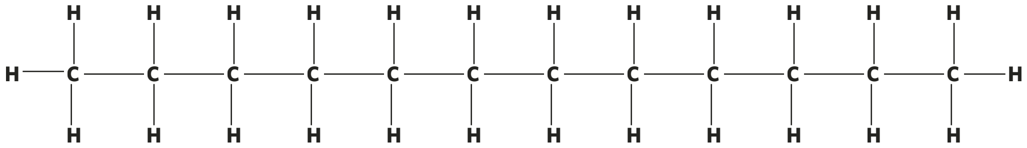


Figure 4 Example of a petrodiesel molecule

Coal seam gas (natural gas), like petroleum and coal, is formed from the remains of plant and animal materials. It is found in deposits in the Earth's crust, bonded to the surface of coal deposits and trapped in shale rock. It is accessed by drilling and by a process known as fracking, to extract it from coal and shale deposits. Fracking involves injecting liquid at high pressure into coal and shale rocks to force open fissures (cracks) to extract the gas. Materials used for this process have harmful impacts on the surrounding environment as well as water supplies. Coal seam gas is burned in a steam generation unit like coal to generate electricity.

Coal is the most common source of electricity, followed by petroleum and natural gas powered plants. However, at the current rates of production, coal, crude oil and coal seam gas won't be available indefinitely. As these resources are limited, it is important to find alternative sources of energy and to consider the impact of burning these fuels on the environment.

Non-renewability of fossil fuels 3.1.1.1.2

OVERVIEW

Although fossil fuels are formed by natural processes, the resources that produce them are not quickly replenished, therefore making them non-renewable.

THEORY DETAILS

A **non-renewable resource** is a substance that is consumed quicker than it can be replenished.

Coal, petroleum and coal seam gas are produced from organic material that has undergone complex natural processes that take millions of years to occur. Therefore, they cannot be replaced in the foreseeable future. These fuels (coal, petroleum and coal seam gas) are classified as non-renewable because they are being used up faster than they can be replaced.

This is a problem in our constantly growing world as the demand for fuel increases with a rising population using fuel dependent technology. Moreover, the extraction methods of each of these fuels is harmful to the environment in different ways, making finding alternative fuels more desirable.

For example, sulfur dioxide (SO_2) emissions from the burning of coal and contaminated petrodiesel contribute to acid rain. Fossil fuel fired electric power stations emit a large amount of carbon dioxide which accumulates in the atmosphere. This accumulation of gases in the atmosphere contributes to what is known as the **greenhouse effect**, where thermal energy is trapped by the atmosphere, causing the planet to become warmer than it normally would be naturally.

The process of drilling and mining for coal, coal seam gas and crude oil disrupts the natural landscape and can disrupt the water table if spills occur. Therefore, fuels from resources that are renewable and less harmful to the environment are very desirable alternatives. These alternative resources are known as biofuels and will be discussed in the following lesson.

Theory summary

- A fuel is a substance that is burned to produce energy in the form of heat or power.
- Coal, which is mined from the ground to be combusted in power plants for electricity, is formed by the natural breakdown of organic material.
- Crude oil is found in reservoirs in porous rocks, extracted through wells and separated in fractional distillation to obtain petrodiesel and other hydrocarbons.
- Petrodiesel is a hydrocarbon obtained from crude oil.
- Coal seam gas (natural gas) is formed from the remains of plants, extracted from shale rocks and burned in a steam-generation unit to generate electricity.
- A fossil fuel, such as natural gas or coal, is a non-renewable energy source, that is formed by natural processes.
- A fuel is considered to be non-renewable if it is consumed faster than it can be replenished.

2A QUESTIONS

Theory review questions

Question 1

Non-renewable resources

A are available in limited supplies.

B are consumed faster than they can be replenished.

C can be reused multiple times.

D take a long period of time to be replenished.

Question 2

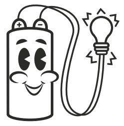
Which of the following is **not** an example of a non-renewable resource?

A Coal

B Natural gas

C Biofuel

D Petroleum



Question 3

Which of the following is a correct statement regarding fossil fuels?

A All fossil fuels are non-renewable resources.
B All non-renewable energy sources are fossil fuels.
C Fossil fuels are renewable resources.
D All renewable energy sources are fossil fuels.

Question 4

Petrodiesel is

I extracted straight from the ground.
II non-renewable.
III separated from crude oil.

A III only
B II and III
C All of the above
D None of the above

Exam-style questions

Within lesson

Question 5 (1 MARK)

Crude oil is used as a fuel for transportation, heating and electricity.

Which of the following best describes crude oil?

A A naturally occurring solid found in coal deposits
B An artificial oil created in labs
C A naturally occurring liquid, composed of hydrocarbons
D Liquid produced from anaerobically fermenting plant material

Question 6 (3 MARKS)

The process of extracting coal is a multi-step process and results in lots of disruptions to the immediate environment.

a Hedi wanted to test the energy content of different fuels obtained from different stages of coal extraction. According to his experimental results, black coal had a higher energy content than peat. Explain this result. (2 MARKS)
b Identify the main use of coal. (1 MARK)

Question 7 (3 MARKS)

A great proportion of large vehicles use petrodiesel as a fuel source.

a From what fuel source is petrodiesel extracted? (1 MARK)
b What are the potential environmental issues with using petrodiesel as a fuel source? (2 MARKS)

Question 8 (4 MARKS)

Methane is a component of natural gas that can be extracted from coal by fracking or produced by the microbial decomposition of plant and animal matter.

In which situation is methane a non-renewable energy source? Explain your answer.

Question 9 (5 MARKS)

Natural gas and coal are both examples of fuel sources that can be used to produce energy.

a Identify whether coal and natural gas are classified as fossil fuels, giving a justification for your response. (3 MARKS)

b Ethanol can be produced from coal. Identify whether or not ethanol produced using this method can be considered as renewable. (2 MARKS)

Question 10 (3 MARKS)

Wood is unable to be grown at the rate at which we are using it.

a Why is wood not considered a fossil fuel? (2 MARKS)

b Identify why sourcing energy from wood is considered an unsustainable process even though wood can be replenished by natural processes. (1 MARK)

Multiple lessons

Question 11 (4 MARKS)

Hydrogen fuel (H_2) is a zero-emission fuel when burned with oxygen, that can power vehicles and electrical devices.

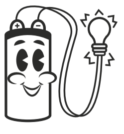
It can be produced from methane by the addition of steam in the following reaction:

$CH_{4(g)} + 2H_2O_{(g)} \rightarrow CO_{2(g)} + 4H_{2(g)}$

It can also be produced by the electrolysis of water, powered by electricity from solar panels, in the following reaction:

$2H_2O_{(l)} \rightarrow O_{2(g)} + 2H_{2(g)}$

Evaluate the environmental impact of each of these methods of producing hydrogen fuel.



2B BIOFUELS

In this lesson, we will explore the different types of biofuels and the effect of their origin on renewability.

2A Fossil fuels	2B Biofuels	2C Comparison of fuels

Study design dot point

- the definition of a fuel, including the distinction between fossil fuels and biofuels with reference to origin and renewability (ability of a resource to be replaced by natural processes within a relatively short period of time)

Key knowledge units

Definition and origin of biofuels	3.1.1.2.1
Renewability of biofuels	3.1.1.2.2

Lesson links

This lesson builds on:

▶ 2A – Fossil fuels

Biofuels are an alternative source of energy to fossil fuels.

Key terms and definitions

- **Biofuel** fuel sourced from organic matter
- **Biogas** gaseous fuel produced by the anaerobic breakdown of organic matter
- **Bioethanol** fuel produced by the fermentation of glucose in organic matter
- **Biodiesel** fuel produced by the esterification of fats and oils in organic matter
- **Carbon neutral** fuel which does not result in a net production of carbon dioxide from sourcing or consumption
- **Fermentation** breakdown of a substance in the presence of microorganisms such as yeast
- **Renewable resource** resource capable of being replenished by natural processes as quickly or faster than it is being consumed
- **Transesterification** reaction that produces biodiesel
- **Triglyceride** fat or oil composed of three fatty acid tails and a glycerol backbone
- **Yeast** variety of microorganism which converts glucose into ethanol

Definition and origin of biofuels 3.1.1.2.1

OVERVIEW

Biofuels are a broad category of fuels sourced from organic matter, and act as an alternative source of energy to fossil fuels.

THEORY DETAILS

In light of our changing climate, world leaders and industry are investigating a range of energy sources to replace fossil fuels. Biofuels may provide a viable alternative.

A **biofuel** is a fuel sourced directly from organic matter, such as sugarcane, wheat, barley, or vegetable oils. The three main types of biofuels we will study are **biogas**, **bioethanol**, and **biodiesel**.

1 Worked example

Explain why methane sourced from natural gas deposits is considered a fossil fuel, but methane sourced from the decomposition of vegetable scraps is considered a biofuel.

What information is presented in the question?

Methane in natural gas is a fossil fuel.

Methane from vegetable scraps is a biofuel.

What is the question asking us to do?

Why can methane be a fossil fuel or a biofuel, depending on the source?

What strategy(ies) do we need in order to answer the question?

1. Identify the characteristics of methane in natural gas that make it a fossil fuel.
2. Identify the characteristics of methane from vegetable scraps that make it a biofuel.

Answer

Methane derived from natural gas is produced by the fossilisation of animal and plant remains over a very long period of time, and so is considered a fossil fuel. Methane derived from the decomposition of vegetable scraps is directly obtained from organic matter, and so is considered a biofuel.

Biogas

Biogas is a mixture of gases produced by the breakdown of organic matter.

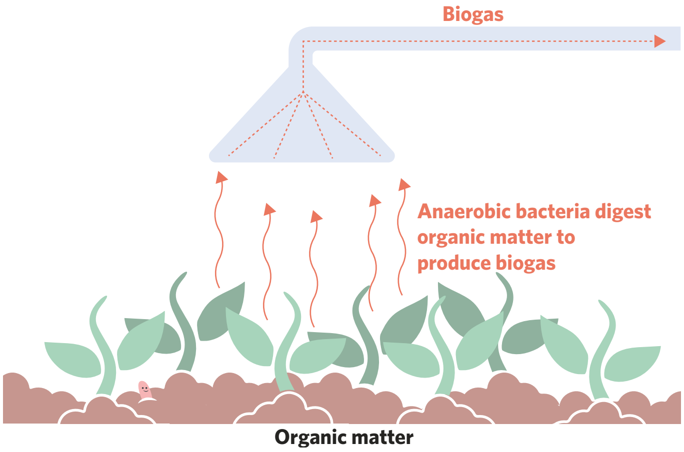


Figure 1 The production of biogas from organic matter

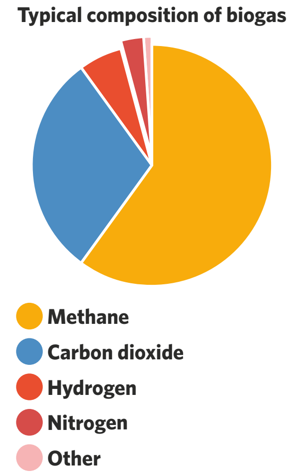


Figure 2 Composition of biogas

As shown in figure 1, organic matter (such as algae, crops, wood, or compostable garbage) is broken down by bacteria into gas. This process is described as anaerobic, because it does not require oxygen to proceed.

The gas that is produced is a mixture of different gases, predominantly methane, but it also contains a large proportion of carbon dioxide. Every sample of biogas will contain different proportions of gases, however figure 2 shows an approximation of the average proportions of different gases in biogas.

Bioethanol

Bioethanol is produced by the **fermentation** of glucose in organic matter by a microorganism called **yeast**. Organic matter commonly fermented by yeast includes crops such as wheat, corn and sugarcane. Ethanol is only considered bioethanol when produced via the fermentation process in figure 3.

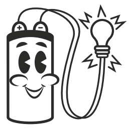
$$\text{Glucose} \xrightarrow{\text{Bacteria}} \text{Ethanol} + \text{Carbon dioxide}$$

$$C_6H_{12}O_{6(aq)} \xrightarrow{\text{Bacteria}} 2CH_3CH_2OH_{(aq)} + 2CO_{2(g)}$$

Figure 3 Fermentation process of glucose into ethanol

E10 is a common fuel available at some service stations in Australia, and is composed of 10% bioethanol and 90% petrol. This demonstrates that biofuels are beginning to enter the mainstream market.

Although the combustion of bioethanol produces CO_2, the process of crop production offsets this release, by the absorption of CO_2 from plants undergoing photosynthesis. This means bioethanol is considered relatively **carbon neutral**, as shown in figure 4. However, it is not completely carbon neutral because the processes involved, such as the transportation, harvesting and production of organic matter, all require energy.



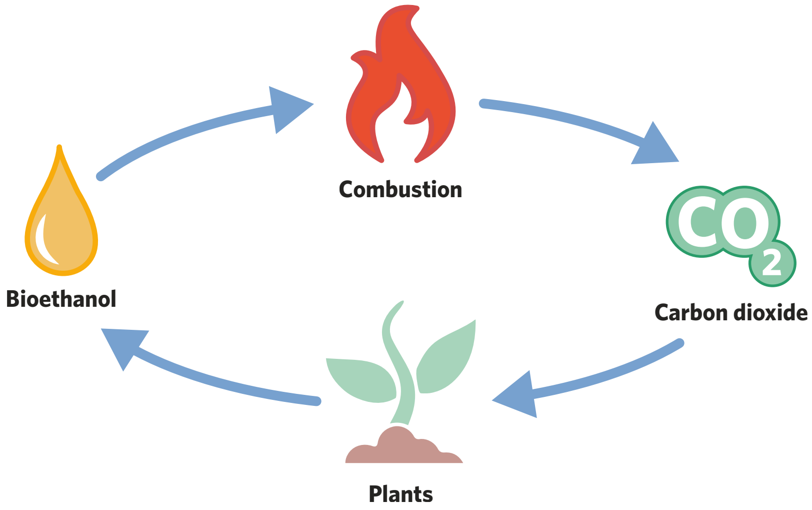


Figure 4 The recycling of carbon dioxide in the production of bioethanol

Biodiesel

Biodiesel is produced by the esterification of fats originating from animal products and oils originating from crops. Animal fats and plant oils such as sunflower, canola and palm are composed of compounds known as **triglycerides**. These triglycerides are composed of three fatty acids and a glycerol molecule, as shown in figure 5. An alcohol, usually methanol, is added to the triglyceride, and with a catalyst such as potassium hydroxide, reacts to form biodiesel, a mixture of fatty acid methyl esters.

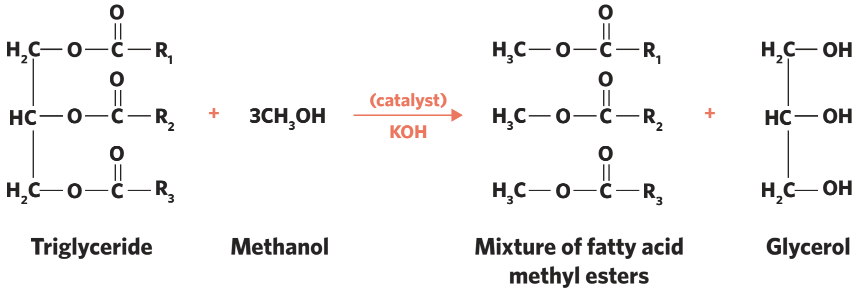


Figure 5 Transesterification of triglycerides

This reaction, and other organic reactions and structures, will be further explored in chapter 7.

The reaction shown in figure 5 to produce biodiesel from triglycerides, is called a **transesterification reaction**. In the breakdown of the word in figure 6, we can see how this name reflects its function, relocating the ester groups from the triglycerides into biodiesel molecules.

Figure 6 Meaning of the word transesterification

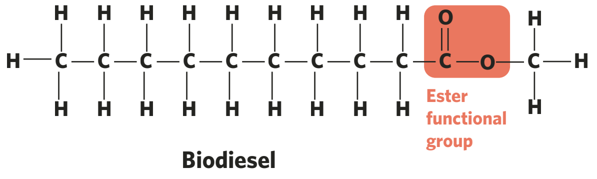


Figure 7 An example of a fatty acid methyl ester from biodiesel

Biodiesel itself has the structure shown in figure 7. It is important to note the presence of the ester group (COO) makes the molecule polar. Depending on the triglyceride used to create biodiesel, the length of the molecule varies.

Renewability of biofuels 3.1.1.2.2

OVERVIEW

We can use our knowledge of the source of a biofuel to determine its renewability.

THEORY DETAILS

A fuel is considered a **renewable resource** if it is replenished by natural process at a rate faster than or equal to the rate it is being consumed.

For example, the fatty acid methyl esters we know as biodiesel are derived from crops and animal fats which can be produced quickly to replenish stores of biodiesel. As a result, we classify biodiesel as a renewable energy source.

Similarly, biogas and bioethanol are both produced directly from organic matter, so can be produced in a relatively short time period.

As a result, we classify all biofuels as renewable energy sources.

Tip When determining the renewability of a fuel, consider how long the production process is, the way in which is it replenished (if at all), and whether it is likely to be consumed quicker than it is produced.

Theory summary

- A biofuel is a fuel sourced directly from plant or animal matter.
- Biogas is a mixture of gases produced by the anaerobic breakdown of organic matter.
- Bioethanol is a fuel produced by the fermentation of glucose.
- Biodiesel is a fuel produced by the transesterification of fats and oils.
- A fuel is renewable if it can be replenished at a rate faster than or equal to the rate at which it is consumed.

2B QUESTIONS

Theory review questions

Question 1

Biogas is mainly composed of __________ and is a __________ energy source.

A carbon dioxide, renewable

B methane, non-renewable

C carbon dioxide, non-renewable

D methane, renewable

Question 2

Fermentation of organic matter by yeast results in the production of

A methane.

B bioethanol.

C fats and oils.

D glucose.

Question 3

Biodiesel is

A composed of sugars.

B non-renewable.

C polar.

D sourced from only plants.

Question 4

Renewable fuels

A release less carbon dioxide than non-renewable fuels.

B are replaced at least at the rate at which they are consumed.

C directly contribute less to global warming than non-renewable fuels.

D are all biofuels.

Exam-style questions

Within lesson

Question 5 (1 MARK)

Which of the following statements is most correct?

A Biogas is derived from the fossilisation of anaerobic bacteria.
B Fatty acid methyl esters are created by the oxidation of fats.
C Methane sourced from the breakdown of compost is a renewable energy source.
D Bioethanol can be obtained from the fractional distillation of crude oil.

Question 6 (1 MARK)

Which of the following compounds is also known as a mixture of fatty acid methyl esters?

A Methane **B** Bioethanol **C** Biodiesel **D** Triglycerides

Question 7 (5 MARKS)

Daisy purchased a new car, only to discover the fuel required is pure biodiesel. Unfortunately, there are no local biodiesel service stations, and so Daisy decides to produce the substance herself from the local sunflower crops, which grow very quickly. She also knows that she will not require all the sunflower crops to power her car.

a Would biodiesel produced in this way be considered renewable? Explain your answer. (2 MARKS)
b List an environmental concern Daisy may have regarding the process with respect to water. (1 MARK)
c Daisy adds methanol and a catalyst to the oil extracted from the sunflower crops. What type of reaction is occuring? (1 MARK)
d Daisy is successful in creating her desired product, however notices an additional product is formed. What is the name of this product? (1 MARK)

Question 8 (5 MARKS)

Sugarcane is a species of tall grasses rich in glucose. When fermented by anaerobic bacteria, the following reaction occurs:

$C_6H_{12}O_{6(aq)} \rightarrow X_{(g)} + Y_{(g)}$

a Name compounds *X* and *Y*. (1 MARK)
b Explain why compound *X* is considered a renewable fuel. (1 MARK)
c The above reaction produces compound *Y*, but this is offset by the production of sugarcane crops. Explain one environmental impact of compound *Y* if it were not offset. (1 MARK)
d Glucose for the above reaction is now sourced from potatoes. Would compound X still be defined as renewable? (2 MARKS)

Multiple lessons

Question 9 (3 MARKS)

A large quantity of canola oil is mistakenly delivered to a coal-fired power station. The manager of the station decides it is most environmentally sustainable to make use of the canola oil, and thus decides to create a fuel from the triglycerides in the crops.

The production of this fuel follows the process: canola oil + methanol → $X_{(l)} + Y_{(l)}$

a Identify the type of biofuel *X* produced. (1 MARK)
b This technique of fuel production attracts media attention, and a number of other companies have begun to adopt a similar practice. Explain why the coal fuelling the station is considered non-renewable, but the fuel produced from canola crops is considered renewable. (2 MARKS)

2C COMPARISON OF FUELS

In this lesson, we will explore the differences between biofuels and fossil fuels.

2A Fossil fuels	2B Biofuels	2C Comparison of fuels

Study design dot points

- the comparison of fossil fuels (coal, crude oil, petroleum gas, coal seam gas) and biofuels (biogas, bioethanol, biodiesel) with reference to energy content, renewability and environmental impacts related to sourcing and combustion
- the comparison of the suitability of petrodiesel and biodiesel as transport fuels with reference to sources, chemical structures, combustion products, flow along fuel lines (implications of hygroscopic properties and impact of outside temperature on viscosity) and the environmental impacts associated with their extraction and production

Key knowledge units

Comparison of fossil fuels and biofuels	3.1.7.1
Comparison of petrodiesel and biodiesel	3.1.8.1

Key terms and definitions

- **Viscosity** resistance of a substance to flow
- **Hygroscopicity** ability to absorb water

Lesson links

This lesson builds on:

▶ 2A – Fossil fuels

Petrodiesel is a type of fossil fuel.

▶ 2B – Biofuels

Biodiesel is a type of biofuel.

Comparison of fossil fuels and biofuels 3.1.7.1

OVERVIEW

Fossil fuels and biofuels are different in terms of renewability, energy content and their environmental impact related to sourcing and combustion.

THEORY DETAILS

As we learned in 2A, fossil fuels (coal, crude oil, petroleum gas, coal seam gas) are formed from the decomposition of plant and animal matter over a very long period of time. This makes them non-renewable as they cannot be replenished as rapidly as they are being consumed. On the other hand, biofuels (biogas, bioethanol, biodiesel), which are produced from organic matter such as corn and sugarcane, are renewable since the organic matter used to make biofuels can be regrown faster than or equal to the rate at which it is consumed.

Another difference between fossil fuels and biofuels is the amount of energy they release when they undergo combustion. The combustion reactions of biodiesel (a type of biofuel) produce less energy per gram than those of fossil fuels. This is due to the fact that the presence of oxygen atoms in biodiesel prevents the carbon atoms from being fully oxidised. However, all biofuels are considered to be more environmentally friendly because burning them produces less particulate matter, such as nitrogen oxides and sulfur oxides, that can lead to global warming. These oxides can also result in acid rain which destroys the natural environment, polluting the ocean and other water sources.

Even though the combustion of both biofuels and fossil fuels releases carbon dioxide and water, the CO_2 consumed by photosynthesis during biofuel production results in partial carbon neutrality. However, the production is not completely carbon neutral because energy is required for the production and transportation of biofuel crops. Moreover, in the short-term, huge volumes of rock and soil left after the process of producing fossil fuels are dumped into adjacent streams and rivers causing water to be polluted. In the long-term, the invasive techniques used to extract fossil fuels result in land degradation and erosion. However, the sourcing of biofuel also has negative impacts. This is because large amounts of land and water are required to produce crops. Over time, this land becomes degraded and food producing land is taken over for the production of biofuels.

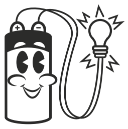


Table 1 Comparison of biofuels and fossil fuels

Biofuels	Fossil fuels
renewable	non-renewable
produce less energy per gram (this only applies to biodiesel)	produce more energy per gram
lower net emission of greenhouse gases due to partial carbon neutrality	greater net emission of greenhouse gases
produce less particulate matter	produce more particulate matter
require land and water	require drilling and/or mining

Comparison of petrodiesel and biodiesel 3.1.8.1

OVERVIEW

Petrodiesel and biodiesel are different in terms of chemical structures, **viscosity**, renewability, hygroscopicity, environmental impact and the amount of energy produced per gram.

THEORY DETAILS

Viscosity is the resistance of a substance to flow. As learned in 2A and 2B, petrodiesel contains a large percentage of straight chain alkanes, while biodiesel is a mixture of fatty acid methyl esters derived from triglycerides, as shown in figure 1. Due to the presence of alkanes, which are non-polar molecules, petrodiesel molecules are held together by weak dispersion forces. Conversely, biodiesel molecules are held tightly by permanent dipole-dipole bonds due to the presence of polar ester COO groups. As a result, it's easier for petrodiesel to flow than biodiesel meaning that petrodiesel has a lower viscosity than biodiesel. Due to the higher viscosity, biodiesel, does not flow as easily through fuel lines. Since the viscosity of a substance increases at lower temperatures, it is also easier to store and use petrodiesel in fuel requiring appliances, such as cars and generators, in cold weather compared to biodiesel.

The COO groups of biodiesel can also form hydrogen bonds with water molecules, making it **hygroscopic**, allowing biodiesel molecules to absorb more water than the non-polar petrodiesel. Therefore, petrodiesel can be stored for longer than biodiesel without compromising the quality of the fuel due to the absorbed water. Moreover, the presence of water in biodiesel lowers the efficiency of combustion reactions.

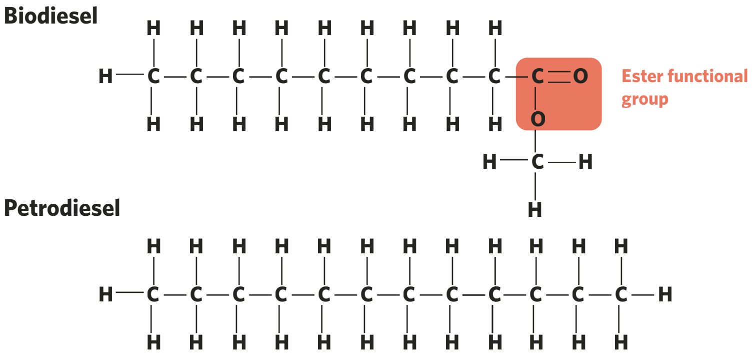


Figure 1 Structure of biodiesel and petrodiesel

Petrodiesel is a type of fossil fuel, while biodiesel is a type of biofuel. As discussed above, biofuels are renewable, whereas fossil fuels are not. This means that biodiesel is a renewable energy source and petrodiesel is not. With respect to sourcing, biodiesel requires intensive farming which consumes a lot of water and land, whereas petrodiesel requires the drilling of crude oil, which can result in oil spills and ecological damage. Another difference between petrodiesel and biodiesel is that the combustion of petrodiesel is able to produce more energy per gram than that of biodiesel. Due to the partial oxidation of biodiesel, there is less potential for biodiesel to be further oxidised when compared to petrodiesel, and as a result releases less energy than petrodiesel during combustion. Furthermore, biodiesel is more likely to be decomposed by living organisms such as bacteria and fungi. Hence, biodiesel is more biodegradable than petrodiesel, which reduces its environmental impact. The combustion of biodiesel also releases less particulate matter such as nitrogen oxides and sulfur oxides as compared to petrodiesel.

Table 2 Comparison of biodiesel and petrodiesel

Biodiesel	**Petrodiesel**
higher viscosity → harder to flow through fuel lines	lower viscosity → easier to flow through fuel lines
more hygroscopic	less hygroscopic
renewable	non-renewable
produces less energy per gram	produces more energy per gram
higher melting point	lower melting point
lower net emission of greenhouse gases due to partial carbon neutrality	greater net emission of greenhouse gases
biodegradable	non-biodegradable
produces less particulate matter from combustion	produces more particulate matter from combustion
requires land and water	requires drilling of crude oil

Theory summary

- Fossil fuels and biofuels are different in terms of renewability, energy content and environmental impact.
- Petrodiesel and biodiesel are different in terms of chemical structures, viscosity, renewability, hygroscopicity, environmental impact and the amount of energy produced per gram.

2C QUESTIONS

Theory review questions

Question 1

Which of the following statements is true about the difference between fossil fuels and biofuels?

A Fossil fuels are renewable while biofuels are not.
B Biofuels are renewable while fossil fuels are not.
C Fossil fuels produce more energy per gram than biodiesel.
D Both B and C

Question 2

Which of the following statements is correct about the difference between petrodiesel and biodiesel?

A Petrodiesel has a higher viscosity than biodiesel.
B Biodiesel has a higher viscosity than petrodiesel.
C Biodiesel is non-renewable while petrodiesel is renewable.
D Both biodiesel and petrodiesel are biodegradable.

Question 3

Which of the following statements best explains why biodiesel is more hygroscopic than petrodiesel?

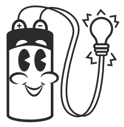
A Biodiesel is heavier.
B COH groups in biodiesel can form hydrogen bonds with water.
C COO groups in biodiesel can form hydrogen bonds with water.
D COO groups in petrodiesel prevent it from interacting with water.

Exam-style questions

Within lesson

Question 4 (1 MARK)

A group of engineers needs to choose a fuel to run a machine in Verkhoyansk, which is considered to be one of the coldest places in the world. The engineers should choose



A petrodiesel because it has a low viscosity so it can flow readily in cold weather.
B petrodiesel because it has a high viscosity so it can flow readily in cold weather.
C biodiesel because it has a high viscosity so it can flow readily in cold weather.
D biodiesel because it is more sustainable in cold weather.

Use the following information to answer questions 5 and 6.

The information for the fuel consumption of two machines is presented below.

Machine	Fuel	Fuel consumption (L/hour)	CO_2 produced (g (CO_2)/L)
1	Bioethanol	15	2100
2	Petrodiesel	9	2708

Question 5 (1 MARK)

Based on the given information, which of the following statements is correct?

A Bioethanol has a higher energy content per gram than biodiesel.
B Petrodiesel and bioethanol produce the same amount of energy per gram.
C Bioethanol produces more g (CO_2) per hour than petrodiesel.
D Petrodiesel is more viscous than bioethanol.

Question 6 (1 MARK)

Between bioethanol and petrodiesel, which fuel is more environmentally friendly?

A Bioethanol because it produces no CO_2 when burnt.
B Petrodiesel because it produces less CO_2 when burnt.
C Bioethanol because its production partially offsets the carbon dioxide released when combusted.
D Petrodiesel because it is replenished by natural processes.

Question 7 (4 MARKS)

Describe and explain the difference between petrodiesel and biodiesel in

a viscosity under the same conditions and how this would affect the flow of each fuel. (2 MARKS)
b net amount of CO_2 released from the combustion (including production) and how this would determine their environmental impacts. (2 MARKS)

Question 8 (6 MARKS)

Describe and explain the difference between fossil fuels and biofuels in

a renewability. (2 MARKS)
b environmental impacts related to sourcing and combustion. (4 MARKS)

Multiple lessons

Question 9 (4 MARKS)

Two tanks of biodiesel and petrodiesel delivered from factories lost their labels. A chemical engineer identified the type of diesel contained in each tank by pouring 5 mL of each type of diesel into two different cylinders labelled A and B. After 1 minute, the engineer marked the position of the diesel at the top and the bottom in each cylinder and measured the distance between the top and the bottom marks. The results of this experiment are shown.

Identify the type of fuel contained in each cylinder. Justify your answer.

Cylinder	Distance between the top and bottom marks
A	5 cm
B	7 cm

Question 10 (5 MARKS)

A farmer, located in a cold region, wants to choose the diesel that can be stored until the next spring to run his crop harvester.

a Which diesel type should the farmer choose? (1 MARK)
b Give two reasons for your choice. Justify your answer. (4 MARKS)

EXPERIMENT

FERMENTATION

Alcoholic beverages are generally made through a process involving fermentation of wheat products. This process is driven by the presence of yeast, which contains an enzyme that helps to speed up the reaction to produce ethanol.

Materials

(per group)

- 5 g glucose
- Kettle
- 100 mL beaker
- 1.0 M $Ca(OH)_2$ solution
- 100 mL conical flask
- 50 mL measuring cylinder
- Mass balance
- Cotton wool
- Test tube
- Test tube rack
- Dry yeast
- Timer

Method

1 Place the conical flask on the mass balance and add a total of 5.0 g of glucose into the flask.
2 Add 25 mL of boiling water from the kettle into a beaker.
3 Using the measuring cylinder, measure 50 mL of tap water and add it into the same beaker.
4 Measure 50 mL of warm water from the beaker and pour it into the conical flask containing glucose. Swirl to dissolve the glucose.
5 Measure and add 1.0 g of dry yeast to the solution.
6 Use cotton wool to plug the conical flask.
7 Start the timer and allow the contents in the conical flask to react for 5 minutes.
8 While the reaction in the conical flask is left to proceed, add 10 mL of a 1.0 M $Ca(OH)_2$ solution into a separate test tube.
9 After 5 minutes, remove the cotton wool from the conical flask and 'pour' the flask into the test tube containing $Ca(OH)_2$ solution. Be careful not to pour any liquid contents from the conical flask into the test tube.
10 Gently swirl the contents of the test tube.
11 Record any observations.

Results

Observations of the contents of the test tube before the substance from the conical flask was poured in	**Observations of the contents of the test tube after the substance from the conical flask was poured in**

QUESTIONS

Question 1 (4 MARKS)

a Write a balanced equation for the fermentation process involving glucose. (1 MARK)

b Carbon dioxide is able to react with $Ca(OH)_{2(aq)}$ according to the equation $CO_{2(g)} + Ca(OH)_{2(aq)} \rightarrow CaCO_{3(s)} + H_2O_{(l)}$

  i Freya conducted this experiment and noticed that the test tube containing $Ca(OH)_{2(aq)}$ changed into a cloudy colour. What does this suggest? (2 MARKS)

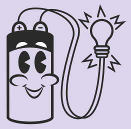
  ii Given that Freya followed the exact same method as identified above, calculate the mass of $CO_{2(g)}$ that would have been produced. (1 MARK)

Question 2 (5 MARKS)

a What is the fuel being produced as a result of this experiment? (1 MARK)

b This fuel source is considered as being almost carbon neutral. Explain. (2 MARKS)

c Two different students conducted the same experiment. One used a scale that was able to read up to 3 decimal places whereas the other student used a kitchen scale that gave measurements up to 1 decimal place. How would this affect the measured results? (2 MARKS)



ANSWERS

1 **a** $C_6H_{12}O_{6(aq)} \rightarrow 2C_2H_5OH_{(aq)} + 2CO_{2(g)}$

b **i** [The cloudiness present in the test tube implies that a reaction may have taken place. Based on the equation shown, the cloudiness may have been as a result of a reaction between $CO_{2(g)}$ and $Ca(OH)_{2(aq)}$ resulting in the production of $CaCO_3$ precipitates.[1]] [This suggests that $CO_{2(g)}$ was produced from the fermentation reaction.[2]]

✓ ✗ I have described the implications of the observation.[1]

✓ ✗ I have identified the link between this reaction and the fermentation process.[2]

ii $n(C_6H_{12}O_6) = \frac{5}{180} = 0.0278$ mol

$n(CO_2) = 0.0278$ mol × 2 = 0.0556 mol

$m(CO_2) = 0.0556 \times 44 = 2.45$ g

2 **a** Bioethanol

b [During the combustion of bioethanol, CO_2 gas is produced.[1]] [However, the CO_2 produced is used to support the growth of neighbouring crops (and even the crop to produce bioethanol) via supplying the CO_2 gas required for photosynthesis to occur.[2]] [This offsets the CO_2 produced and as a result, bioethanol is often considered as being almost carbon neutral.[3]]

✓ ✗ I have identified CO_2 as a product of the combustion of ethanol.[1]

✓ ✗ I have described the relationship between the CO_2 produced and photosynthesis.[2]

✓ ✗ I have linked my answer to the question.[3]

c [This would affect the accuracy of the results obtained[1]] [whereby the student using the scale that is able to read up to 3 decimal places would have more accurate results.[2]]

✓ ✗ I have identified the feature of the experiment affected by the scales.[1]

✓ ✗ I have identified the effect of this feature on the accuracy of measurements.[2]

CHAPTER 2 QUESTIONS

MULTIPLE CHOICE (10 MARKS)

Question 1 (1 MARK)

Which of the following lists of energy sources contains only fossil fuels?

A Wood, tar, charcoal

B Natural gas, coal seam gas, coal

C Biogas, bioethanol, biodiesel

D LPG, petrol, biodiesel

Question 2 (1 MARK)

A sample of biodiesel is tested to determine its suitability as a fuel source in a low-temperature environment.

Of the following properties of the fuel, which would increase in a colder environment?

I Viscosity

II Density

III The amount of energy obtained per mol of biodiesel

A I, II only

B II only

C II, III only

D I, III only

Question 3 (1 MARK)

Which of the following molecular formulae is most likely to be that of biodiesel?

A $C_4H_8O_2$

B $C_{17}H_{34}O_2$

C C_8H_{18}

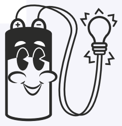
D $C_{17}H_{36}$

Question 4 (1 MARK)

Kimia, a chemical engineer, is tasked with selecting an appropriate fuel for a new client's energy plant. Unfortunately, Kimia's research documents are compromised on a rainy day.

Which of the following pieces of data is most likely to have been part of her analysis?

	Biodiesel	Petrodiesel
A	Lower flashpoint	Higher flashpoint
B	Non-renewable	Renewable
C	Lower boiling point	Higher boiling point
D	Higher viscosity	Lower viscosity



Question 5 (1 MARK)

Which of the following statements is **not** correct?

A Petroleum gas is a non-renewable source of energy.

B Electricity can be generated by burning coal.

C Biogas is renewable because it does not produce carbon dioxide when burnt.

D Biodiesel can be sourced from both plant and animal matter.

Question 6 (1 MARK)

Biodiesel can be categorised as a renewable fuel. Which of the following definitions best defines a renewable fuel?

A A fuel that will not be entirely consumed in a relatively short period of time

B A fuel that does not produce greenhouse gases

C A fuel derived from organic matter

D A fuel that will be replenished naturally within a relatively short period of time

Question 7 (1 MARK)

A sample of crude oil is obtained from underground deposits and its contents are analysed using a process known as fractional distillation. Which of the molecules listed below is most likely to have been found in the sample?

A Bioethanol

B Butyne

C Petrodiesel

D Biogas

Question 8 (1 MARK)

Which of the following statements about petrodiesel are true?

I Petrodiesel can be obtained through the separation of the components of crude oil.

II Petrodiesel has a higher energy content per gram than biodiesel.

III Petrodiesel can be refined to obtain biodiesel.

IV Petrodiesel contains a mixture of fatty acid methyl esters.

A I, II, IV only

B II, IV only

C I, II only

D I, IV only

Question 9 (1 MARK)

Dr Hisako is looking for a compound with a minimal density of carbon for his research project. Of the following available materials, which would be most suitable for this requirement?

A Wood

B Black coal

C Peat

D Brown coal

Question 10 (1 MARK)

Biodiesel can be obtained via

A addition of methanol to triglycerides from organic matter.

B transesterification of triglycerides from fossilised remains.

C fractional distillation of crude oil.

D oxidation of fatty acid methyl esters.

SHORT ANSWER (29 MARKS)

Question 11 (6 MARKS)

A global ethanol production company is investigating a potential new source for their fuel. Currently, ethanol is sourced from coal deposits underground, but researchers have proposed the use of sweet potatoes as an alternative source. Sweet potatoes are harvested from crops and fermented by bacteria, which produce ethanol.

a Explain how ethanol sourced from coal can be considered non-renewable, whereas ethanol sourced from sweet potatoes is considered renewable. (2 MARKS)

b The researchers of the company are interested in the specific process of the fermentation of the sweet potatoes. Complete the chemical equation for the fermentation process given below. (2 MARKS)

$$C_6H_{12}O_{6(aq)} \longrightarrow$$

c Describe one environmental advantage, with respect to the production of carbon dioxide, of switching to the use of sweet potatoes as an energy source as opposed to coal. (1 MARK)

d Identify one negative impact that the growth of sweet potato crops may have on the environment. (1 MARK)

Question 12 (8 MARKS)

One process of extracting petrodiesel from the environment is summarised below.

Underground deposits —Drilling→ **Crude oil** —Fractional distillation→ **Petrodiesel**

a Would the product of this process be considered a renewable or non-renewable fuel? Justify your answer. (2 MARKS)

b A sample of petrodiesel is extracted and analysed. What intermolecular force(s) would you expect to observe in this sample? Use the structure of petrodiesel in your explanation. (2 MARKS)

c Through an error in the transport of the crude oil from the drilling facility to the refinery, the sample of petrodiesel was actually contaminated with biodiesel to a large extent. Would this contamination lead to a higher or lower boiling point compared to a pure sample of petrodiesel? Explain. (3 MARKS)

d The pure product petrodiesel is now combusted in a vehicle's engine to harness its energy. Identify one negative effect of this combustion reaction on the environment. (1 MARK)

Question 13 (8 MARKS)

Year 12 Chemistry students Ruchika and Katrina each attain their probationary licenses and begin researching options for the purchase of their first cars. Both students are looking for a renewable energy source to fuel their car. Ruchika is interested in an electric car, whereas Katrina is looking for a car fuelled by biodiesel.

a Ruchika proposes that her car would be running on a renewable energy source because the electricity is generated from the combustion of natural gas. Comment on the truth of this statement. (2 MARKS)

b On weekends, both students enjoy driving to the ski slopes nearby. Explain how the viscosity of the biodiesel fueling Katrina's car is affected by these reduced temperatures. (2 MARKS)

c Ruchika hires an expert to investigate the fuel efficiency of a range of models she is interested in. The results of this investigation are summarised below.

	Car 1	**Car 2**	**Car 3**	**Car 4**
Fuel efficiency (L/100 km)	21.3	17.6	17.3	11.4
CO_2 produced g (CO_2)/L	1750	2479	2453	2871

If the journey to the ski lodge is 75 km, which car would produce the least amount of CO_2 for this trip? (2 MARKS)

d Katrina is looking to compare bioethanol and petrodiesel and finds that bioethanol produces 1.91 kg of CO_2 per kg of fuel, compared with 3.17 kg of CO_2 per kg for petrodiesel. However, the overall impact of the carbon dioxide released by bioethanol is significantly lower than that of petrodiesel. Explain this result with reference to the origin of bioethanol. (2 MARKS)

Question 14 (7 MARKS)

Petrodiesel and biodiesel are two fuels with a number of similarities and differences with respect to their structure and chemical properties.

a **i** Identify and explain, with reference to structure and intermolecular bonding, which fuel has a lower viscosity. (3 MARKS)

ii Name one advantage of a fuel with lower viscosity. (1 MARK)

b **i** Identify and explain, with reference to structure, which fuel has a lower hygroscopicity. (2 MARKS)

ii Name one advantage of a fuel with lower hygroscopicity. (1 MARK)

KEY SCIENCE SKILL QUESTION

Question 15 (6 MARKS)

Julius, an automobile safety engineer tasked with testing an engine's capacity to combust different fuels, conducts the following experiment to investigate the boiling point of a range of different molecules. The engineer is supplied with a large supply of petrodiesel, biodiesel and bioethanol with which to perform his experiment. In a controlled environment, 100 gram samples of each fuel were heated until vapourised, and their respective boiling points were recorded with a digital thermometer.

a Name the independent and dependent variables in this experiment. (2 MARKS)

b The experimentally determined values of the boiling points for each of the fuels were, in increasing order:

Ethanol	78 °C
Petrodiesel	250 °C
Biodiesel	360 °C

Julius notes that the boiling point for petrodiesel, which he knows is a non-polar hydrocarbon, is in fact higher than the boiling point of ethanol, which he also knows is a highly polar molecule. If, in fact, Julius' experimental results are accurate, suggest a reason for the difference in these values. (2 MARKS)

c If the engineer only has access to the resources mentioned above, identify a method to improve the precision of his results. Explain your answer. (2 MARKS)

UNIT 3 AOS 1, CHAPTER 3

Combustion

03

3A Combustion reactions

3B Energy changes during combustion

3C Gases

3D Calculating energy changes from combustion reactions

Key knowledge

- combustion of fuels as exothermic reactions with reference to the use of the joule as the SI unit of energy, energy transformations and their efficiencies and measurement of enthalpy change including symbol (ΔH) and common units (kJ mol^{-1}, kJ g^{-1}, MJ/tonne)
- the comparison of exothermic and endothermic reactions including their enthalpy changes and representations in energy profile diagrams
- the use of specific heat capacity of water to determine the approximate amount of heat energy released in the combustion of a fuel
- the writing of balanced thermochemical equations, including states, for the complete and incomplete combustion of hydrocarbons, methanol and ethanol, using experimental data and data tables
- the definition of gas pressure including units, the universal gas equation and standard laboratory conditions (SLC) at 25 °C and 100 kPa
- calculations related to the combustion of fuels including use of mass-mass, mass-volume and volume-volume stoichiometry in calculations of enthalpy change (excluding solution stoichiometry) to determine heat energy released, reactant and product amounts and net volume of greenhouse gases at a given temperature and pressure (or net mass) released per MJ of energy obtained

Image by IanRedding/Shutterstock.com

3A COMBUSTION REACTIONS

In this lesson we will explain the different types of combustion reactions as well as the basic principles which allow them to release energy to the environment.

3A Combustion reactions	**3B Energy changes during combustion**	**3C Gases**	**3D Calculating energy changes from combustion reactions**

Study design dot points

- combustion of fuels as exothermic reactions with reference to the use of the joule as the SI unit of energy, energy transformations and their efficiencies and measurement of enthalpy change including symbol (ΔH) and common units (kJ mol^{-1}, kJ g^{-1}, MJ/tonne)
- the comparison of exothermic and endothermic reactions including their enthalpy changes and representations in energy profile diagrams

Key knowledge units

Types of combustion reactions	3.1.2.1
Exothermic and endothermic reactions	3.2.2.1.1

Key terms and definitions

- **Chemical energy** energy stored in the bonds of chemical compounds
- **Exothermic** chemical reaction accompanied by the release of energy (in the form of heat)
- **Endothermic** chemical reaction which absorbs energy (in the form of heat) from the surrounding environment
- **Enthalpy** measurement of the internal energy of a system
- **Complete combustion** reaction of a substance with oxygen to produce carbon dioxide and water
- **Incomplete combustion** partial burning of a substance to produce carbon monoxide (or solid carbon) and water

Lesson links

This lesson builds on:

▶ 2A – Fossil fuels

Fuels undergo combustion

Types of combustion reactions 3.1.2.1

OVERVIEW

Either complete or incomplete combustion can occur depending on the availability of oxygen.

THEORY DETAILS

Combustion reactions are a type of chemical reaction between a substance, usually a fuel, and oxygen. This means that anytime something burns in air, like a match or a candle, a combustion reaction is involved. It is also a type of redox reaction which will we cover later in chapter 4.

There are two types of combustion reactions which occur depending on the supply of oxygen. If oxygen is in excess, **complete combustion** will occur. If there is a low supply of oxygen, **incomplete combustion** will occur. The products of complete combustion and incomplete combustion are different therefore it is important to note which reaction is occurring before writing the equation.

Complete combustion results in the production of only carbon dioxide and water. An example involving octane is shown below:

$$2C_8H_{18(l)} + 25O_{2(g)} \rightarrow 16CO_{2(g)} + 18H_2O_{(g)}$$

1 Worked example

What is the chemical equation when ethanol is combusted in an excess supply of oxygen?

What information is presented in the question?

Ethanol is being combusted

Excess supply of oxygen (this means complete combustion)

What is the question asking us to do?

Write the chemical equation for the complete combustion of ethanol

What strategy(ies) do we need in order to answer the question?

1. Write out the reactants
2. Write out the products
3. Balance the carbon atoms, hydrogen atoms and then oxygens atoms

Answer

$CH_3CH_2OH_{(l)} + O_{2\,(g)} \rightarrow CO_{2(g)} + H_2O_{(g)}$

is the unbalanced chemical reaction for the complete combustion of ethanol.

Balance the carbon atoms first:

$CH_3CH_2OH_{(l)} + O_{2\,(g)} \rightarrow 2CO_{2(g)} + H_2O_{(g)}$

Balance the hydrogen atoms next:

$CH_3CH_2OH_{(l)} + O_{2\,(g)} \rightarrow 2CO_{2(g)} + 3H_2O_{(g)}$

Balance the oxygen atoms next:

$CH_3CH_2OH_{(l)} + 3O_{2\,(g)} \rightarrow 2CO_{2(g)} + 3H_2O_{(g)}$

This is the balanced complete combustion reaction of ethanol.

Incomplete combustion results in the production of carbon monoxide and water. In reality, other carbon compounds such as soot are formed but for the purposes of the VCE Chemistry course, equations only need to include carbon monoxide and water. An example involving octane is shown below:

$2C_8H_{18(l)} + 17O_{2(g)} \rightarrow 16CO_{(g)} + 18H_2O_{(g)}$

2 Worked example

What is the chemical equation when methanol is combusted in a limited supply of oxygen?

What information is presented in the question?

Methanol is being combusted

Limited supply of oxygen (this means incomplete combustion)

What is the question asking us to do?

Write the chemical equation for the incomplete combustion of methanol

What strategy(ies) do we need in order to answer the question?

1. Write out the reactants
2. Write out the products
3. Balance the carbon atoms, hydrogen atoms and then oxygens atoms

Answer

$CH_3OH_{(l)} + O_{2(g)} \rightarrow CO_{(g)} + H_2O_{(g)}$

is the unbalanced chemical reaction for the incomplete combustion of methanol.

Balance the carbon atoms first:

$CH_3OH_{(l)} + O_{2(g)} \rightarrow CO_{(g)} + H_2O_{(g)}$

Balance the hydrogen atoms next:

$CH_3OH_{(l)} + O_{2(g)} \rightarrow CO_{(g)} + 2H_2O_{(g)}$

This is the balanced incomplete combustion reaction of methanol.

Exothermic and endothermic reactions 3.2.2.1.1

OVERVIEW

All combustion reactions are exothermic because they release energy into the surrounding environment.

THEORY DETAILS

As energy cannot be created or destroyed, as stated by the law of conservation of energy, when energy is transferred in reactions, the total amount of energy remains the same. We learned in chapter 2 that fuels undergo combustion reactions to release energy that can be used for cars or electricity. In the case of using fuel for cars, the energy released is converted into mechanical energy. Regardless of the situation, all combustion reactions are **exothermic**.

These reactions are exothermic as the total **chemical energy** of the products is less than the total chemical energy of the reactants, due to the energy lost to the surroundings. Conversely, when the total amount of chemical energy of the products is greater than the reactants, the reaction is known as **endothermic** because energy is absorbed during the reaction.

The chemical energy of a substance is known as its **enthalpy** or heat content and is represented by the symbol H. As most reactions occur in open systems, energy is not just transferred between products and reactants, some is lost to the surroundings or absorbed from the surroundings. The overall energy change that occurs as a result of a chemical reaction is known as the enthalpy change, or heat of reaction, and is represented by the symbol ΔH. The delta symbol (Δ) represents "change in" and is used in many different formulas, not just for enthalpy change.

For a general reaction, the enthalpy change is equal to the enthalpy of the products minus the enthalpy of the reactants.

$\Delta H = H_p - H_r$

As discussed above, when the enthalpy of the products is less than the enthalpy of the reactants, the reaction is exothermic, therefore $\Delta H < 0$ as the system has lost energy. When the reverse is true, the reaction is endothermic and $\Delta H > 0$. In other words, exothermic reactions result in a negative ΔH whereas endothermic reactions result in a positive ΔH.

Tip If enthalpy is positive, include a "+" symbol. If negative, include a "–" symbol.

One way of observing this is to see a change in state. If we boil a liquid to convert it into a gas, an endothermic reaction has occurred because energy was absorbed by the liquid to break the intermolecular bonds which hold the liquid molecules together.

Theory summary

- Complete combustion occurs when there is a plentiful supply of oxygen, allowing the reaction to proceed to completion. Products of the complete combustion of fuels are carbon dioxide and water.
- Incomplete combustion occurs when there is a limited supply of oxygen. Products of the incomplete combustion of fuels are carbon monoxide and water.
- All combustion reactions are exothermic.
- A reaction is exothermic if the enthalpy change (ΔH) is negative and endothermic if the enthalpy change (ΔH) is positive.

3A QUESTIONS

Theory review questions

Question 1

A reaction is endothermic if

A energy is released during the reaction.

B energy is absorbed during the reaction.

C energy does not change during the reaction.

D None of the above

Question 2

The following reaction is an example of what type of reaction?

$2CH_{4(g)} + 3O_{2\,(g)} \rightarrow 2CO_{(g)} + 4H_2O_{(g)}$

A Complete combustion reaction
B Semi-complete combustion reaction
C Incomplete combustion reaction
D Enthalpy reaction

Question 3

The sign of the enthalpy change of a combustion reaction is

A negative because endothermic reactions have a negative enthalpy change value.
B positive because exothermic reactions have a positive enthalpy change value.
C negative because exothermic reactions have a negative enthalpy change value.
D positive because endothermic reactions have a positive enthalpy change value.

Exam-style questions

Within lesson

Question 4 (1 MARK)

Which of the following reactions represents the balanced equation for the incomplete combustion of ibuprofen ($C_{13}H_{18}O_{2\,(s)}$)?

A $C_{13}H_{18}O_{2(s)} + 9O_{2(g)} \rightarrow 13CO_{(g)} + 9H_2O_{(g)}$
B $C_{13}H_{18}O_{2(s)} + 10O_{2(g)} \rightarrow 13CO_{2(g)} + 9H_2O_{(g)}$
C $C_{13}H_{18}O_{2(s)} + 10O_{2(g)} \rightarrow 13CO_{(g)} + 9H_2O_{(g)}$
D $C_{13}H_{18}O_{2(s)} + 10O_{2(g)} \rightarrow 13CO_{2(g)} + 10H_2O_{(g)}$

Question 5 (2 MARKS)

Alcohols can be found in fuels as they are able to undergo combustion to provide energy for motor vehicles. Provided is an example of a chemical reaction involving an alcohol.

$CH_3(CH_2)_7OH_{(l)} + XO_{2(g)} \rightarrow YCO_{2(g)} + ZH_2O_{(g)}$

a Identify the values of X, Y and Z. (1 MARK)
b Write the equation representing enthalpy change of this reaction using the symbols ΔH, H_r, H_p. (1 MARK)

Question 6 (3 MARKS)

The chemical reactions provided both convert chemical energy into electrical energy.

1 $Pb_{(s)} + PbO_{2(s)} + 2H_2SO_{4(aq)} \rightarrow 2PbSO_{4(aq)} + 2H_2O_{(l)}$
2 $2C_4H_{10(g)} + 13O_{2(g)} \rightarrow 8CO_{2(g)} + 10H_2O_{(l)}$

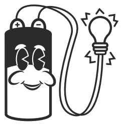
a Is equation 1 or equation 2 a combustion reaction? Justify your answer. (2 MARKS)
b For the equation that is a combustion reaction, identify the sign of its enthalpy change. (1 MARK)

Question 7 (5 MARKS)

Bilbo wanted to develop a more efficient fuel source and wanted to test if octanol is a suitable substitute for ethanol (which is currently being used in fuels). Bilbo's balanced thermochemical equation involving octanol has been provided.

$C_8H_{17}OH_{(l)} + 12O_{2(g)} \rightarrow 8CO_{2(g)} + 9H_2O_{(g)} \quad \Delta H = +5294 \text{ kJ mol}^{-1}$

a When checking his work, he realised that there was an error in his thermochemical equation. Identify the error and justify your answer. (3 MARKS)
b Upon repeating his test, he noticed that there was soot being produced as a result of the reaction. Describe the implication of this observation on the reaction. (2 MARKS)



Question 8 (5 MARKS)

Tiberius decided to burn some butane to see what the products of the reaction would be. He set up a device which could detect the presence of water and carbon dioxide. When he burnt the butane, water as steam was present but no carbon dioxide.

a Write the balanced complete combustion reaction of butane. (2 MARK)

b What would the lack of carbon dioxide indicate about the type of combustion reaction that occurred? (1 MARK)

c Is the conversion of liquid water to steam, a process which occurred in this reaction, an endothermic or exothermic process. Justify your answer. (2 MARKS)

Multiple lessons

Question 9 (8 MARKS)

Clodia was experimenting with biodiesel and decided to write an equation for the complete combustion of a mixture consisting entirely of $C_{17}H_{34}O_{2(l)}$.

a What is the balanced chemical equation for the complete combustion reaction of $C_{17}H_{34}O_{2(l)}$? (1 MARK)

b Clodia decides to burn $C_{17}H_{34}O_{2(l)}$ underneath a beaker of cold water. Will the temperature of the water increase or decrease? Explain your answer. (2 MARKS)

c When she is doing this experiment, the carbon monoxide alarm in her lab starts to sound. Explain what has happened and why. (2 MARKS)

d Using your knowledge of types of combustion reactions, explain how she might ensure that carbon monoxide, a deadly gas, is **not** produced at all. (1 MARK)

e Is biodiesel a renewable energy source? Explain why or why not. (2 MARKS)

3B ENERGY CHANGES DURING COMBUSTION

In this lesson, we will learn how to measure and calculate energy changes during combustion reactions, as well as how to classify these reactions based on their energy changes.

3A Combustion reactions	3B Energy changes during combustion	3C Gases	3D Calculating energy changes from combustion reactions

Study design dot points

- combustion of fuels as exothermic reactions with reference to the use of the joule as the SI unit of energy, energy transformations and their efficiencies and measurement of enthalpy change including symbol (ΔH) and common units (kJ mol^{-1}, kJ g^{-1}, MJ/tonne)
- the use of specific heat capacity of water to determine the approximate amount of heat energy released in the combustion of a fuel
- the writing of balanced thermochemical equations, including states, for the complete and incomplete combustion of hydrocarbons, methanol and ethanol, using experimental data and data tables

Key knowledge units

Energy changes during combustion reactions	3.1.2.2
Specific heat capacity	3.1.6.1
Thermochemical equations	3.1.3.1

Key terms and definitions

- **Energy profile diagram** representation of the energy transformation of a chemical reaction
- **Activation energy** minimum amount of energy required for a reaction to proceed
- **Heat of combustion** amount of heat released by the complete combustion of a substance
- **Specific heat capacity, *c*** heat required to raise the temperature of 1 gram of a given substance by 1°C
- **Thermochemical equation** balanced stoichiometric equation that includes the enthalpy change, ΔH, of the reaction

Lesson links

This lesson builds on:

▶ 2A – Fossil fuels

Fossil fuels undergo energy changes in combustion reactions.

▶ 2B – Biofuels

Biofuels undergo energy changes in combustion reactions.

▶ 3A – Combustion reactions

Exothermic and endothermic reactions relate to energy changes in combustion reactions.

Energy changes during combustion reactions 3.1.2.2

OVERVIEW

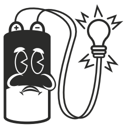
All substances contain chemical energy, the energy stored in the bonds of compounds, which can be released and absorbed in chemical reactions from the breaking and formation of new chemical bonds.

THEORY DETAILS

As we learned in lesson 3A, the combustion of fuels is an exothermic reaction because energy is released during the reaction as heat. We can measure this by looking at state changes of a reaction, that is whether a substance starts as a liquid and is released as a gas, or by measuring the production of heat by the reaction's change in temperature.

To be more precise about the energy changes that occur during a reaction, **energy profile diagrams** are used as they not only show whether a reaction is exothermic or endothermic, but also how much energy may be needed to initiate the reaction. They also show the difference in chemical energy between reactants and products, known as enthalpy (ΔH), which we learned about in lesson 3A.

Figure 1 shows what an exothermic reaction looks like in an energy profile diagram, compared to an endothermic reaction. For an exothermic reaction, such as a combustion reaction, the enthalpy of the products is always less than the reactants due to the release of energy.



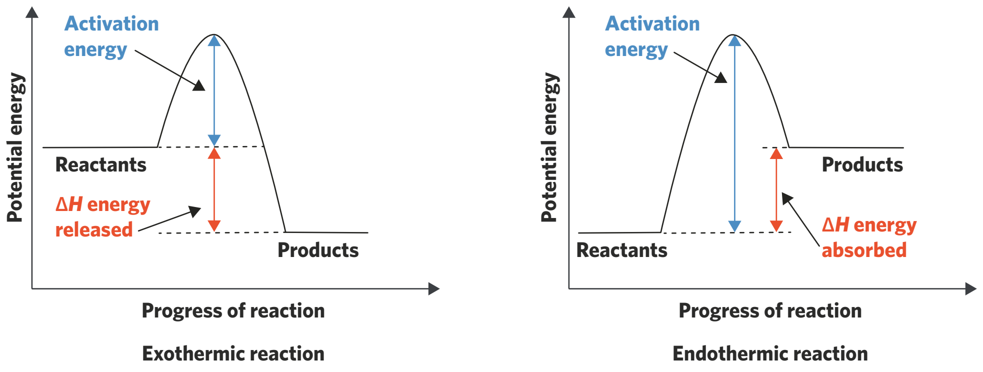


Figure 1 Energy profile diagrams of exothermic reactions and endothermic reactions

The opposite is shown for endothermic reactions. However, both energy profile diagrams show the **activation energy** of the reaction which is the minimum initial energy required to break the bonds of the reactants so that the reaction can proceed. It is represented as E_a. It is an energy barrier that first needs to be overcome in order for a reaction to take place and whilst it cannot be represented in thermochemical equations, it is shown in energy profile diagrams. It exists for both endothermic and exothermic reactions but varies in magnitude depending on the reaction.

Tip The heat of combustion of some common fuels can be found in the data book.

The heat energy released when one mole of a fuel undergoes complete combustion is known as the heat of combustion, which is measured in kJ mol^{-1}. It is important to note that this is represented as a positive value, even though the enthalpy change of a combustion reaction is exothermic, requiring a negative value.

Many fuels such as petrodiesel are a mixture of compounds and so their **heat of combustion** cannot be measured in kJ mol^{-1} as molecular weight cannot be determined, hence moles cannot be calculated. Therefore, their heats of combustion are measured in kJ g^{-1}.

The heat of combustion value can be used to compare the energy released from the combustion of different substances, regardless of the efficiency of the reaction. To calculate the energy released when n mol of fuel burns, or is combusted, use the following equation.

$$E = n \times \Delta H_c$$

The subscript c in ΔH_c denotes that it is the enthalpy value for a combustion reaction.

Tip To calculate the heat of combustion of a substance per gram, divide the heat of combustion per mol by the molar mass of the substance.

1 Worked example

Calculate the amount of energy released when 2.6 kg of propane (C_3H_8) is burned in an excess supply of oxygen, given that the heat of combustion of propane is 2220 kJ mol^{-1}.

What information is presented in the question?

Molecular formula of propane C_3H_8

2.6 kg of propane was burnt.

$\Delta H\ (C_3H_8) = -2220\ \text{kJ mol}^{-1}$

What is the question asking us to do?

Calculate the energy released in the combustion of 2.6 kg of propane.

What strategy(ies) do we need in order to answer the question?

1. Convert the mass of propane to grams.
2. Calculate the number of moles of propane.
3. Multiply the number of moles by the heat of combustion to calculate the energy released.

Answer

$n(C_3H_8) = \dfrac{2.6 \times 10^3}{44.0}$

$= 59.09$ mol

Energy released $= 59.09 \times 2220$

$= 131\,182$ kJ

$= 1.3 \times 10^5$ kJ (2 s.f)

Specific heat capacity 3.1.6.1

OVERVIEW

We have just learned about how to calculate the energy released from burning a fuel and now we will look at how we can use it to determine the specific heat capacity of combustion reactions.

THEORY DETAILS

The **specific heat capacity** of a substance is the heat required to raise the temperature of 1 gram of a substance by 1°C. It is given the symbol *c* and is most commonly expressed in $\text{J g}^{-1}\,°\text{C}^{-1}$. The specific heat capacity of a substance is also a reflection of the type of bonds holding the compound together. For example, water has a specific heat capacity of $4.18\ \text{J g}^{-1}\,°\text{C}^{-1}$, meaning that it would take 4.18 J of energy to increase the temperature of 1.0 g of water by 1°C. The relatively high value is due to the fact that water molecules are held together by strong hydrogen bonds. Therefore, a high specific heat capacity indicates that a substance more effectively stores heat energy.

The heat energy required to raise the temperature of a given substance by a particular amount can be calculated by the following equation.

$q = m \times c \times \Delta T$

where q is the amount of heat energy in joules, m is the mass of the substance in grams, *c* is its specific heat capacity in $\text{J g}^{-1}\,°\text{C}^{-1}$ and ΔT is the temperature change in °C.

2 Worked example

Calculate the heat energy, in kJ, required to raise the temperature of 700 mL of water by 17°C.

What information is presented in the question?

Volume = 700 mL

$\Delta T = 17°\text{C}$

What is the question asking us to do?

Calculate *q*, heat energy in kJ

What strategy(ies) do we need in order to answer the question?

1. Find the mass of water present using the density of water value found in the databook.
2. Find the specific heat capacity of water in the databook.
3. Use the specific heat formula $q = m \times c \times \Delta T$
4. Convert to kJ

Answer

$m = 700 \times 0.997 = 697.9\ \text{g}$

$c = 4.18\ \text{J g}^{-1}\,°\text{C}^{-1}$

$\Delta T = 17°\text{C}$

$q = m \times c \times \Delta T$

$= 697.9 \times 4.18 \times 17$

$= 49593\ \text{J}$

$= 49.6\ \text{kJ}$ (3 s.f)

This formula can now be used experimentally to calculate the heat of combustion of a substance. Chemical energy is converted into thermal (heat) energy in a combustion reaction. We can therefore use this released energy to heat a measured volume of water to determine the amount of energy released by the fuel – that is, its heat of combustion. This is done experimentally by burning a fuel using a method like the one illustrated in figure 2, beneath a can of water so that the heat released from the burning fuel can be measured by recording the change in temperature of the water.

To calculate the molar heat of combustion from this experiment:

1. Record the mass and change in temperature of the water.
2. Calculate the energy released using the formula $q = m \times c \times \Delta T$.
3. Calculate the number of moles of the substance combusted using $n = \frac{m}{M}$
4. Calculate the heat of combustion by the following equation:

$$\text{heat of combustion} = \frac{\text{heat energy released } (q)}{\text{number of moles of the sample}}$$

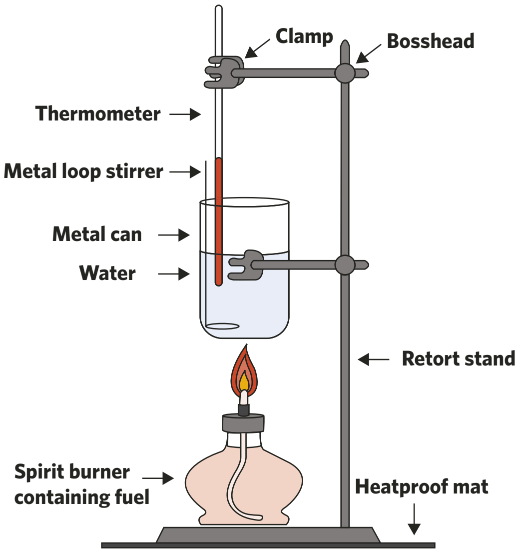


Figure 2 Apparatus for measuring heat of combustion of a fuel

In the following section, we will learn how to write **thermochemical equations** and how to determine the heat of combustion for thermochemical equations.

▶ Important note

For an exothermic reaction, remember that the heat energy released is expressed with a negative sign.

Thermochemical equations 3.1.3.1

OVERVIEW

Thermochemical equations indicate the type of energy change (endothermic or exothermic) and its magnitude.

THEORY DETAILS

In a thermochemical equation, we write the balanced chemical equation, including the states, and to the right of the equation we add the enthalpy change to signify the amount of energy that is lost or gained by the system corresponding to the mole amounts specified by the coefficients in the equation.

For example, consider the combustion of methanol shown in the equation below.

$$CH_3OH_{(l)} + \frac{3}{2}O_{2(g)} \rightarrow CO_{2\,(g)} + 2H_2O_{(l)} \qquad \Delta H = -726.56 \text{ kJ mol}^{-1}$$

The enthalpy change of this reaction is negative meaning the reaction is exothermic. That is, heat is released during the reaction. The reaction also tells us that when 1 mole of methanol is reacted with 1.5 moles of oxygen, 1 mole of carbon dioxide and 2 moles of water are formed and 726.56 kJ of energy is released as heat.

As the enthalpy change corresponds to the mole amounts specified by the equation, if the coefficients are changed, the enthalpy will change as well. Using the above example of the combustion of methanol, if twice as much methanol were reacted with oxygen then twice as much energy would be released in the reaction.

It is also important to write the correct states as it affects the enthalpy change of the reaction. Using the example of water, the enthalpy change of solid ice melting to liquid water, as shown in the equation below, is +6 kJ mol^{-1}. Whilst, the enthalpy change of water boiling from a liquid to a gas is +40.7 kJ mol^{-1}.

$H_2O_{(s)} \rightarrow H_2O_{(l)}$ $\Delta H = +6$ kJ mol^{-1}

$H_2O_{(l)} \rightarrow H_2O_{(g)}$ $\Delta H = +40.7$ kJ mol^{-1}

If a chemical reaction were to reverse, that is proceeding in the opposite direction, the sign of ΔH would change but its magnitude (size) would stay the same. Using the above example again, if the reaction of the combustion of methanol were reversed, the sign of ΔH would be positive and the reaction would be endothermic, as shown below.

$$CO_{2(g)} + 2H_2O_{(l)} \rightarrow CH_3OH_{(l)} + \frac{3}{2}O_{2(g)} \qquad \Delta H = +726.56 \text{ kJ mol}^{-1}$$

3 Worked example

Ethanol reacts with oxygen according to the following equation:

$C_2H_5OH_{(l)} + 3O_{2(g)} \rightarrow 2CO_{2(g)} + 3H_2O_{(l)}$ $\Delta H = -1366.8$ kJ mol^{-1}

Calculate ΔH for the following reaction:

$4CO_{2(g)} + 6H_2O_{(l)} \rightarrow 2C_2H_5OH_{(l)} + 6O_{2(g)}$

What information is presented in the question?

The equation for the combustion of ethanol and its enthalpy of combustion: $\Delta H = -1366.8$ kJ mol^{-1}

The reaction is given in reverse, with the stoichiometric ratio doubled.

What is the question asking us to do?

Calculate ΔH for the given reaction.

What strategy(ies) do we need in order to answer the question?

1. Reverse the sign of ΔH as the reaction has reversed.
2. Double ΔH as the number of moles of the constituents has doubled.

Answer

ΔH for the second equation is positive.

The mole amount for each of the constituents has doubled.

$2 \times 1366.8 = 2733.6$

$\Delta H = +2733.6$ kJ mol^{-1}

Heat of combustion values can also be used to determine the enthalpy change for a thermochemical equation. Make sure to note the units as heat of combustion is often measured in kJ g^{-1} so it should be converted to kJ mol^{-1} for use in thermochemical equations. For example, the equation for the complete combustion of octane is:

$2C_8H_{18(l)} + 25O_{2(g)} \rightarrow 16CO_{2(g)} + 18H_2O_{(l)}$ $\Delta H = ?$

Given that the molar heat of combustion of octane is –5460 kJ mol^{-1}, and the coefficient of octane in the combustion of octane is 2, we must multiply the heat of combustion of octane by 2 to get the enthalpy change. Therefore in this case

$\Delta H = 2 \times -5450$

$= -1.09 \times 10^4$ kJ mol^{-1}

Theory summary

- Chemical reactions can either release energy, making them exothermic, or absorb energy, making them endothermic.
- Heat of combustion (ΔH_c) of a fuel indicates the maximum amount of energy that can be released when the fuel undergoes complete combustion.
- Energy released when a fuel undergoes complete combustion is calculated by the following equation: $E = n \times \Delta H_c$.
- Energy profile diagrams represent energy changes during a reaction.
- Specific heat capacity, c, is an indication of the effectiveness of a compound to store heat energy.
- The heat required to raise the temperature of a certain mass of a given substance by a specified amount is calculated by the equation: $q = m \times c \times \Delta T$.
- The heat energy released, q, can then be used to calculate the heat of combustion of a substance by the following equation: heat of combustion = heat energy released/number of moles combusted.
- Thermochemical equations include the enthalpy change (ΔH) at the end of the equation to indicate the heat released (negative sign) or absorbed by (positive sign) the reaction.
- Heat of combustion data can be used to calculate the enthalpy change of a reaction.

3B QUESTIONS

Theory review questions

Question 1

What is a good physical indicator of whether a reaction is endothermic or exothermic?

A Change of states

B Activation energy

C Enthalpy change

D Change in mass of reactants

Question 2

Which of the following is an example of a thermochemical equation?

A $C_2H_5OH_{(l)} + 3O_{2(g)} \rightarrow 2CO_{2(g)} + 3H_2O_{(l)}$

B $C_2H_5OH_{(l)} + 3O_{2(g)} \rightarrow 2CO_{2(g)} + 3H_2O_{(l)}$ $\Delta H = -1366.8$ kJ mol^{-1}

C $\Delta H = -1366.8$ kJ mol^{-1}

D All of the above

Question 3

The heat of combustion of fuels that contain a mixture of compounds can be measured in

A kJ mol^{-1} **B** J mol^{-1} **C** J g^{-1} °C^{-1} **D** kJ g^{-1}

Question 4

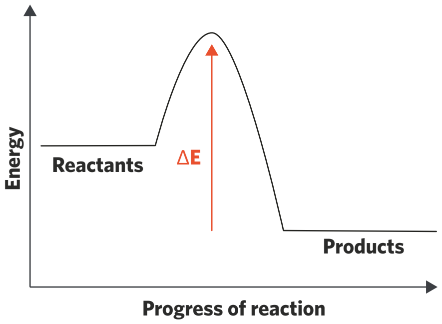
The change in energy labelled ΔE in the energy profile diagram is

A The energy required to initiate the forward reaction.

B The activation energy for the forward reaction.

C The enthalpy of the reaction.

D The activation energy for the reverse reaction



Exam-style questions

Within lesson

Question 5 (1 MARK)

What is closest to the total energy released when 100 g of butane and 200 g of octane undergo combustion in the presence of excess oxygen?

A 10000 kJ

B 1500 kJ

C 15000 kJ

D 20000 kJ

Question 6 (1 MARK)

The reaction

A + B → C; ΔH = positive

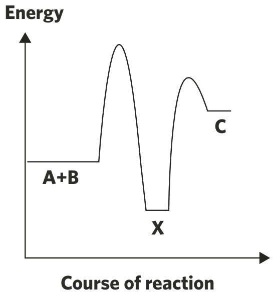
Involves a two-step process

A + B → X; ΔH = negative

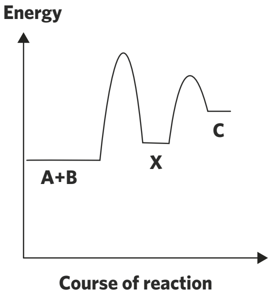
X → C; ΔH = positive

Which one of the following diagrams best represents the energy changes during the course of the reaction?

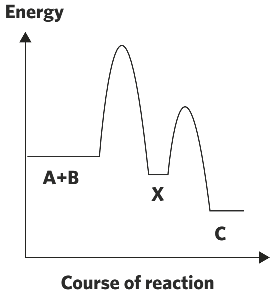
A



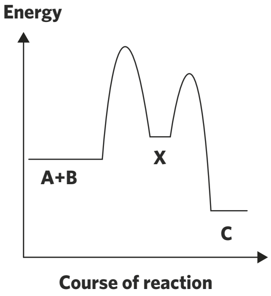
B



C



D



Adapted from VCAA 2007 Exam 1 Section A Q19

Question 7 (1 MARK)

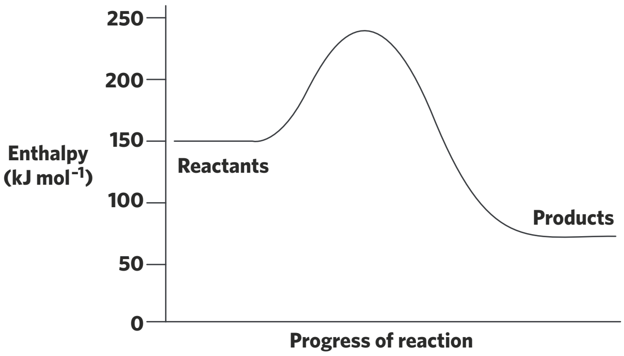
0.65 moles of ethanol undergoes complete combustion in the following equation

$C_2H_5OH_{(l)} + 3O_{2(g)} \rightarrow 2CO_{2(g)} + 3H_2O_{(l)}$

How much energy is released, given that the heat of combustion of ethanol is 1360 kJ mol^{-1}?

Question 8 (1 MARK)

A chemical reaction has the following energy profile.



What is the enthalpy change for the forward reaction?

Question 9 (2 MARKS)

Magnesium metal burns in air according to the following equation.

$2Mg_{(s)} + O_{2(g)} \rightarrow 2MgO_{(s)}\ \Delta H = -1200\ \text{kJ mol}^{-1}$

Calculate how much energy is released when 6.7 g of magnesium is burned.

Question 10 (2 MARKS)

Given the equation for cellular respiration,

$C_6H_{12}O_{6(aq)} + 6O_{2(g)} \rightarrow 6CO_{2(g)} + 6H_2O_{(l)}$

When 65.0 g of glucose ($C_6H_{12}O_6$) is metabolised in cellular respiration, the total energy released is 1.126×10^3 kJ.

Calculate the molar heat of combustion of glucose, given that the molecular weight of glucose is 180.0 g mol^{-1}.

Question 11 (2 MARKS)

An equation for the complete combustion of methanol is

$2CH_3OH_{(l)} + 3O_{2(g)} \rightarrow 2CO_{2(g)} + 4H_2O_{(g)}$

Given that the enthalpy change of this reaction is –1452 kJ mol^{-1}, what is the molar heat of combustion of methanol. Justify your answer with a statement.

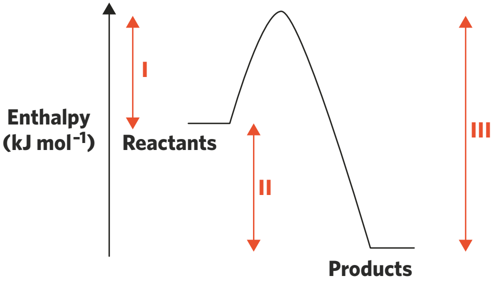
Question 12 (2 MARKS)

Calculate the heat energy, in kJ, required to raise the temperature of 200 mL of water by 22°C.

Question 13 (3 MARKS)

Consider the following energy profile diagram for a particular chemical reaction.

What do I, II and III represent, respectively?



Multiple lessons

Question 14 (5 MARKS)

A student combusted 250 g of butane gas in a metal canister to heat a 100 mL beaker of water. The temperature of the water increased from 15°C to 28°C.

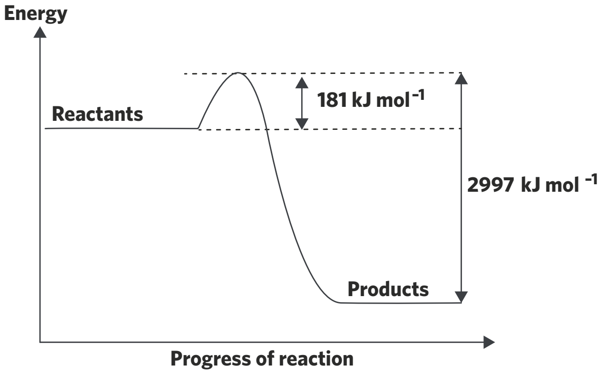
a Given that the theoretical molar heat of combustion of butane is –2880 kJ mol^{-1}, write the thermochemical equation for the complete combustion of butane. (2 MARKS)

b Calculate the amount of heat energy, in kJ, absorbed by the water when it was heated by burning butane. (2 MARKS)

c The student calculated an experimental value for the enthalpy change of butane to be -1.5×10^3 kJ mol^{-1}. Calculate the percentage energy loss in this experiment, which can be calculated with the following equation. Percentage energy loss = (theoretical value of $\Delta H -$ experimental value of ΔH) ÷ theoretical value of $\Delta H \times 100$. (1 MARK)

Question 15 (5 MARKS)

For the combustion of a pure solution of glucose, $C_6H_{12}O_6$, the following energy profile diagram was produced.



a Write the balanced thermochemical equation for the combustion of glucose. (2 MARKS)

b Calculate the energy released per gram of glucose burned. (1 MARK)

c The average cyclist uses 75 kJ of energy for every km travelled. If the glucose content of an energy bar is 25.0 g, how far can an average cyclist travel on the glucose content of only one energy bar (to 2 significant figures)? (2 MARKS)

3C GASES

In this lesson, we will cover the general properties of gases, and calculations involving pressure, temperature, volume and the number of moles.

3A Combustion reactions	3B Energy changes during combustion	3C Gases	3D Calculating energy changes from combustion reactions

Study design dot point

- the definition of gas pressure including units, the universal gas equation and standard laboratory conditions (SLC) at 25°C and 100 kPa

Key knowledge units

How gases behave	3.1.4.1.1
Defining pressure	3.1.4.1.2
The universal gas law	3.1.4.2

Key terms and definitions

- **Gas** state of matter with no fixed shape or volume and which fills the available space
- **Ideal gas** substance assumed to be composed of molecules of negligible volume with no intermolecular interactions
- **Pressure** force a gas exerts on the walls of its container
- **Standard Laboratory Conditions (SLC)** set of conditions used as a standard for experiments (25°C and 100 kPa)

Lesson links

This lesson builds on:

- 3B – Energy changes during combustion

We can apply these calculations to the reactions of fuels in gas form.

How gases behave 3.1.4.1.1

OVERVIEW

The particles within a gas can be modelled by the ideal gas approximation.

THEORY DETAILS

A **gas** can be described as a substance with no fixed shape or volume.

For example, the air in the atmosphere around us consists of gases and does not have a constant shape. It can expand or condense to fill the available volume.

For the purposes of VCE Chemistry, we will assume all gases are **ideal gases**, as real gases are quite complicated to work with. This means we assume that molecules within a gas:

- experience no intermolecular forces.
- have zero volume individually.
- exchange no energy when a collision occurs.

This assumption makes our calculations far simpler, and allows us to approximate the properties of gases relatively well.

Defining pressure 3.1.4.1.2

OVERVIEW

Pressure is a property of a gas and can be expressed in a number of different units.

THEORY DETAILS

We define **pressure** as the force exerted by a gas on the walls of the container enclosing it. The molecules within a gas are constantly moving around as shown in figure 1, colliding with each other and the walls of the container or vessel they are in. The collisions of molecules with the container wall collectively result in a force we define as pressure.

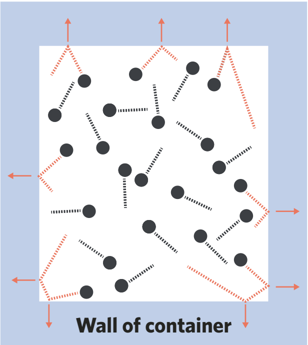
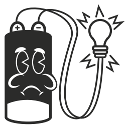


Figure 1 Representation of collisions within a closed volume



We quantify pressure by identifying the force exerted by the gas per unit area of the container. Therefore:

$$\text{Pressure} = \frac{\text{force}}{\text{area}}$$

where area is the surface area of the container that the gas collides with.

In this equation, we conventionally use force measured in Newtons (N), and area measured in metres squared (m^2), meaning pressure has the units Newtons per metre squared (Nm^{-2}).

This unit Nm^{-2} is more commonly referred to as the Pascal (Pa).

However, pressure can also be expressed in other units. Refer to figure 2 for conversions of common units to kPa.

mmHg	:	kPa	:	atm
750 mmHg	:	100 kPa	:	0.987 atm

Figure 2 The conversion of units of pressure

Tip All the information to convert pressure units can be found in the data book.

1 Worked example

An ideal gas is stored in a cylinder at a pressure of 15 atm. Express this pressure in pascals.

What information is presented in the question?	Answer
We have a gas at a pressure of 15 atmospheres. **What is the question asking us to do?** Convert atmospheres to pascals. **What strategy(ies) do we need in order to answer the question?** **1.** Use our data book to find the relationship between atmospheres and pascals **2.** Apply this to our pressure value	The data book states 0.987 atm is equivalent to 100 kPa. $0.987 \text{ atm} = 100 \times 10^3$ Pa $= \frac{15}{0.987} \times 100 \times 10^3 = 1.5 \times 10^6$

The universal gas law 3.1.4.2

OVERVIEW

We can quantify the properties of a gas using an equation known as the universal gas law.

THEORY DETAILS

The properties of a gas such as temperature, pressure, volume and number of moles are related and dependent on each other. We can represent this relationship with the equation given in figure 3. This equation holds true for all ideal gases.

Note that R is a constant number known as the Universal Gas Constant. It can be found in the data booklet and has a value of 8.31 J mol^{-1} K^{-1}

The units of the variables used in this equation are also given in figure 3 and are a guide to the calculations we require to obtain the above units. The conversions for pressure were covered previously, and the calculation required for temperature conversion is given in figure 4.

$$PV = nRT$$

Symbol	Quantity	Unit
P	Pressure	kPa
V	Volume	L
n	Number of moles	mol
R	Universal gas constant	J mol^{-1} K^{-1}
T	Temperature	K

Figure 3 The universal gas equation and the units of quantities

$$\text{Celsius} \xrightarrow{\text{Add 273}} \text{Kelvin}$$

Figure 4 The conversion for temperature

2 Worked example

15 L of gas is stored in a cylinder at pressure 2.0 kPa. If the temperature of the cylinder is 25°C, how many moles of gas are contained?

What information is presented in the question?

Volume = 15 L

Pressure = 2.0 kPa

Temperature = 25°C

What is the question asking us to do?

Find the number of moles.

What strategy(ies) do we need in order to answer the question?

1. Convert all quantities to the required units
2. Rearrange the universal gas law for the required variable
3. Apply the gas law

Answer

Volume = 15 L

Pressure = 2.0 kPa

Temperature = 25° C = (25 + 273) K = 298 K

The universal gas equation is $PV = nRT$

We can rearrange this for n, giving

$$n = \frac{PV}{RT}$$

So $n = \frac{2.0 \times 15}{8.31 \times 298}$

$n = 1.2 \times 10^{-2}$ mol

In order to compare ideal gases and experiments with gases it is useful to have a standard set of conditions under which experiments are conducted. The scientific community has agreed upon a set of conditions known as **Standard Laboratory Conditions (SLC)** that provide this consistency. The SLC conditions are:

- Temperature of 25°C
- Pressure of 100 kPa

These numbers can be found in the data book.

Let's apply these conditions to the universal gas equation.

3 Worked example

One mole of a gas is stored at SLC. Calculate the volume the gas occupies.

What information is presented in the question?

Pressure = 100 kPa

Temperature = 25°C

Number of moles = 1 mol

What is the question asking us to do?

Find the volume.

What strategy(ies) do we need in order to answer the question?

1. Convert all quantities to required units
2. Rearrange equations for required quantity
3. Calculate volume

Answer

Pressure = 100 kPa

Temperature = 25° C = (25 + 273) K = 298 K

Number of moles = 1 mol

The universal gas equation is $PV = nRT$

We can rearrange this for V, giving

$$V = \frac{nRT}{P}$$

So $V = \frac{1 \times 8.31 \times 298}{100}$

V= 24.8 L

The result above demonstrates a shortcut for calculating the volume of a gas.

We calculated that one mole of any ideal gas at SLC occupies 24.8 L. We can infer from this that the relationship between the number of moles and volume for an ideal gas is:

$$n = \frac{V}{V_m}$$

Here V_m is the value of 24.8 L which was calculated in worked example 3. This value, known as the molar volume of an ideal gas, can be found in the data book.

Theory summary

- A gas is a state of matter with no fixed shape or volume where molecules fill the available space.
- Pressure is the force a gas exerts on its surrounding container.
- Pressure is given by force per unit area.
- The universal gas law $PV = nRT$ can be used to determine the volume, pressure, temperature or number of moles of a gas, assuming an ideal gas.
- SLC is a set of conditions used to standardise scientific experiments.
- We can apply $n = \frac{V}{V_m}$ when a gas is at SLC.

3C QUESTIONS

Theory review questions

Question 1

A sample of argon gas occupies a 37 L sealed container and is at 35°C at 1 atm. Under these conditions, it would be expected that a different gas under the same conditions would have

A the same number of moles.
B a greater number of moles.
C a smaller number of moles.
D an unknown number of moles.

Question 2

Pressure is best defined as

A the area per unit of gas in a container.
B the amount of gas per unit area of its container.
C the force per unit area of a gas on its container.
D the area per unit force of a gas in a container.

Question 3

1.3 mol of neon gas at 17°C and 380 kPa would have ___________ mass than a sample of nitrogen gas at the same conditions, and ___________ volume.

A the same; a greater
B a smaller; the same
C a greater; a greater
D the same; the same

Question 4

A sealed flask of oxygen is at pressure 1 atm. This can be given in kPa as

A 100 kPa
B 101.3 kPa
C 9.87×10^{-3} kPa
D 1.00 kPa

Exam-style questions

Within lesson

Question 5 (1 MARK)

Under SLC, which of the following statements is true?

A One mole of chlorine gas occupies the same volume as one mole of neon gas.

B 20 grams of chlorine gas occupies exactly double the volume of 10 grams of neon gas.

C One mole of chlorine gas occupies a greater volume than one mole of neon gas.

D 20 grams of chlorine gas occupies the same volume as 10 grams of neon gas.

Question 6 (1 MARK)

Two cylinders with the same volume, labelled *D* and *G*, are at SLC and contain 10.0 grams of Cl_2 gas and 2.85 grams of an unknown gas respectively.

Which of the following is the identity of the unknown gas?

A Hydrogen **B** Oxygen **C** Neon **D** Argon

Question 7 (3 MARKS)

A 250 mL aerosol can contains 4.6 grams of carbon monoxide (CO). The label contains a warning that at temperatures exceeding 65°C the can may explode.

a At the point of explosion, what pressure is the gas inside the can? (2 MARKS)

b Express the pressure at the point of explosion in atmospheres. (1 MARK)

Question 8 (6 MARKS)

A sealed flask containing an unknown gas *Y* contains 10.0 L of gas at 32° C and 12 mmHg.

a Express the pressure of the gas in pascals. (1 MARK)

b How many moles of gas are in the flask? (2 MARKS)

c Can we determine the identity of the gas based on the information given? Explain. (2 MARKS)

d Scientists determine gas *Y* is carbon dioxide. What mass of carbon dioxide is present in the flask? (1 MARK)

Question 9 (3 MARKS)

Nitrous oxide (N_2O) is a colourless, non-flammable gas commonly used as an anaesthetic. Nitrous oxide is administered to a patient from a tank of fixed volume of 50 L in a hospital room of steady temperature 25°C. If the patient requires 2.0 grams of nitrous oxide, and the entire volume of the tank is delivered, what pressure should the tank be designed to hold?

Question 10 (5 MARKS)

Chemical engineer Zoe is investigating the properties of a range of different gases. A 5.0 gram sample of each of carbon dioxide, sulfur dioxide and nitrogen gas are analysed in the laboratory at SLC.

a Will the three gases occupy the same volume? Justify your answer with calculations and assume that each gas is added to a separate container. (3 MARKS)

b Zoe decides to further analyse the carbon dioxide sample. A cylinder of the sample is removed from SLC and the temperature increased to 40°C. Would you expect the pressure to increase, decrease, or remain constant given that the volume is kept constant? Justify your answer using the universal gas law. (2 MARKS)

Multiple lessons

Question 11 (9 MARKS)

Propane gas was combusted in the presence of abundant oxygen at 1 atm and 25°C , with 0.1 L of propane reacting.

a Write a balanced thermochemical equation for the combustion of propane. (2 MARKS)

b Calculate the volume of carbon dioxide produced by this reaction, after the system has returned to the original pressure, but at temperature 48°C. (4 MARKS)

c Calculate the mass of carbon dioxide produced by this reaction. (1 MARK)

d Calculate the total energy released by propane in this reaction. (1 MARK)

e Explain an environmental impact of this process, given that carbon dioxide is a product. (1 MARK)

3D CALCULATING ENERGY CHANGES FROM COMBUSTION REACTIONS

In this lesson, you will be learning about how to manipulate the stoichiometry of combustion reaction equations to solve for unknown volumes, masses and molar amounts.

3A Combustion reactions	3B Energy changes during combustion	3C Gases	**3D Calculating energy changes from combustion reactions**

Study design dot point

- calculations related to the combustion of fuels including use of mass-mass, mass-volume and volume-volume stoichiometry in calculations of enthalpy change (excluding solution stoichiometry) to determine heat energy released, reactant and product amounts and net volume of greenhouse gases at a given temperature and pressure (or net mass) released per MJ of energy obtained

Key knowledge units

Mass to mass calculations involving combustion	3.1.5.1.1
Mass to volume calculations involving combustion	3.1.5.1.2
Volume to volume calculations involving combustion	3.1.5.1.3
Hess's law	3.1.5.2

Key terms and definitions

- **Stoichiometry** study and calculations of mole ratios of substances involved in chemical reactions
- **Hess's law** overall enthalpy change of a reaction is independent of the pathway between the initial and final stages

---

Mass to mass calculations involving combustion 3.1.5.1.1

OVERVIEW

The mass of a reactant or product of a balanced chemical equation can be used to calculate the mass of any other species in the reaction by use of **stoichiometry**.

Tip Recall from Units 1 & 2, the relationship between the known and unknown species in a chemical reaction is given by:

$$n(\text{unknown}) = \frac{\text{coefficient of the unknown species}}{\text{coefficient of the known species}} \times n(\text{known})$$

THEORY DETAILS

There are often situations where it is more convenient to measure the quantities of reactants and products of a chemical reaction by their mass, not in molar amounts. However, we will still need to convert between masses and molar amounts for our laws of stoichiometry to still work. In this section, we will only focus on calculations involving the combustion of fuels.

To convert between the mass of a species and the number of moles, we use the formula

$$n = \frac{m}{M}$$

where m represents the mass in grams (g) and M represents the molar mass of the species in grams per mol (g mol^{-1}).

1 Worked example

3.00 kg of ethane gas undergoes combustion in an excess of oxygen according to the following equation.

$C_2H_{6(g)} + \frac{7}{2}O_{2(g)} \rightarrow 2CO_{2(g)} + 3H_2O_{(g)}$

Calculate the mass, in grams, of CO_2 produced if the reaction goes to completion.

What information is presented in the question?

The amount of C_2H_6 that is reacting.

The balanced reaction for the combustion of ethane.

What is the question asking us to do?

Calculate the mass, in grams, of CO_2 produced.

What strategy(ies) do we need in order to answer the question?

1. Determine the $n(C_2H_6)$, our known amount
2. Calculate the $n(CO_2)$, our unknown amount
3. Determine the $m(CO_2)$ to answer the question

Answer

$m(C_2H_6) = 3.00 \text{ kg} \times 1000 = 3000 \text{ g}$

$M(C_2H_6) = 2 \times 12 + 6 \times 1 = 30 \text{ g mol}^{-1}$

$n(C_2H_6) = \frac{m}{M}$

$= \frac{3000}{30}$

$= 100 \text{ mol}$

$n(C_2H_6) : n(CO_2)$

$1 : 2$

$n(CO_2) = \frac{\text{coefficient of unknown}}{\text{coefficient of known}} \times n(\text{known})$

$= \frac{2}{1} \times 100$

$= 200 \text{ mol}$

$m(CO_2) = n \times M$

$= 200 \times (1 \times 12 + 2 \times 16)$

$= 200 \times 44$

$= 8800 \text{ g}$

$= 8.80 \times 10^3$ g of CO_2 produced

Mass to volume calculations involving combustion 3.1.5.1.2

OVERVIEW

The mass of a reactant or product of a balanced chemical equation can also be used to calculate the volume of any other gaseous species in the reaction.

THEORY DETAILS

The stoichiometric calculations introduced in the previous section can also be applied to find the volume of gas produced when a fuel undergoes combustion. These calculations are particularly important for fuels as the gases produced, CO_2 and H_2O, are potent greenhouse gases that trap and emit heat and infrared radiation, which contributes to global warming by keeping heat confined to the lower atmosphere.

The volume of gas produced during combustion is calculated using either of the following two formulas, depending on the surrounding conditions of temperature and pressure.

1 If the reaction occurs at Standard Laboratory Conditions (SLC) of 25°C and 100 kPa, then we use the formula:

$n = \frac{V}{V_m}$

Where volume V is measured in L and molar volume V_m, which is the volume of one mole of any gas at SLC, is given by 24.8 mol L^{-1}. This value is given in the data book.

2 If the reaction occurs under any other conditions of temperature and pressure (non-standard conditions), the universal gas equation is used:

$PV = nRT$

Where pressure P is measured in kPa

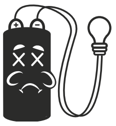
volume V is measured in L

number of mol n is measured in mol

the gas constant R is given by 8.31 J K^{-1} mol^{-1}

and the temperature T is measured in Kelvin

Worked examples 2 and 3 demonstrate how to calculate the amount of volume of a chemical produced for both of these conditions. Remember that using the universal gas equation will still lead to the correct answer if the system is under SLC and the values of 25°C and 100 kPa are used.



2 Worked example

Methane gas undergoes complete combustion according to the following reaction.

$\mathbf{CH_{4(g)} + 2O_{2(g)} \rightarrow CO_{2(g)} + 2H_2O_{(g)}}$

In a reaction vessel at SLC, 2.50 g of H_2O is produced.

Calculate the volume of methane that must have been present in the reaction vessel.

What information is presented in the question?

The balanced equation for the combustion of methane.

The reaction is occurring at SLC.

2.50 g of H_2O has been produced.

What is the question asking us to do?

Find the volume of methane that has been combusted.

What strategy(ies) do we need in order to answer the question?

1. Calculate n(known)
2. Use this and the molar ratios to find n(unknown)

Answer

$n(H_2O) = \frac{m}{M} = \frac{2.50}{18.0}$

$= 0.1389$ mol

$n(H_2O) : n(CH_4)$

$2 : 1$

$n(CH_4) = \frac{\text{coefficient of unknown}}{\text{coefficient of known}} \times n(\text{known})$

$= \frac{1}{2} \times 0.1389$

$= 0.0694$ mol

$V(CH_4) = n \times V_m$

$= 0.0694 \times 24.8$

$= 1.72$ L

3 Worked example

4.50 kg of the fatty acid oleic acid (M = 282 g mol^{-1}) undergoes complete combustion in excess oxygen according to the following reaction. The reaction vessel is kept at a constant temperature of 43.0°C and pressure of 4.00 atm.

$\mathbf{C_{17}H_{33}COOH_{(l)} + \frac{51}{2}O_{2(g)} \rightarrow 18CO_{2(g)} + 17H_2O_{(g)}}$

Determine the total volume of greenhouse gases produced if the reaction proceeds to completion.

What information is presented in the question?

The mass of oleic acid in kg and its molar mass.

The temperature and pressure of the reaction vessel.

The balanced equation for the complete combustion of oleic acid.

What is the question asking us to do?

Find the total volume of greenhouse gases that the combustion reaction will produce.

What strategy(ies) do we need in order to answer the question?

1. Recognise that the reaction is occuring at non-standard conditions, meaning that we will need the universal gas equation $PV = nRT$.
2. Calculate the amount of oleic acid in mol that is present.
3. Recall that both CO_2 and H_2O are greenhouse gases.
4. Calculate the combined volume of CO_2 and H_2O produced.

Answer

$n(\text{oleic acid}) = \frac{4.5 \times 1000}{282}$

$= 15.96$ mol

$n(\text{oleic acid}) : n(CO_2)$

$1 : 18$

$n(CO_2) = \frac{\text{coefficient of the unknown}}{\text{coefficient of the known}} \times n(\text{known})$

$= \frac{18}{1} \times 15.96$

$= 287.2$ mol

$n(H_2O) = \frac{\text{coefficient of the unknown}}{\text{coefficient of the known}} \times n(\text{known})$

$= \frac{17}{1} \times 15.96$

$= 271.3$ mol

Temperature = 273 + 43 = 316 K

Pressure = $4 \times \frac{100}{0.987} = 405.3$ kPa

Since 1.0 mol of any gas occupies the same volume,

$PV = nRT$

$405.3 \times V = (287.2 + 271.3) \times 8.31 \times 316$

$V = 3619$ L

$= 3.62 \times 10^3$ L

Volume to volume calculations involving combustion 3.1.5.1.3

OVERVIEW

The volume of a gaseous reactant or product of a balanced chemical equation can be used to calculate the volume of any other gaseous species in the reaction.

THEORY DETAILS

For the special case where both the known and unknown chemicals are gases and can be measured in volume amounts, it is often easiest to convert directly between volumes, rather than calculating the number of moles.

$2C_4H_{10(g)} + 13O_{2(g)} \rightarrow 8CO_{2(g)} + 10H_2O_{(g)}$

In our previous example for the combustion of butane, we discovered that the reaction occurs in a constant ratio of 2:13:8:10 for each of the chemicals. We also learnt in lesson 3C that all gases occupy the same volume for a given temperature and pressure. This means that the volumes of the gases in the reaction will also follow the same ratio as the moles. So, for the combustion of butane we don't have to calculate any amounts in mol and still know that 2.0 L of butane will react with 13.0 L of oxygen to produce 8.0 L of carbon dioxide and 10.0 L of water vapour.

Note that this is only true for reactions where both the temperature and pressure at which the reaction occurs are kept constant. An example of applying this shortcut is shown in worked example 4.

4 Worked example

Gaseous pentan-1-ol undergoes complete combustion in the presence of excess oxygen according to the following reaction.

$2C_5H_{11}OH_{(g)} + 15O_{2(g)} \rightarrow 10CO_{2(g)} + 12H_2O_{(g)}$

If 5.3 L of pentan-1-ol is burnt in the presence of excess oxygen under conditions of constant temperature and pressure, calculate the volume of carbon dioxide produced.

What information is presented in the question?

The equation for the combustion of pentan-1-ol.

The initial amount of pentan-1-ol present in litres.

The reaction is occurring at constant temperature and pressure.

What is the question asking us to do?

Find the volume of CO_2 that was produced.

What strategy(ies) do we need in order to answer the question?

Use the molar ratios of the reaction to determine the unknown volume.

Answer

$$V(CO_2) = \frac{\text{coefficient of unknown volume}}{\text{coefficient of known volume}} \times V(C_5H_{11}OH)$$

$$= \frac{10}{2} \times 5.3$$

$= 27$ L of CO_2 produced

Hess's law 3.1.5.2

OVERVIEW

Hess's law allows the overall enthalpy change for a reaction to be calculated from the sum of the enthalpies of the individual reactions comprising it.

THEORY DETAILS

We have already learnt that both the sign and magnitude of a reaction's enthalpy change depends on the number of moles specified by the equation. If the direction of the reaction is reversed, the sign of the enthalpy change will also change from negative to positive or vice-versa. If the coefficients of the reaction are changed by some factor, the value of the enthalpy change will also be multiplied by that same factor.

So far, we have only considered the enthalpy of single reactions. We will now investigate the effect of adding multiple reactions together to calculate the overall enthalpy change. This process of adding reactions together follows what is known as **Hess's law**, which states that the overall enthalpy change of a reaction is independent of the pathway between the initial and final states.

This means that the energy change in an overall chemical reaction is equal to the sum of all the energy changes of the reactions that make it up. The ΔH values for the individual reactions in this process are simply added together to find the ΔH for the final reaction. As we saw in 3B it is important to note that the state (solid, liquid, gas) of a species in a reaction will also affect its enthalpy change.

The primary purpose of Hess's law is to determine the enthalpy change for a reaction that is a combination of known reactions. To do this, we have to find some combination of the given reactions that will add together to produce the reaction under investigation. Remember that any changes we make to these reactions will also affect their enthalpies and that adding two reactions together will also add their enthalpies. This process of adding reactions together is investigated in worked example 5.

5 Worked example

The thermochemical equations for two different reactions involving nitrogen, oxygen and chlorine are shown below.

Reaction 1 $NO_{(g)} \rightarrow \frac{1}{2}N_{2(g)} + \frac{1}{2}O_{2(g)}$ **ΔH = –90.3 kJ mol^{-1}**

Reaction 2 $N_{2(g)} + O_{2(g)} + Cl_{2(g)} \rightarrow 2NOCl_{(g)}$ **ΔH = +103.4 kJ mol^{-1}**

Calculate ΔH for the following reaction:

$2NOCl_{(g)} \rightarrow 2NO_{(g)} + Cl_{2(g)}$ ΔH = ?

What information is presented in the question?

Two thermochemical equations with their enthalpy changes. A third reaction with an unknown enthalpy.

What is the question asking us to do?

Calculate ΔH for the unknown reaction.

What strategy(ies) do we need in order to answer the question?

1. Reverse the sign of ΔH when reactions are reversed.
2. Multiply reaction 1 and its enthalpy by two.
3. Add together reactions and their enthalpies to create the equation with the unknown enthalpy.

Answer

To achieve the reaction in question, we can see that reaction 1 has been doubled and reaction two has been reversed.

If we add the reverse of double reaction 1 to the reverse of reaction 2, we get

$N_{2(g)} + O_{2(g)} \rightarrow 2NO_{(g)}$ ΔH = +180.6

$2NOCl_{(g)} \rightarrow N_{2(g)} + O_{2(g)} + Cl_{2(g)}$ ΔH = –103.4

$N_{2(g)} + O_{2(g)} + 2NOCl_{(g)} \rightarrow 2NO_{(g)} + N_{2(g)} + O_{2(g)} + Cl_{2(g)}$

Any identical molecules in the same state that are present on both sides of the equation can be removed, leaving the desired reaction:

$\cancel{N_{2(g)}} + \cancel{O_{2(g)}} + 2NOCl_{(g)} \rightarrow 2NO_{(g)} + \cancel{N_{2(g)}} + \cancel{O_{2(g)}} + Cl_{2(g)}$

$2NOCl_{(g)} \rightarrow 2NO_{(g)} + Cl_{2(g)}$

Adding the individual enthalpy changes gives the overall enthalpy change for the reaction.

+180.6 + (–103.4) = +77.2 kJ mol^{-1}

Theory summary

- A balanced equation for a chemical reaction describes the ratio for the amount (measured in moles) of reactants and products for the reaction.
- The amount of moles of a species can be calculated using the formulas
  - $n = \frac{m}{M}$ for calculations involving masses.
  - $n = \frac{V}{V_m}$ for calculations involving volumes at SLC.
  - $PV = nRT$ for calculation involving volumes at non-standard conditions.
- An unknown amount of a species can be determined once one amount, in mole, is calculated by using the coefficients of the balanced equation. The unknown amount is given by $n(\text{unknown}) = \frac{\text{coefficient of the unknown species}}{\text{coefficient of the known species}} \times n(\text{known})$.

- For reactions at constant temperature and pressure with gaseous reactants or products, the molar ratio of the balanced equation is the same as the ratio of volumes.
- Hess's law states that the overall enthalpy change of a reaction is independent of the pathway between the initial and final states.
- When two reactions are added together, their respective enthalpies are also added.

3D QUESTIONS

Theory review questions

Question 1

Propene combusts in the presence of excess oxygen as shown by the following reaction.

$2C_3H_{6(l)} + 9O_{2(g)} \rightarrow 6CO_{2(g)} + 6H_2O_{(g)}$

If *d* mol of propene reacts completely, the number of moles of CO_2 that is produced could be calculated by

A $d \times \frac{2}{6}$

B $d \times \frac{3}{1}$

C $\frac{d}{6} \times 9$

D $\frac{6}{d} \times 2$

Question 2

Hess's law is best described as stating that

A two reactions with enthalpies of similar magnitude, when added together, must always have an enthalpy equal to the sum of these two magnitudes.

B there are no reactions that have an enthalpy change of 0 kJ mol^{-1}.

C any enthalpy change in a reaction depends only on the chemical species involved, not their physical states.

D the overall enthalpy change of a reaction is independent of the pathway between the initial and final states.

Exam-style questions

Within lesson

Question 3 (1 MARK)

The balanced combustion reaction equation for ethanol is shown.

$C_2H_5OH_{(g)} + 3O_{2(g)} \rightarrow 2CO_{2(g)} + 3H_2O_{(g)} \qquad \Delta H = -1360 \text{ kJ mol}^{-1}$

For every 4.0 mol of ethanol that is consumed, what is the amount of oxygen required for the reaction to occur?

A 1.33 mol B 4.0 mol C 8.0 mol D 12.0 mol

Question 4 (1 MARK)

The combustion reaction of methane in the presence of excess oxygen occurs according to the given unbalanced equation.

$CH_{4(g)} + O_{2(g)} \rightarrow CO_{2(g)} + H_2O_{(g)} \qquad \Delta H = -890 \text{ kJ mol}^{-1}$

If 100.0 L of methane were to react completely in the presence of excess O_2, then the volume of greenhouse gases that is evolved is

A 100.0 L B 200.0 L C 300.0 L D 400.0 L

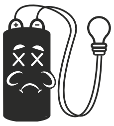
Question 5 (1 MARK)

Consider the following reactions.

$\frac{1}{2} N_{2(g)} + O_{2(g)} \rightarrow NO_{2(g)} \qquad \Delta H = +30 \text{ kJ mol}^{-1}$

$N_{2(g)} + 2O_{2(g)} \rightarrow N_2O_{4(g)} \qquad \Delta H = +10 \text{ kJ mol}^{-1}$

What is the enthalpy change for the reaction $N_2O_{4(g)} \rightarrow 2NO_{2(g)}$?



Question 6 (5 MARKS)

For the combustion of octane

$2C_8H_{18(g)} + 25O_{2(g)} \rightarrow 16CO_{2(g)} + 18H_2O_{(g)}$

Calculate

a the volume, in litres, of CO_2 produced at SLC when 3.65 g of C_8H_{18} undergoes complete combustion. (2 MARKS)

b the mass of H_2O produced when 9.05×10^4 g of O_2 reacts completely with octane. (2 MARKS)

c the volume, in litres, of O_2 gas consumed if 12.0 L of CO_2 is produced, assuming the reaction occurs under constant temperature and pressure. (1 MARK)

Question 7 (6 MARKS)

Propane undergoes combustion according to the following thermochemical equation.

$C_3H_{8(g)} + 5O_{2(g)} \rightarrow 3CO_{2(g)} + 4H_2O_{(g)} \qquad \Delta H = -2220 \text{ kJ mol}^{-1}$

a If 2.30 g of propane undergoes complete combustion, calculate

  i the volume and the number of mol of CO_2 produced at SLC. (2 MARKS)

  ii the volume and the number of mol of CO_2 produced under the conditions of 76°C and 895 mm Hg. (2 MARKS)

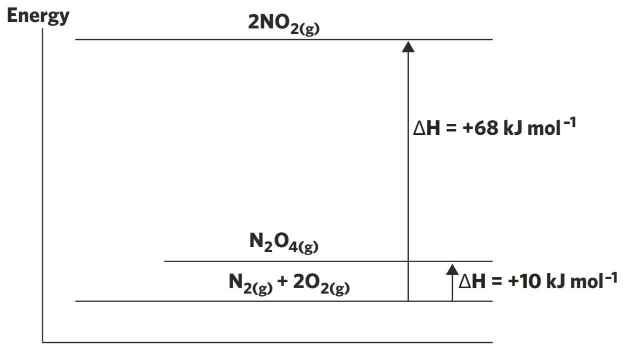
b If the 2.30 g of propane were instead burnt in its liquid form, would this reaction produce more or less energy than if it were burnt in its gaseous form? Justify your answer. (2 MARKS)

Question 8 (3 MARKS)

The energy diagram below relates to the enthalpies of the following two reactions.

$N_{2(g)} + 2O_{2(g)} \rightarrow 2NO_{2(g)}$

$N_{2(g)} + 2O_{2(g)} \rightarrow N_2O_{4(g)}$



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Calculate the enthalpy change for the reaction $3NO_{2(g)} \rightarrow \frac{3}{2} N_2O_{4(g)}$.

Question 9 (2 MARKS)

An experiment to determine the volume of CO_2 released from the combustion of pentan-1-ol is performed under constant temperature and pressure. Gaseous pentan-1-ol undergoes complete combustion in the presence of excess oxygen according to the following reaction.

$2C_5H_{11}OH_{(g)} + 15O_{2(g)} \rightarrow 10CO_{2(g)} + 12H_2O_{(g)}$

The chemists conducting the experiment calculated the exact minimum amount of O_2 required such that all of the pentan-1-ol reacts and inject the required mass of oxygen into the reaction vessel before triggering the combustion reaction with an electric spark. If exactly 37.0 L of gas is produced, determine the initial volume of pentan-1-ol present in the reaction vessel.

Multiple lessons

Question 10 (8 MARKS)

The fuel ethane combusts in excess oxygen according to the following reaction.

$2C_2H_{6(g)} + 7O_{2(g)} \rightarrow 4CO_{2(g)} + 6H_2O_{(g)}$ $\Delta H = -3120$ kJ mol^{-1}

a Calculate the pressure at which the reaction occurred, given that the combustion of 4.56 mol of ethane led to the formation of 20.0 L of CO_2 at a constant temperature of 31°C. (2 MARKS)

b If the heat energy released by the combustion of 3.60 g of ethane were used to heat 750 mL of water initially at 13°C to a temperature of 47°C, calculate the percentage heat loss to the environment. (3 MARKS)

c In order to determine the specific heat capacity of a contaminated solution, a chemist decides to completely combust a sample of ethane beneath the solution and measure the temperature change. The chemist sets up an experiment under SLC with 960 g of the contaminated solution and an apparatus to measure the volume of CO_2 that is produced from the combustion reaction above. If the reaction produced 12.0 L of CO_2 and the solution increased in temperature by 39.0 °C, calculate its specific heat capacity in J g^{-1} K^{-1}. Assume that 100% of the heat energy is transferred directly to the contaminated solution. (3 MARKS)

Question 11 (1 MARK)

It can be calculated that the molar volume V_m on Mars, due to its much thinner atmosphere, is 2300 L mol^{-1}. Scientists debating the efficacy of using methane as a fuel source for the Mars rover are considering its combustion reaction.

$CH_{4(g)} + 2O_{2(g)} \rightarrow CO_{2(g)} + 2H_2O_{(g)}$ $\Delta H = -890$ kJ mol^{-1}

The Mars rover is empty when it leaves earth, but manages to harvest 3.3 L of methane from the Martian atmosphere and can supply an excess of oxygen. The amount of water vapour that will be produced in the complete combustion of the fuel will be closest to

A 3.3 L

B 6.6 L

C 306 L

D 612 L

Question 12 (1 MARK)

Two reactions and their enthalpy changes are given. The values *a* and *b* are whole numbers.

$Pb_{(s)} + PbO_{2(s)} + 2SO_{3(g)} \rightarrow 2PbSO_{4(s)}$ $\Delta H = a$ kJ mol^{-1}

$SO_{3(g)} + H_2O_{(l)} \rightarrow H_2SO_{4(aq)}$ $\Delta H = -b$ kJ mol^{-1}

Which of the following could be the enthalpy change for some combination of the two reactions? All answers have the units kJ mol^{-1}.

I $2a - b$

II $7a^2b$

III $\frac{a}{b}$

IV $-3b + \frac{1}{2}a$

V 0

A I, II, IV only

B I, IV only

C I, IV, V only

D I, II, III, IV, V

Question 13 (9 MARKS)

A chemist tasked with investigating the relative environmental impact of different fuels decided to compare octane and ethanol. Since these fuels are used on such a large scale, he reasoned that a relevant way of comparing them would be to calculate the volume of greenhouse gases each fuel produced for each MJ of energy they provided.

The thermochemical equations for the combustion of octane and ethanol are shown. Assume each reaction goes to completion with an excess of oxygen supplied.

$2C_8H_{18(l)} + 25O_{2(g)} \rightarrow 16CO_{2(g)} + 18H_2O_{(g)} \quad \Delta H = -10920 \text{ kJ mol}^{-1}$

$C_2H_5OH_{(l)} + 3O_{2(g)} \rightarrow 2CO_{2(g)} + 3H_2O_{(g)} \quad \Delta H = -1360 \text{ kJ mol}^{-1}$

a Calculate the amount in mol of octane and ethanol required to produce 1.0 MJ of energy. ($1.0 \text{ MJ} = 1.0 \times 10^6 \text{ J}$) (2 MARKS)

b If the experiment is performed under Standard Laboratory Conditions, calculate the total amount in mol of CO_2 and H_2O that each fuel would produce for this amount of energy. (2 MARKS)

c If the experiment is performed under Standard Laboratory Conditions, calculate the total volume of greenhouse gases that each fuel would produce for every 1.0 MJ of energy obtained. (2 MARKS)

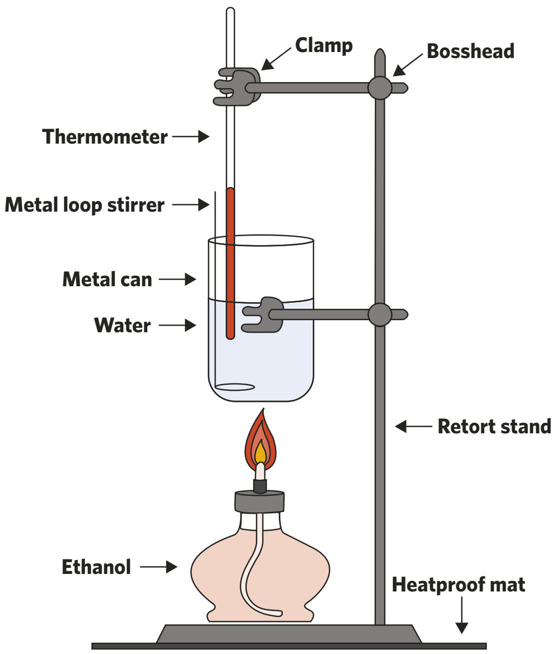
d Which of the two fuels does this suggest is more environmentally-friendly? (1 MARK)

e If the ethanol fuel used in this experiment were actually bioethanol, how would this impact the answer given in **d**? Why? (2 MARKS)

EXPERIMENT

COMBUSTION OF FUELS

The combustion of organic compounds produces large quantities of energy, making compounds like alcohol useful as fuels. Fuels, like ethanol, undergo combustion to produce energy for cars and machinery. The combustion of ethanol can be performed on a smaller scale in labs using spirit burners, as seen in the diagram.



Materials

- Retort stand
- Bosshead
- Clamp
- Heat-proof mat
- Thermometer
- 100 mL measuring cylinder
- Metal loop stirrer
- Metal can*
- 150 mL of water
- Spirit burner
- 50 mL of ethanol
- Lighter
- Timer

* A 150 mL conical flask can be used in place of the metal can.

Method

1 Clamp the metal can to the retort stand.
2 Measure 150 mL of water and pour it in the metal can.
3 Attach a thermometer to a second clamp situated above the metal can. Lower the thermometer so that it is submerged in the water in the can, making sure that it does not touch the bottom of the can.
4 Record the initial temperature of the water.
5 Using the measuring cylinder, measure 50 mL of ethanol and add it into the spirit burner.
6 Record the mass of the spirit burner containing the ethanol.
7 Place the spirit burner directly under the metal can on top of a heat proof mat.
8 Light the spirit burner to start heating the water. Start the timer.
9 Stir the water in the metal can continuously.
10 After 5 minutes, extinguish the burner.
11 Record the temperature of the water.
12 Carefully record the mass of the burner and the remaining fuel.

Results

Quantity	Measurement
Initial temperature of water (°C)	
Final temperature of water (°C)	
Mass of spirit burner + ethanol before heating (g)	
Mass of spirit burner + ethanol after heating (g)	

QUESTIONS

Question 1 (2 MARKS)

Name the independent and dependent variable.

Question 2 (2 MARKS)

Write the balanced thermochemical equation for the complete combustion of ethanol including states.

Question 3 (5 MARKS)

a A group of students performed the above experiment and recorded the following results.

Quantity	**Measurement**
Mass of empty can	43 g
Mass of can + water before heating	193 g
Initial temperature of water	21°C
Final temperature of water	46°C
Mass of ethanol + spirit burner before heating	225.0 g
Mass of ethanol + spirit burner after heating	223.7 g

Calculate the amount of heat, in kJ, absorbed by the water when it was heated by burning ethanol. (3 MARKS)

b Calculate the experimental value of the molar heat of combustion of ethanol, in kJ mol^{-1}. (2 MARKS)

Question 4 (2 MARKS)

Give two reasons why the experimental value of the molar heat of combustion of ethanol is different to the theoretical value given in the data book.

Question 5 (3 MARKS)

Using the data collected in this experiment, calculate the molar heat of combustion of ethanol, in kJ mol^{-1}.

ANSWERS

1 The independent variable is the mass of ethanol burnt. The dependent variable is the change in temperature of the water.

2 $C_2H_5OH_{(l)} + 3O_{2(g)} \rightarrow 2CO_{2(g)} + 3H_2O_{(g)}\ \Delta H = -1360 \text{ kJ mol}^{-1}$

3 **a** $m(\text{water}) = 193 - 43 = 150$ g

$\Delta T = 46 - 21 = 25°C$

$q = m \times C \times \Delta T$

$= 150 \times 4.18 \times 25$

$= 15675$ J

$= 16$ kJ

b $m(\text{ethanol})$ reacted $= 225 - 223.7 = 1.3$ g

$n(\text{ethanol})$ reacted $= \frac{1.3}{46.0}$

$= 0.028$ mol

Energy released per mol of ethanol $= \frac{16}{0.028}$

$= 571$ kJ

$= 5.5 \times 10^2$ kJ

Molar heat of combustion of ethanol $= 5.5 \times 10^2$ kJ correct to 2 sig figs

4 [The can of water was not insulated so heat was lost to the environment, affecting the ΔH value.[1]][Some of the ethanol underwent incomplete combustion resulting in a lower value of ΔH.[2]]

✓ ✗ I have identified heat loss as a potential explanation for the different values.[1]

✓ ✗ I have identified incomplete combustion as a potential explanation for the different values.[2]

5 Please check your answer with your teacher.

CHAPTER 3 QUESTIONS

MULTIPLE CHOICE QUESTIONS (10 MARKS)

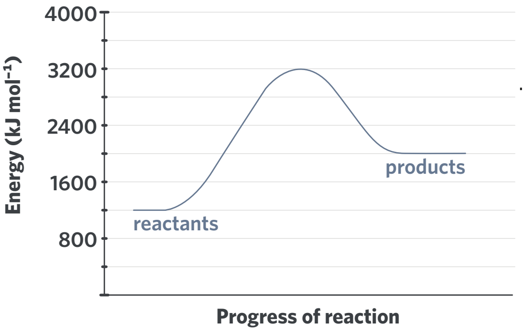
Question 1 (1 MARK)

The amount of energy released when 250 g of methane undergoes complete combustion is

- **A** 2.39×10^4 kJ
- **B** 1.39×10^4 kJ
- **C** 1.40×10^2 kJ
- **D** 2.40×10^2 kJ

Question 2 (1 MARK)

The following diagram is an energy profile diagram for a chemical reaction.



A catalyst reduces the activation energy by 300 kJ mol^{-1}
The value of the enthalpy change, in kJ mol^{-1},of the catalysed reaction is

- **A** +1000
- **B** −800
- **C** +1200
- **D** +800

Question 3 (1 MARK)

What mass of butane must undergo complete combustion to raise the temperature of 100.0 g of water by 18°C? Assume no heat loss.

- **A** 8.4 g
- **B** 0.15 g
- **C** 15 g
- **D** 0.50 g

Question 4 (1 MARK)

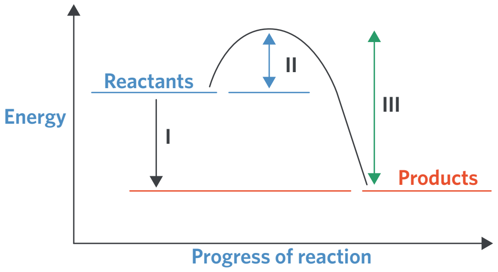
For an endothermic reaction,

- **A** the reaction absorbs energy from its surroundings.
- **B** $\Delta H < 0$.
- **C** the enthalpy of the reactants is higher than the enthalpy of the products.
- **D** equilibrium can never be achieved.

Question 5 (1 MARK)

For a gas phase reaction, which of the quantities, labelled in the energy profile diagram, are affected by decreasing the volume of the reaction vessel at constant temperature?

- **A** I only
- **B** II only
- **C** I and III only
- **D** None of the above



Question 6 (1 MARK)

Iron burns when ignited according to the following equation

$4Fe_{(s)} + 3O_{2(g)} \rightarrow 2Fe_2O_{3(s)}$ $\Delta H = -1.22 \times 10^2$ kJ mol^{-1}

How much energy is released when 4.6 g of iron is burned?

A 0.31 kJ

B 30.5 kJ

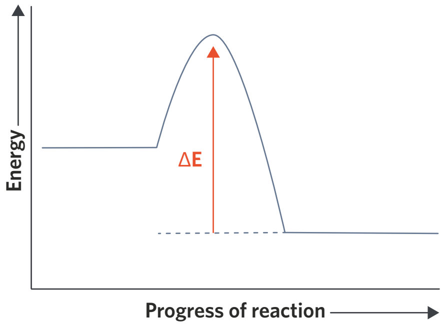
C 0.08 kJ

D 2.5 kJ

Question 7 (1 MARK)

The change in energy during a reaction is represented in the following energy profile diagram.

The change in energy labelled ΔE in the above energy profile diagram is



A the energy required to initiate the reaction.

B the activation energy for the forward reaction.

C the enthalpy of reaction.

D the activation energy for the reverse reaction.

Question 8 (1 MARK)

Given the following reaction

$4CO_{2(g)} + 6H_2O_{(l)} \rightarrow 2C_2H_5OH_{(g)} + 6O_{2(g)}$; $\Delta H = +2728$ kJ mol^{-1}

We would expect the ΔH value for the following reaction to be:

$C_2H_5OH_{(g)} + 3O_{2(g)} \rightarrow 2CO_{2(g)} + 3H_2O_{(l)}$

A +1364 kJ mol^{-1}

B −1364 kJ mol^{-1}

C +5456 kJ mol^{-1}

D −5456 kJ mol^{-1}

Question 9 (1 MARK)

The following table contains information about three experiments performed with alkanes. In each experiment, 0.10 mol of either propane, butane or octane was burned completely, with all the energy released heating 1.0 L of water.

Experiment	Alkane	Molecular Formula
I	propane	C_3H_8
II	butane	C_4H_{10}
III	octane	C_8H_{18}

If the water had an initial temperature of 20°C, in which of the three experiments will the water be heated to its boiling temperature?

A I, II and III

B III only

C II and III

D None of the above

Question 10 (1 MARK)

A 0.33 mol sample of an ideal gas at 17°C occupies a volume of 4.2 L. What is the pressure of the gas?

A 2.0×10^2 kPa

B 1.1×10^1 kPa

C 1.9×10^2 kPa

D 1.3×10^2 kPa

SHORT ANSWER (32 MARKS)

Question 11 (2 MARKS)

Calculate the volume that 5.00 mol of gas will occupy at 26°C and 520 kPa.

Question 12 (6 MARKS)

Methane (CH_4) is a flammable gas used as fuel to make light and heat. It can be obtained from natural gas deposits or as a biofuel from biomass.

a Which of these sources of methane would be considered renewable? Explain. (3 MARKS)

b Write the balanced equation for the complete combustion of methane. (2 MARKS)

c How much energy would be released by burning 2.0 g of methane? (1 MARK)

Question 13 (3 MARKS)

Propane (C_3H_8) is an important fuel particularly for running cars. To get the most value for money it is important that propane combusts to completion so that it gives off the maximum amount of heat energy to run the engine. Therefore, it is not only important for propane to undergo complete combustion to save money but it is also important as the incomplete combustion of propane yields a toxic gas.

a Write the incomplete combustion equation of propane and identify what this toxic by-product is. (2 MARKS)

b What is a physical sign of the incomplete combustion of propane? (1 MARK)

Question 14 (6 MARKS)

Butan-1-ol is an alcohol used as a fuel for internal combustion engines.

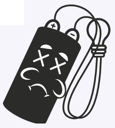
a Write the balanced chemical equation for the complete combustion of butan-1-ol. (2 MARKS)

b A scientist measured the heat of combustion of four different fuels, the results are shown in the table below.

Fuel	**Heat of combustion ($kJ\,g^{-1}$)**
T	45
X	35
Y	25
Z	15

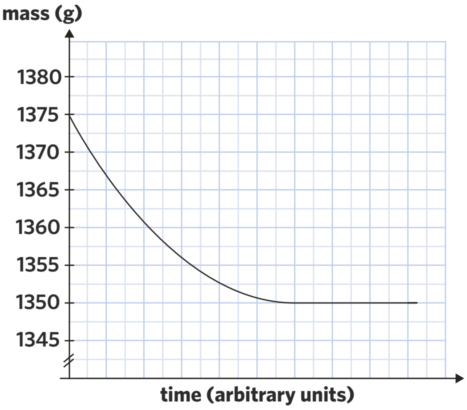
The published value for the heat of combustion of butan-1-ol is 2676 $kJ\,mol^{-1}$, which fuel from the table is most likely to be butan-1-ol? Justify your answer. (3 MARKS)

c Why would the resultant heat of combustion of butan-1-ol be significantly lower than the published value? (1 MARK)



Question 15 (5 MARKS)

Vlad conducted an experiment to determine the changes that occur as a result of the combustion of butane. In this experiment, the spirit burner was placed into a container. During the course of the experiment, Vlad measured the mass of the container. The result can be seen in the graph. In this case, water is produced as a liquid.



a Identify the cause of the change in mass of the container. (1 MARK)

b Assuming the experiment was conducted at SLC, calculate the volume of product lost during the combustion reaction. (2 MARKS)

c The temperature of the room increased to 30°C. What amount of carbon dioxide would need to be produced in the reaction to produce the same volume as calculated in part b if the pressure was measured at 400 kPa? (2 MARKS)

Question 16 (7 MARKS)

A student performed an experiment where an unknown mass of ethanol was burnt to increase the temperature of 200.0 g of water by 55°C.

a If exactly half of the heat released by the combustion of ethanol is lost to the surroundings, calculate the mass of ethanol burnt. (3 MARKS)

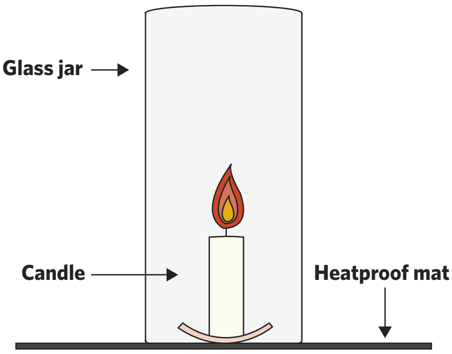
b What are two ways that the heat lost to the surroundings could be limited in this experiment? (1 MARK)

c The second time the student performed the experiment 60% of the heat from the burning ethanol was transferred to the water. Using the mass of ethanol determined in a, calculate the change in temperature. (3 MARKS)

KEY SCIENCE SKILL

Question 17 (3 MARKS)

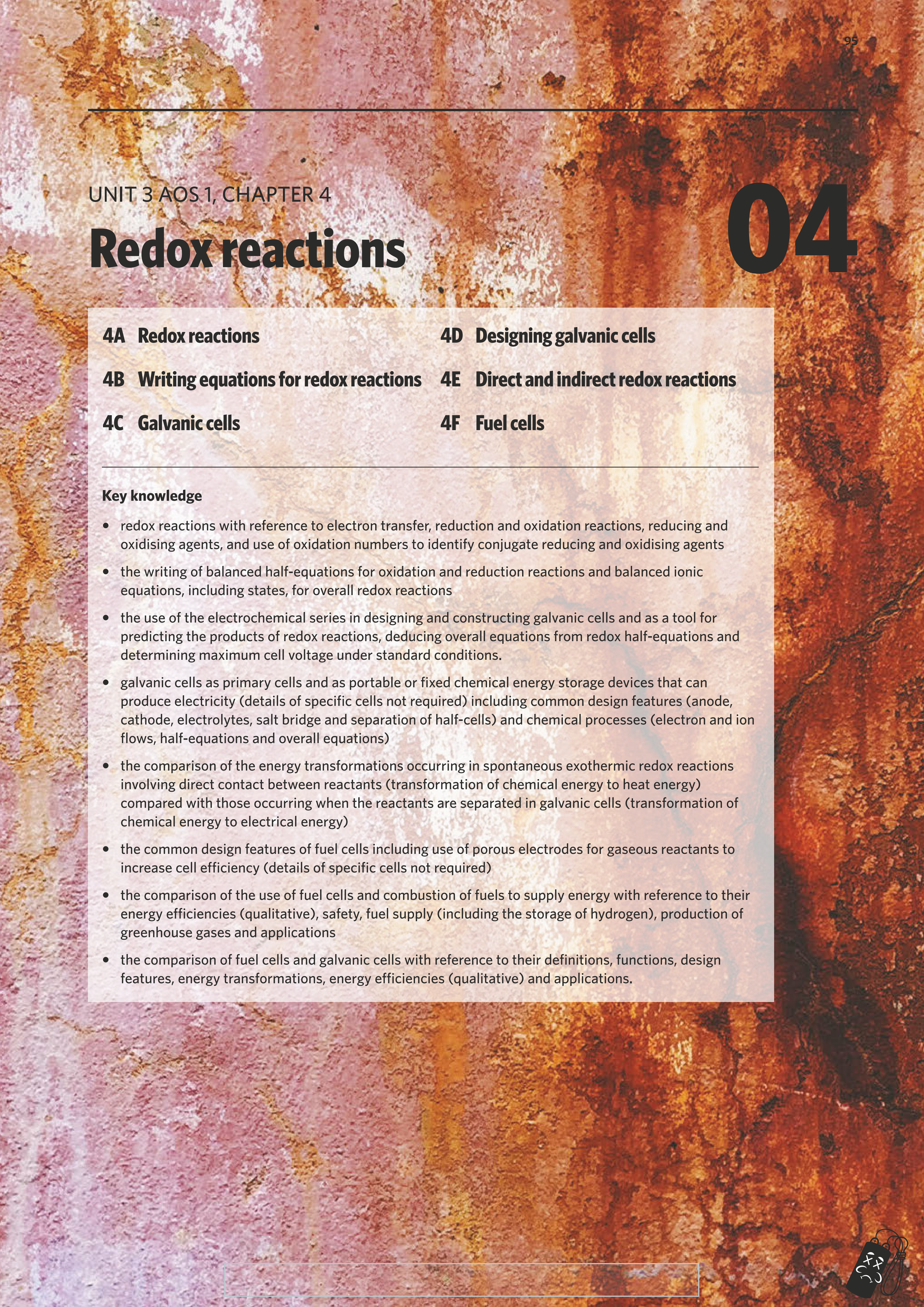
When a hydrocarbon undergoes complete combustion two substances are produced; carbon dioxide and water. Candle wax is made predominantly of hydrocarbons so to test whether hydrocarbons need oxygen to undergo combustion, a student lit a candle and placed it under an upturned glass jar, as shown in the diagram.



a The first test to see if a combustion reaction was taking place is to observe if the candle stopped burning after a short period of time under the glass jar. What does the observation of the flame extinguishing after a few seconds, indicate? (1 MARK)

b The student conducted a limewater test to detect if carbon dioxide was produced. However, the result was weak indicating that there wasn't a noticeable amount of carbon dioxide produced. Identify one reason for why the test result was not noticeable. (1 MARK)

c Identify how the reliability of this experiment could be improved. (1 MARK)



UNIT 3 AOS 1, CHAPTER 4

Redox reactions

04

4A Redox reactions

4B Writing equations for redox reactions

4C Galvanic cells

4D Designing galvanic cells

4E Direct and indirect redox reactions

4F Fuel cells

Key knowledge

- redox reactions with reference to electron transfer, reduction and oxidation reactions, reducing and oxidising agents, and use of oxidation numbers to identify conjugate reducing and oxidising agents
- the writing of balanced half-equations for oxidation and reduction reactions and balanced ionic equations, including states, for overall redox reactions
- the use of the electrochemical series in designing and constructing galvanic cells and as a tool for predicting the products of redox reactions, deducing overall equations from redox half-equations and determining maximum cell voltage under standard conditions.
- galvanic cells as primary cells and as portable or fixed chemical energy storage devices that can produce electricity (details of specific cells not required) including common design features (anode, cathode, electrolytes, salt bridge and separation of half-cells) and chemical processes (electron and ion flows, half-equations and overall equations)
- the comparison of the energy transformations occurring in spontaneous exothermic redox reactions involving direct contact between reactants (transformation of chemical energy to heat energy) compared with those occurring when the reactants are separated in galvanic cells (transformation of chemical energy to electrical energy)
- the common design features of fuel cells including use of porous electrodes for gaseous reactants to increase cell efficiency (details of specific cells not required)
- the comparison of the use of fuel cells and combustion of fuels to supply energy with reference to their energy efficiencies (qualitative), safety, fuel supply (including the storage of hydrogen), production of greenhouse gases and applications
- the comparison of fuel cells and galvanic cells with reference to their definitions, functions, design features, energy transformations, energy efficiencies (qualitative) and applications.

4A REDOX REACTIONS

In this lesson we will learn about what a redox reaction is and how we can identify redox reactions using oxidation numbers.

4A Redox reactions	4B Writing equations for redox reactions	4C Galvanic cells	4D Designing galvanic cells	4E Direct and indirect redox reactions	4F Fuel cells

Study design dot point

- redox reactions with reference to electron transfer, reduction and oxidation reactions, reducing and oxidising agents, and use of oxidation numbers to identify conjugate reducing and oxidising agents

Key knowledge units

Defining redox reactions	3.1.9.1
Identifying redox reactions using oxidation numbers	3.1.9.2

Key terms and definitions

- **Redox reaction** chemical reaction that involves the transfer of electrons between two species
- **Reduction** chemical reaction where a species decreases its oxidation number by gaining electrons
- **Oxidation** chemical reaction where a species increases its oxidation number by losing electrons
- **Oxidising agent** species that oxidises another substance and is itself reduced
- **Reducing agent** species that reduces another substance and is itself oxidised
- **Oxidation number** number assigned to an element, representing the number of electrons lost or gained by an atom of that element to form a chemical bond with another species
- **Conjugate redox pair** electron donor (reducing agent) and its corresponding electron acceptor (oxidising agent)

Defining redox reactions 3.1.9.1

OVERVIEW

Redox reactions involve the transfer of electrons from one species to another in two half-reactions known as reduction and oxidation reactions.

THEORY DETAILS

Redox reactions occur frequently in our everyday life, whether that's in hair salons bleaching hair, the combustion of fuels in our cars or respiration and photosynthesis in nature. These reactions involve the transfer of electrons from one chemical species to another.

The word redox can be split in two to reveal the two half-reactions involved in a redox reaction – **reduction** and **oxidation**. In a reduction reaction, one of the reactants gains electrons. Whilst one would assume that to reduce would mean that the molecule is losing something, it is important to remember that electrons are negative, meaning if you add a negative, the value goes down – or reduces. Conversely, in an oxidation reaction, one of the reactants loses electrons. These two reactions are known as half-reactions because they occur simultaneously with electrons being transferred (lost and gained) between reactants. The entire reaction is therefore known as a redox reaction.

Consider a reaction occurring between A and B where A is undergoing oxidation and B is undergoing reduction as shown in figure 1.

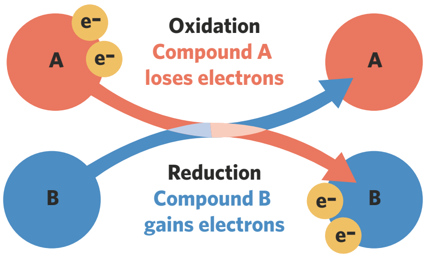


Figure 1 Model representing redox reactions

Image: Red ivory/Shutterstock.com

Tip an easy way to remember what is happening in a redox reaction is to remember **OILRIG**.

OIL – oxidation is loss of electrons

RIG – reduction is gain of electrons

Identifying redox reactions using oxidation numbers 3.1.9.2

OVERVIEW

Oxidation numbers are assigned to atoms in an equation in order to identify which elements have been oxidised and reduced in a redox reaction.

THEORY DETAILS

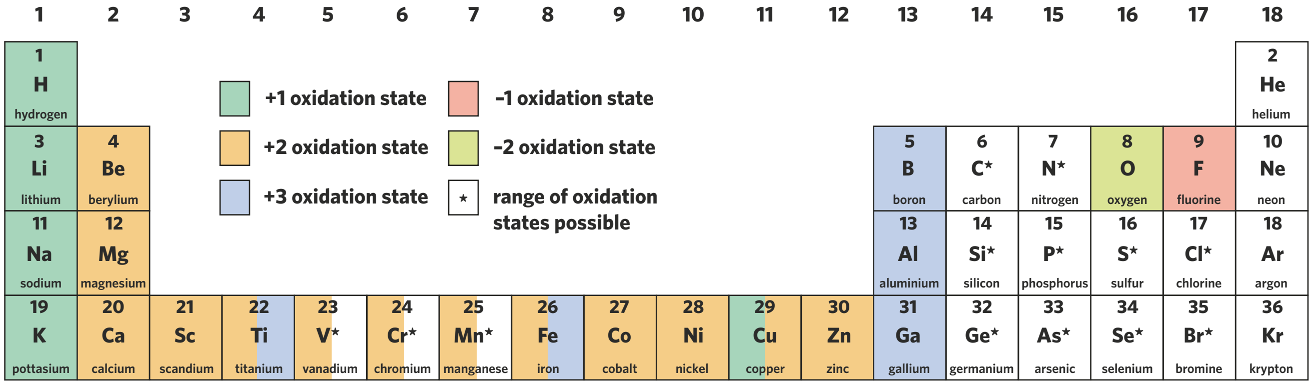
Chemists have created a system involving **oxidation numbers** which represent the number of electrons lost or gained by an atom of that element when it forms a chemical bond with another species. Through this method, we are able to determine which species undergoes what type of reaction; either oxidation or reduction.

Table 1 shows some common rules for determining the oxidation number of elements.

Table 1 Common rules to determine the oxidation number of elements

Rule	**Example**
Oxidation number of a free element is zero	O_2, C, Cl_2
Oxidation number of a simple ion is equal to the charge of the ion	Na^+, Cl^-, O^{2-}, Al^{3+}
The sum of oxidation numbers in a neutral compound is 0	KCl, CO_2, $MgSO_4$
The sum of oxidation numbers in a polyatomic ion is equal to the charge of the ion	SO_4^{2-}, NH_4^+
The normal oxidation number for hydrogen in a compound is +1 except in metal hydrides where it is –1	HCl v.s. CaH_2
The normal oxidation number for oxygen in a compound is –2 except in peroxides where it is –1	H_2O v.s. H_2O_2

The following figure of the periodic table will also help determine the oxidation number of individual elements when in a compound.



🟩 **+1 oxidation state**
🟧 **+2 oxidation state**
🟦 **+3 oxidation state**
🟥 **–1 oxidation state**
🟨 **–2 oxidation state**
⋆ **range of oxidation states possible**

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
🟩 1 H hydrogen																	2 He helium
🟩 3 Li lithium	🟧 4 Be berylium											🟦 5 B boron	6 C* carbon	7 N* nitrogen	🟨 8 O oxygen	🟥 9 F fluorine	10 Ne neon
🟩 11 Na sodium	🟧 12 Mg magnesium											🟦 13 Al aluminium	14 Si* silicon	15 P* phosphorus	16 S* sulfur	17 Cl* chlorine	18 Ar argon
🟩 19 K pottasium	🟧 20 Ca calcium	🟧 21 Sc scandium	🟧🟦 22 Ti titanium	🟧 23 V* vanadium	🟧 24 Cr* chromium	🟧 25 Mn* manganese	🟧🟦 26 Fe iron	🟧 27 Co cobalt	🟧 28 Ni nickel	🟩🟧 29 Cu copper	🟧 30 Zn zinc	🟦 31 Ga gallium	32 Ge* germanium	33 As* arsenic	34 Se* selenium	35 Br* bromine	36 Kr krypton

Figure 2 Periodic table showing the oxidation states of some common elements

To find the oxidation number of each element in $KClO_4$, we first look at the periodic table, figure 2. Potassium (K) is a metal in group 1 and therefore has an oxidation number of +1. Looking at figure 1 again, oxygen has an oxidation number of –2. Chlorine has a range of possible oxidation states therefore we will let the oxidation number of chlorine in $KClO_4$ be x.

Solving for x, the following expression can be written:

$+1 + x + (4 \times -2) = 0$

$+1 + x - 8 = 0$

$x - 7 = 0$

$x = +7$

Therefore, $\overset{+1}{K}\overset{+7}{Cl}\overset{-2}{O}_4$.

Note that the oxidation number of oxygen is written as –2 and not –8, even though there are 4 oxygen atoms. This is due to the fact that oxidation numbers are allocated to individual atoms rather than a group. So in this case, we are after the oxidation number for the oxygen atom, as opposed to all four oxygen atoms.

The difference between an oxidation number and the charge of the ion is whether the plus or minus precedes the number or not. For example the charge of the oxide ion (O^{2-}) is 2– whilst its oxidation number is –2.

Remember that the oxidation number indicates whether an atom has lost or gained an electron.

Consider the given redox reaction between iron and chlorine.

$2Fe^{2+}_{(aq)} + Cl_{2(g)} \rightarrow 2Fe^{3+}_{(aq)} + 2Cl^{-}_{(aq)}$

$Fe^{2+}_{(aq)}$ is oxidised as the oxidation number starts as +2 and by the end of the reaction changes to +3. This indicates that $Fe^{2+}_{(aq)}$ has lost an electron as the oxidation number increased by one. Whereas the oxidation number of chlorine in $Cl_{2(g)}$ decreased from 0 to –1 indicating that each chlorine atom in $Cl_{2(g)}$ gained an electron, giving it a negative charge.

As concluded from the reaction above, $Fe^{2+}_{(aq)}$ undergoes an oxidation reaction whilst $Cl_{2(g)}$ undergoes a reduction reaction. As $Fe^{2+}_{(aq)}$ is donating its electrons to $Cl_{2(g)}$, thereby reducing $Cl_{2(g)}$, we can call $Fe^{2+}_{(aq)}$ the **reducing agent**. As $Cl_{2(g)}$ is causing $Fe^{2+}_{(aq)}$ to release its electrons, thereby oxidising $Fe^{2+}_{(aq)}$, we can call $Cl_{2(g)}$ the **oxidising agent**. These terms are commonly used in redox reactions to identify which elements (and sometimes compounds) are bringing about oxidation and reduction.

Tip if a reaction involves spectator ions (ions which are not involved in the redox reaction and have no change in oxidation numbers), they cannot be the oxidising or reducing agent.

If there is no change in the oxidation number of all elements in a reaction, then the reaction is not a redox reaction.

1 Worked example

Identify the oxidising and reducing agents for the overall reaction between aluminum and iodine.

$2Al_{(s)} + 3I_{2(s)} \rightarrow 2AlI_{3(s)}$

What information is presented in the question?

The overall reaction between aluminium and iodine.

What is the question asking us to do?

Identify the oxidising and reducing agents.

What strategy(ies) do we need in order to answer the question?

1. Use the periodic table (figure 2)/ common rules (table 1) to identify possible oxidation numbers for the elements involved.
2. Use the known value from step 1 to calculate the oxidation number of the remaining element.
3. Use the change in oxidation numbers to determine the species acting as the oxidising and reducing agents.

Answer

As all free elements have an oxidation number of 0, $Al_{(s)}$ and $I_{2(s)}$ both have an oxidation number of 0.

According to the periodic table shown in figure 2, aluminium has an oxidation state of +3. We can use this information to calculate the oxidation number of I in $AlI_{3(s)}$

$+3 + (3 \times x) = 0$

$x = -1$

Therefore the oxidation number of I in AlI_3 is –1.

Al : 0 → +3

I: 0 → –1

Aluminum is being oxidised by iodine as it has lost 3 electrons, therefore it is the reducing agent.

Iodine is being reduced by aluminum as it has gained 2 electrons, therefore it is the oxidising agent.

We can use oxidation numbers to identify conjugate reducing and oxidising agents, also known as a **conjugate redox pair**. For example, let's look at the redox reaction between copper and silver.

$Cu_{(s)} + 2Ag^{+}_{(aq)} \rightarrow Cu^{2+}_{(aq)} + 2Ag_{(s)}$

The reaction can be written as two half-equations as follows.

$Cu_{(s)} \rightarrow Cu^{2+}_{(aq)} + 2e^{-}$

$Ag^{+}_{(aq)} + e^{-} \rightarrow Ag_{(s)}$

$Cu_{(s)}$ is being oxidised as its oxidation number increases from 0 to +2 and if the half equation were reversed $Cu^{2+}_{(aq)}$ would be reduced as its oxidation number would decrease from +2 to 0. We can therefore say that $Cu_{(s)}/Cu^{2+}_{(aq)}$ is a conjugate redox pair because $Cu_{(s)}$ is an electron donor and $Cu^{2+}_{(aq)}$ is its electron acceptor. $Ag^{+}_{(aq)}$ is being reduced as its oxidation number decreases from +1 to 0 and if the half equation were reversed $Ag_{(s)}$ would be oxidised as its oxidation number would increase from 0 to +1. It can then be said that $Ag^{+}_{(aq)}/Ag_{(s)}$ is also a conjugate redox pair as $Ag_{(s)}$ is an electron donor and $Ag^{+}_{(aq)}$ is its electron acceptor.

We can therefore define a conjugate redox pair as an electron donor and its corresponding electron acceptor.

Tip

Reduction **Oxidising agent + e- ⟶ Product**
Oxidation number decreases

Oxidation **Reducing agent ⟶ Product + e-**
Oxidation number increases

Theory summary

- Redox reactions involve the transfer of electrons from one species to another.
- Oxidation reactions, loss of electrons, and reduction reactions, gain of electrons, occur simultaneously.
- A reducing agent which is itself oxidised causes another species to be reduced by donating electrons to that species.
- An oxidising agent which is itself reduced causes another species to be oxidised by accepting electrons from that species.
- An increase in oxidation number of a species indicates oxidation has occurred.
- A decrease in oxidation number indicates reduction has occurred.
- A conjugate redox pair consists of an oxidising agent (electron acceptor) and its corresponding reducing agent (electron donor).

4A QUESTIONS

Theory review questions

Question 1

An increase in the oxidation number of an element in a reaction indicates

A only oxidation has occurred.

B only reduction has occurred.

C a redox reaction has occurred.

D None of the above.

Question 2

A reducing agent

A oxidises the oxidising agent.

B loses electrons.

C is the reactant in the reduction half-equation.

D accepts electrons.

Question 3

What is the following reaction an example of?

$Mg_{(s)} \rightarrow Mg^{2+}_{(aq)} + 2e^-$

A An oxidation half-equation

B A reduction half-equation

C A redox reaction

D A species gaining electrons

Exam-style questions

Within lesson

Question 4 (1 MARK)

Which of the following represents a reduction half-equation in its simplest form for the redox reaction below?

$Cu_{(s)} + 2Ag^+_{(aq)} \rightarrow Cu^{2+}_{(aq)} + 2Ag_{(s)}$

A $Ag^+_{(aq)} + e^- \rightarrow Ag_{(s)}$

B $Cu_{(s)} \rightarrow Cu^{2+}_{(aq)} + 2e^-$

C $Cu_{(s)} \rightarrow Cu^{2+}_{(aq)} + e^-$

D $2Ag^+_{(aq)} + 2e^- \rightarrow 2Ag_{(s)}$

Question 5 (2 MARKS)

Zinc chloride can be produced in a reaction between zinc sulphate ($ZnSO_4$) and hydrochloric acid (HCl) according to the following equation.

$ZnSO_{4(aq)} + 2HCl_{(aq)} \rightarrow ZnCl_{2(aq)} + H_2SO_{4(aq)}$

Is this reaction an example of a redox reaction? Explain.

Question 6 (3 MARKS)

During an experiment, solid zinc metal was burned in a crucible, resulting in the formation of a white substance. Based on the chemical equation provided:

$2Zn_{(s)} + O_{2(g)} \rightarrow 2ZnO_{(s)}$

a Identify the species undergoing oxidation. Justify your answer by using oxidation numbers. (2 MARKS)

b Identify the oxidising agent in this reaction. (1 MARK)

Question 7 (2 MARKS)

Sulfuric acid is widely used to produce fertilisers. In particular, it reacts with ammonia to produce ammonium nitrate as shown in the reaction provided.

$2NH_{3(g)} + H_2SO_{4(aq)} \rightarrow (NH_4)_2SO_{4(aq)}$

a Find the oxidation number for sulfur in H_2SO_4. (1 MARK)

b Which species in the reaction has not experienced a change in oxidation number? (1 MARK)

Question 8 (2 MARKS)

The following reaction is an example of a redox reaction

$Na_{(s)} + Ag^+_{(aq)} \rightarrow Na^+_{(aq)} + Ag_{(s)}$

a Determine the conjugate redox pair for the oxidation process and for the reduction process, respectively. (1 MARK)

b Identify the reducing agent. (1 MARK)

Question 9 (5 MARKS)

A student set up an experiment according to the equation provided.

$Fe_{(s)} + CuSO_{4\,(aq)} \rightarrow FeSO_{4\,(aq)} + Cu_{(s)}$

a Determine the oxidation number of sulfur (S) in $CuSO_4$. (1 MARK)

b Identify the species being reduced and the species being oxidised. (2 MARKS)

c Identify the conjugate redox pairs for the oxidation and reduction processes. (2 MARKS)

Question 10 (8 MARKS)

Identify the oxidising and reducing agent in each of the following reactions. Justify your answer.

a $Cu_{(s)} + 4HNO_{3(aq)} \rightarrow Cu(NO_3)_{2(aq)} + 2NO_{2(g)} + 2H_2O_{(l)}$ (4 MARKS)

b $Al_{(s)} + H_2SO_{4(aq)} \rightarrow Al_2(SO_4)_{3(aq)} + H_{2(g)}$ (4 MARKS)

Multiple lessons

Question 11 (4 MARKS)

Propane (C_3H_8) is a hydrocarbon that is commonly used as a fuel source.

a Write the balanced complete combustion reaction of propane. (2 MARKS)

b What chemical species is being oxidised and what chemical species is being reduced? (2 MARKS)

4B WRITING EQUATIONS FOR REDOX REACTIONS

In this lesson, we will learn how to write half-equations and from these, we will be able to write out the full balanced redox reaction that is occurring.

4A Redox reactions	**4B Writing equations for redox reactions**	**4C Galvanic cells**	**4D Designing galvanic cells**	**4E Direct and indirect redox reactions**	**4F Fuel cells**

Study design dot points

- the writing of balanced half-equations for oxidation and reduction reactions and balanced ionic equations, including states, for overall redox reactions
- the use of the electrochemical series in designing and constructing galvanic cells and as a tool for predicting the products of redox reactions, deducing overall equations from redox half-equations and determining maximum cell voltage under standard conditions.

Key knowledge units

Balancing redox half equations	3.1.10.1
Balancing overall redox equations	3.1.10.2
Using the electrochemical series to predict spontaneous redox reactions	3.1.13.1

Key terms and definitions

- **Electrochemical series** arrangement of chemical species in order of their reducing and oxidising strength
- **Redox half equation** one of two equations (oxidation or reduction) which describes one half of a redox reaction

Lesson links

This lesson builds on:

▶ 4A – Redox reactions

The basic principles of redox reactions are important to understand in order to write out equations for redox reactions.

Balancing redox half equations 3.1.10.1

OVERVIEW

Using our knowledge of which chemical species are being reduced and oxidised, the appropriate half equations can be constructed and balanced, depending on the conditions of the reaction.

THEORY DETAILS

As we learned in 4A, redox reactions are a type of chemical reaction which involves the simultaneous transfer of electrons between one chemical species and another. In order to correctly balance **redox half equations**, which are either the oxidation or reduction half of a redox reaction, the following pieces of information are needed:

- Does the half equation involve oxidation or reduction?
- What is the chemical species involved being oxidised/reduced to?

This first and second questions can be answered with the use of oxidation numbers. If there is an increase in the oxidation number, we know that the chemical species has been oxidised. If there is a decrease in the oxidation number, then we know that the chemical species has been reduced. After we have determined these pieces of information, we can then balance basic equations by making sure that the charge is equal on both sides of the half-equation by adding negatively charged electrons.

1 Worked example

What is the balanced reduction half equation for the following redox reaction:

$Cu^{2+}{}_{(aq)} + Pb_{(s)} \rightarrow Cu_{(s)} + Pb^{2+}{}_{(aq)}$

What information is presented in the question?

The complete redox reaction equation.

What is the question asking us to do?

Deduce a reduction half equation from the complete redox equation.

What strategy(ies) do we need in order to answer the question?

1. Use oxidation numbers to determine the chemical species that is being reduced and what it is reduced to.
2. Balance the charge of this equation using electrons.
3. Write out the complete reduction half-equation.

Answer

$Cu^{2+}{}_{(aq)} + Pb_{(s)} \rightarrow Cu_{(s)} + Pb^{2+}{}_{(aq)}$

The oxidation number of $Cu^{2+}{}_{(aq)}$ is +2

The oxidation number of $Pb_{(s)}$ is 0

The oxidation number of $Cu_{(s)}$ is 0

The oxidation number of $Pb^{2+}{}_{(aq)}$ is +2

Since the oxidation number of the chemical species involving copper has decreased, this indicates that $Cu^{2+}{}_{(aq)}$ has been reduced to $Cu_{(s)}$.

The unbalanced reduction half equation is:

$Cu^{2+}{}_{(aq)} \rightarrow Cu_{(s)}$

Using electrons to balance the charge results in the following half equation:

$Cu^{2+}{}_{(aq)} + 2e^{-} \rightarrow Cu_{(s)}$

Therefore, this is the balanced reduction half equation.

However, this was only a simple case of balancing a half reaction as only the charge needed to be balanced. In more complex cases, the following acronym KOHES describes all the different steps that have to be taken in order to correctly balance a half equation.

Key elements need to be balanced

Oxygen atoms need to be balanced

Hydrogen atoms need to be balanced

Electrons need to be added to balance charge

States need to be included

The number of oxygen atoms on each side of a half-equation can be balanced by adding the appropriate number of $H_2O_{(l)}$ molecules to the side of the equation which is lacking oxygen atoms. However, this may mean that there is an unequal number of hydrogen atoms on each side of the equation. Hydrogen can be balanced by the addition of positively charged $H^{+}{}_{(aq)}$ (protons) onto the side of the half equation which is lacking in hydrogen atoms. This implies the reaction is occurring under acidic conditions as there is a supply of protons.

However, sometimes redox reactions occur under basic conditions, rather than acidic conditions. In order to write a balanced half equation for a reaction in a basic solution, for every $H^{+}{}_{(aq)}$ that is added, add an $OH^{-}{}_{(aq)}$ to both sides of the equation. From acid-base chemistry, we know that

$H^{+}{}_{(aq)} + OH^{-}{}_{(aq)} \rightarrow H_2O_{(l)}$

Therefore, the half equation will only be balanced with $OH^{-}{}_{(aq)}$ (hydroxide ions) indicating that the reaction is occurring under basic conditions.

2 Worked example

The dichromate ion $Cr_2O_7{}^{2-}{}_{(aq)}$ is a very common oxidising agent and it is reduced to $Cr^{3+}{}_{(aq)}$. Balance the half-equation for the reduction of $Cr_2O_7{}^{2-}{}_{(aq)}$ under acidic conditions and basic conditions.

What information is presented in the question?

$Cr_2O_7{}^{2-}{}_{(aq)}$ is reduced to $Cr^{3+}{}_{(aq)}$

There is a source of $H^+{}_{(aq)}$ ions under acidic conditions.

There is a source of $OH^-{}_{(aq)}$ ions under basic conditions.

What is the question asking us to do?

Write out the balanced reduction half-equation.

What strategy(ies) do we need in order to answer the question?

1. Use the acronym KOHES
2. Balance the key element(s) first (in this case, Cr)
3. Balance oxygen atoms using $H_2O_{(l)}$
4. Balance hydrogen atoms using $H^+{}_{(aq)}$ ions
5. Balance charge by using electrons
6. Include states
7. In order to find the half equation under basic conditions add $OH^-{}_{(aq)}$ ions to both sides of the equation to react with the $H^+{}_{(aq)}$ ions to form water.

Answer

We know that

$Cr_2O_7{}^{2-}{}_{(aq)} \rightarrow Cr^{3+}{}_{(aq)}$

Balancing Cr means:

$Cr_2O_7{}^{2-}{}_{(aq)} \rightarrow 2Cr^{3+}{}_{(aq)}$

Balancing oxygen means:

$Cr_2O_7{}^{2-}{}_{(aq)} \rightarrow 2Cr^{3+}{}_{(aq)} + 7H_2O_{(l)}$

Balancing hydrogen means:

$Cr_2O_7{}^{2-}{}_{(aq)} + 14H^+{}_{(aq)} \rightarrow 2Cr^{3+}{}_{(aq)} + 7H_2O_{(l)}$

Balancing charge means:

$Cr_2O_7{}^{2-}{}_{(aq)} + 14H^+{}_{(aq)} + 6e^- \rightarrow 2Cr^{3+}{}_{(aq)} + 7H_2O_{(l)}$

This is the balanced half-equation under acidic conditions.

For basic conditions, add $14OH^-{}_{(aq)}$ ions to both sides of the equation

$Cr_2O_7{}^{2-}{}_{(aq)} + 14H^+{}_{(aq)} + 14OH^-{}_{(aq)} + 6e^- \rightarrow 2Cr^{3+}{}_{(aq)} + 7H_2O_{(l)} + 14OH^-{}_{(aq)}$

Removing the water which appears on both sides leaves us with:

$Cr_2O_7{}^{2-}{}_{(aq)} + 7H_2O_{(l)} + 6e^- \rightarrow 2Cr^{3+}{}_{(aq)} + 14OH^-{}_{(aq)}$

This is the balanced reduction half-equation under basic conditions.

Sometimes during reactions involving basic conditions, hydrogen ions and hydroxide ions found on the same side of the equation can combine to form water. This will then be expressed as $H_2O_{(l)}$ in the full equation rather than the individual ions.

Balancing overall redox equations 3.1.10.2

OVERVIEW

The skills learnt for balancing redox half equations can now be applied to balancing more complex redox reactions.

THEORY DETAILS

Since a redox reaction consists of both a reduction half-equation and an oxidation half-equation, the overall redox reaction can be determined by adding these two half-equations together. The important thing to note is that for this to be possible, there has to be the same number of electrons on either side of the half-equations as electrons are not present in the overall redox equation. This can be achieved by multiplying the half equations by a constant factor.

Redox reactions can range from very simple reactions with only a few chemical species involved to much more complicated reactions involving many chemical species. An example of a complex unbalanced redox reaction is shown.

3 Worked example

Write the complete redox reaction which involved the following reduction and oxidation half-equations:

$Cr_2O_7^{2-}{}_{(aq)} + 14H^+{}_{(aq)} + 6e^- \rightarrow 2Cr^{3+}{}_{(aq)} + 7H_2O_{(l)}$

$Cu_{(s)} \rightarrow Cu^{2+}{}_{(aq)} + 2e^-$

What information is presented in the question?

The reduction and oxidation half-equations.

What is the question asking us to do?

Write out the balanced overall redox equation

What strategy(ies) do we need in order to answer the question?

1. Make the oxidation half-equation have the same number of electrons as the reduction equation.
2. Add the half equations together and cancel the chemical species which appear on both sides of the equation.

Answer

Multiply the oxidation half-equation by a factor of 3:

$3Cu_{(s)} \rightarrow 3Cu^{2+}{}_{(aq)} + 6e^-$

Add the reduction and oxidation half-equations together:

$3Cu_{(s)} + Cr_2O_7^{2-}{}_{(aq)} + 14H^+{}_{(aq)} + 6e^-$
$\rightarrow 3Cu^{2+}{}_{(aq)} + 6e^- + 2Cr^{3+}{}_{(aq)} + 7H_2O_{(l)}$

Cancel out the electrons to give the following balanced overall redox equation:

$3Cu_{(s)} + Cr_2O_7^{2-}{}_{(aq)} + 14H^+{}_{(aq)}$
$\rightarrow 3Cu^{2+}{}_{(aq)} + 2Cr^{3+}{}_{(aq)} + 7H_2O_{(l)}$

$Cr_2O_7^{2-}{}_{(aq)} + HNO_{2(aq)} \rightarrow Cr^{3+}{}_{(aq)} + NO_3^-{}_{(aq)}$

If we were to balance this equation without using half-equations, it would take us a very long time as there are many chemical species and different charges involved. However, using the knowledge developed in the previous component of this lesson, we can find the respective reduction and oxidation equations and then add them together. This is only possible when there is the same number of electrons on either side of the half-equations because we want electrons not to appear in the full redox reactions. To accomplish this, the half-equations can again be multiplied by a whole number. This process is shown in detail in the following worked example.

4 Worked example

Balance the following redox reaction in acidic conditions:

$Cr_2O_7^{2-}{}_{(aq)} + HNO_{2(aq)} \rightarrow Cr^{3+}{}_{(aq)} + NO_3^-{}_{(aq)}$

What information is presented in the question?

The unbalanced chemical equation under acidic conditions.

What is the question asking us to do?

Write out the balanced chemical equation.

What strategy(ies) do we need in order to answer the question?

1. Identify which chemical species are being oxidised and reduced using oxidation numbers.
2. Balance the reduction and oxidation half-equations using KOHES.
3. Make the number of electrons equal in each half-equation by multiplying one/both by a constant.
4. Add the half-equations together to determine the balanced overall redox equation.

Answer

The oxidation number of Cr in $Cr_2O_7^{2-}{}_{(aq)}$ is +6

The oxidation number of Cr in $Cr^{3+}{}_{(aq)}$ is +3

The oxidation number of N in $HNO_{2(aq)}$ is +3

The oxidation number of N in $NO_{3(aq)}$ is +5

Therefore, $Cr_2O_7^{2-}{}_{(aq)}$ is being reduced and $HNO_{2(aq)}$ is being oxidised.

Using KOHES and under acidic conditions,

$Cr_2O_7^{2-}{}_{(aq)} \rightarrow Cr^{3+}{}_{(aq)}$

Is balanced to:

$Cr_2O_7^{2-}{}_{(aq)} + 14H^+{}_{(aq)} + 6e^- \rightarrow 2Cr^{3+}{}_{(aq)} + 7H_2O_{(l)}$

Using KOHES and under acidic conditions,

$HNO_{2(aq)} \rightarrow NO_3^-{}_{(aq)}$ is balanced to:

$HNO_{2(aq)} + H_2O_{(l)} \rightarrow NO_3^-{}_{(aq)} + 3H^+{}_{(aq)} + 2e^-$

Multiplying the oxidation half-equation by a factor of 3 and adding the reduction and oxidation half-equations together gives us:

$Cr_2O_7{}^{2-}{}_{(aq)} + 14H^+{}_{(aq)} + 6e^- + 3HNO_{2(aq)} + 3H_2O_{(l)} \rightarrow 2Cr^{3+}{}_{(aq)} + 7H_2O_{(l)}\ 3NO_3{}^-{}_{(aq)} + 9H^+{}_{(aq)} + 6e^-$

Cancelling species, leaves us with:

$Cr_2O_7{}^{2-}{}_{(aq)} + 5H^+{}_{(aq)}\ 3HNO_{2(aq)} \rightarrow 2Cr^{3+}{}_{(aq)} + 3NO_3{}^-{}_{(aq)} + 4H_2O_{(l)}$

This is the balanced chemical equation.

Using the electrochemical series to predict spontaneous redox reactions 3.1.13.1

OVERVIEW

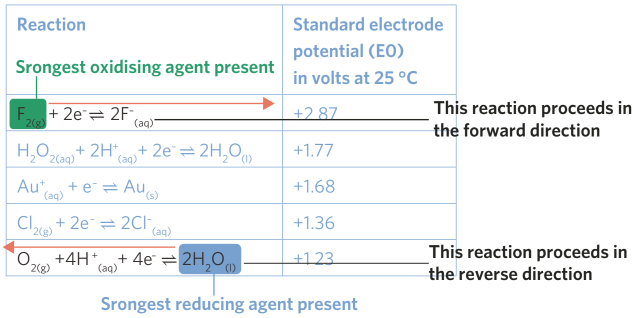
The **electrochemical series** is a useful guide that can be used to predict which chemical species undergoes oxidation or reduction when reacted together.

THEORY DETAILS

Since redox reactions involve both oxidation and reduction half-equations, it is important to understand which chemical species are undergoing oxidation and which chemical species are undergoing reduction. This is where the electrochemical series located in your data book comes into play.

As can be seen by the arrows on either side of the electrochemical series, the strongest reducing agent is located at the bottom right of the table and the strongest oxidising agent is located at the top left of the table. The redox reaction that will occur involves the strongest reducing agent and the strongest oxidising agent. This will become very important when we react multiple reducing and oxidising agents together.

The strongest oxidising agent will undergo reduction as per the chemical equation on the electrochemical series and the strongest reducing agent will undergo oxidation. As the electrochemical series is a list of reduction reactions, it is important to remember to read the equation in reverse for oxidation reactions. When writing the half equation, the arrow pointing both ways (⇌) also needs to be changed to only pointing in one direction (→). This is shown below in figure 2 using the example of a solution of water with fluorine gas.

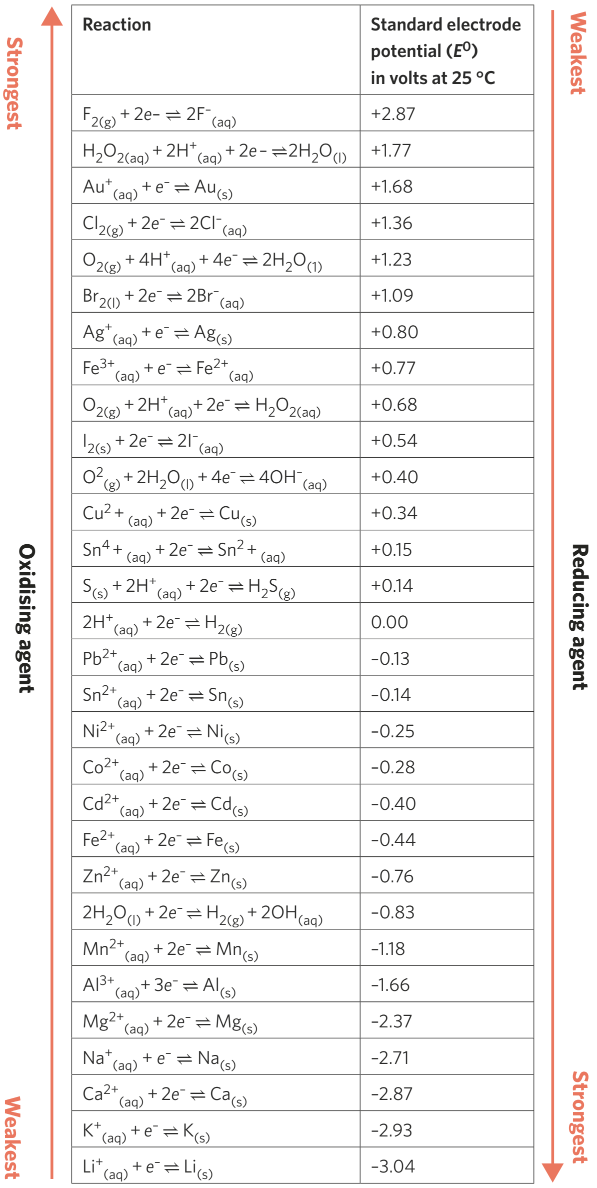


Reaction	Standard electrode potential (E0) in volts at 25 °C
$F_{2(g)} + 2e^- \rightleftharpoons 2F^-{}_{(aq)}$	+2.87
$H_2O_{2(aq)} + 2H^+{}_{(aq)} + 2e^- \rightleftharpoons 2H_2O_{(l)}$	+1.77
$Au^+{}_{(aq)} + e^- \rightleftharpoons Au_{(s)}$	+1.68
$Cl_{2(g)} + 2e^- \rightleftharpoons 2Cl^-{}_{(aq)}$	+1.36
$O_{2(g)} + 4H^+{}_{(aq)} + 4e^- \rightleftharpoons 2H_2O_{(l)}$	+1.23

Figure 2 Annotated segment of the electrochemical series

Source: VCAA data booklet

A spontaneous redox reaction will not occur if the strongest oxidising agent present is positioned below the strongest reducing agent present. This scenario will be discussed in more depth in chapter 6.



Reaction	Standard electrode potential (E^0) in volts at 25 °C
$F_{2(g)} + 2e- \rightleftharpoons 2F^-{}_{(aq)}$	+2.87
$H_2O_{2(aq)} + 2H^+{}_{(aq)} + 2e- \rightleftharpoons 2H_2O_{(l)}$	+1.77
$Au^+{}_{(aq)} + e^- \rightleftharpoons Au_{(s)}$	+1.68
$Cl_{2(g)} + 2e^- \rightleftharpoons 2Cl^-{}_{(aq)}$	+1.36
$O_{2(g)} + 4H^+{}_{(aq)} + 4e^- \rightleftharpoons 2H_2O_{(1)}$	+1.23
$Br_{2(l)} + 2e^- \rightleftharpoons 2Br^-{}_{(aq)}$	+1.09
$Ag^+{}_{(aq)} + e^- \rightleftharpoons Ag_{(s)}$	+0.80
$Fe^{3+}{}_{(aq)} + e^- \rightleftharpoons Fe^{2+}{}_{(aq)}$	+0.77
$O_{2(g)} + 2H^+{}_{(aq)} + 2e^- \rightleftharpoons H_2O_{2(aq)}$	+0.68
$I_{2(s)} + 2e^- \rightleftharpoons 2I^-{}_{(aq)}$	+0.54
$O^2{}_{(g)} + 2H_2O_{(l)} + 4e^- \rightleftharpoons 4OH^-{}_{(aq)}$	+0.40
$Cu^2+{}_{(aq)} + 2e^- \rightleftharpoons Cu_{(s)}$	+0.34
$Sn^4+{}_{(aq)} + 2e^- \rightleftharpoons Sn^2+{}_{(aq)}$	+0.15
$S_{(s)} + 2H^+{}_{(aq)} + 2e^- \rightleftharpoons H_2S_{(g)}$	+0.14
$2H^+{}_{(aq)} + 2e^- \rightleftharpoons H_{2(g)}$	0.00
$Pb^{2+}{}_{(aq)} + 2e^- \rightleftharpoons Pb_{(s)}$	-0.13
$Sn^{2+}{}_{(aq)} + 2e^- \rightleftharpoons Sn_{(s)}$	-0.14
$Ni^{2+}{}_{(aq)} + 2e^- \rightleftharpoons Ni_{(s)}$	-0.25
$Co^{2+}{}_{(aq)} + 2e^- \rightleftharpoons Co_{(s)}$	-0.28
$Cd^{2+}{}_{(aq)} + 2e^- \rightleftharpoons Cd_{(s)}$	-0.40
$Fe^{2+}{}_{(aq)} + 2e^- \rightleftharpoons Fe_{(s)}$	-0.44
$Zn^{2+}{}_{(aq)} + 2e^- \rightleftharpoons Zn_{(s)}$	-0.76
$2H_2O_{(l)} + 2e^- \rightleftharpoons H_{2(g)} + 2OH_{(aq)}$	-0.83
$Mn^{2+}{}_{(aq)} + 2e^- \rightleftharpoons Mn_{(s)}$	-1.18
$Al^{3+}{}_{(aq)} + 3e^- \rightleftharpoons Al_{(s)}$	-1.66
$Mg^{2+}{}_{(aq)} + 2e^- \rightleftharpoons Mg_{(s)}$	-2.37
$Na^+{}_{(aq)} + e^- \rightleftharpoons Na_{(s)}$	-2.71
$Ca^{2+}{}_{(aq)} + 2e^- \rightleftharpoons Ca_{(s)}$	-2.87
$K^+{}_{(aq)} + e^- \rightleftharpoons K_{(s)}$	-2.93
$Li^+{}_{(aq)} + e^- \rightleftharpoons Li_{(s)}$	-3.04

Figure 1 VCAA electrochemical series showing the trends in oxidising and reducing agent strength

5 Worked example

What will be the redox reaction occurring if a rod of iron $Fe_{(s)}$ is placed into a solution containing $Ag^{+}{}_{(aq)}$.

What information is presented in the question?

The chemical species present are $Fe_{(s)}$, $Ag^{+}{}_{(aq)}$ and $H_2O_{(l)}$.

What is the question asking us to do?

Write out the complete redox reaction that is occurring.

What strategy(ies) do we need in order to answer the question?

1. Identify which chemical species are being oxidised and reduced using the electrochemical series.
2. Determine the reduction and oxidation half-equations.
3. Make the number of electrons equal in each half-equation by multiplying one/both by a constant.
4. Add the half-equations together to determine the balanced redox equation.

Answer

According to the electrochemical series, $Ag^{+}{}_{(aq)}$ is the strongest oxidising agent present and $Fe_{(s)}$ is the strongest reducing agent present. Therefore, $Ag^{+}{}_{(aq)}$ will be reduced and the following half-equation will occur

$Ag^{+}{}_{(aq)} + e^{-} \rightarrow Ag_{(s)}$

$Fe_{(s)}$ will be oxidised and the following half-equation will occur

$Fe_{(s)} \rightarrow Fe^{2+}{}_{(aq)} + 2e^{-}$

In order to add half-equations, we need both the oxidising and reducing agents to have the same number of electrons. Therefore, multiplying the reduction equation by 2 balances the number of electrons

$2Ag^{+}{}_{(aq)} + 2e^{-} \rightarrow 2Ag_{(s)}$

Adding this with the oxidation equation gives us

$Fe_{(s)} + 2Ag^{+}{}_{(aq)} \rightarrow Fe^{2+}{}_{(aq)} + 2Ag_{(s)}$

Theory summary

- Half-equations can be balanced using KOHES.
- KOHES states the order in which half-equations should be balanced, as represented by the following: key elements → oxygen atoms → hydrogen atoms → electrons → states.
- Half-equations can be balanced under acidic conditions using H^{+}, or basic conditions using OH^{-}.
- A complete redox reaction can be determined by adding the reduction and oxidation half-equations together if they both contain the same number of electrons.
- The electrochemical series is able to tell us what the strongest oxidising agent is and what the strongest reducing agent is and predict possible reactions.

4B QUESTIONS

Theory review questions

Question 1

Which of the following descriptions aligns with the chemical reaction provided

$Cr_2O_7{}^{2-}{}_{(aq)} + 6e^{-} + 14H^{+}{}_{(aq)} \rightarrow 2Cr^{3+}{}_{(aq)} + 7H_2O_{(l)}$

A The reaction is occurring in basic conditions.

B The reaction is occurring in acidic conditions.

C The reaction represented is a hydrolysis reaction.

D The reaction represented is an oxidation reaction.

Question 2

The main difference when balancing redox reactions occurring in acidic and basic conditions is that

A only electrons are required to balance equations involving acidic conditions.

B only electrons are required to balance equations involving basic conditions.

C OH^{-} ions are used to balance equations in acidic conditions and H^{+} ions are used to balance in basic conditions.

D H^{+} ions are used to balance equations in acidic conditions and OH^{-} ions are used to balance equations in basic conditions.

Question 3

To create a balanced complete redox reaction from the half equations presented, we would need to balance

$Fe^{3+}{}_{(aq)} + e^- \rightarrow Fe^{2+}{}_{(aq)}$

$Pb_{(s)} \rightarrow Pb^{2+}{}_{(aq)} + 2e^-$

A electrons.
B oxygen.
C water.
D hydroxide ions.

Question 4

With respect to writing balanced redox reactions, the electrochemical series can help to

I identify the strongest oxidising agent and reducing agent.
II identify only the reduction half equation.
III identify only the oxidation half equation.

A I only
B I & II only
C II & III only
D I & III only

Exam-style questions

Within lesson

Question 5 (1 MARK)

The manganese ion, $MnO_4^-{}_{(aq)}$, is an important oxidising agent. What is the balanced reduction half-equation when it is reduced to $Mn^{2+}{}_{(aq)}$ in basic conditions?

A $MnO_4^-{}_{(aq)} + 8H^+{}_{(aq)} + 5e^- \rightarrow Mn^{2+}{}_{(aq)} + 4\,H_2O_{(l)}$
B $MnO_4^-{}_{(aq)} + 4H_2O_{(l)} + 5e^- \rightarrow Mn^{2+}{}_{(aq)} + 8OH^-{}_{(aq)}$
C $Mn^{2+}{}_{(taq)} + 8OH^-{}_{(aq)} \rightarrow MnO_4^-{}_{(aq)} + 4H_2O_{(l)} + 5e^-$
D $Mn^{2+}{}_{(aq)} + 4H_2O_{(l)} \rightarrow MnO_4^-{}_{(aq)} + 8H^+{}_{(aq)} + 5e^-$

Question 6 (1 MARK)

The following equation is an example of an unbalanced chemical reaction.

$MnO_4^-{}_{(aq)} + H^+{}_{(aq)} + Li_{(s)} \rightarrow Mn^{2+}{}_{(aq)} + H_2O_{(l)} + Li^+{}_{(aq)}$

When it is correctly balanced, what is the coefficient of $Li_{(s)}$?

A 3 **B** 4 **C** 5 **D** 6

Question 7 (2 MARKS)

Chromium (III) hydroxide can be used as a pigment. Based on the incomplete redox reaction provided,

$Se_{(s)} + Cr(OH)_{3(aq)} \rightarrow Cr_{(s)} + SeO_3^{2-}{}_{(aq)}$

a write the balanced oxidation half equation for the reaction (1 MARK)

b write the full balanced redox equation for this reaction (1 MARK)

Question 8 (3 MARKS)

A student decided to set up a redox reaction involving the oxidising agent $Cr_2O_7^{2-}{}_{(aq)}$ in order to oxidise ethanol, CH_3CH_2OH. The following half-equations represent what happened but are incomplete

$Cr_2O_7^{2-}{}_{(aq)} \rightarrow Cr^{3+}{}_{(aq)}$

$CH_3CH_2OH_{(l)} \rightarrow CH_3COOH_{(l)}$

a Write out the reduction and oxidation half-equations under acidic conditions, denoting which is the reduction and which is the oxidation-half equation. (2 MARKS)

b Write out the complete equation under acidic conditions. (1 MARK)

Question 9 (4 MARKS)

For the following unbalanced equation between iron (III) sulfate $Fe_2(SO_4)_3$ and magnesium (Mg),

$Fe_2(SO_4)_{3(aq)} + Mg_{(s)} \rightarrow Fe_{(s)} + MgSO_{4(aq)}$

a write the balanced reduction half-reaction and the balanced oxidation half-reaction. (2 MARKS)

b write the balanced overall redox equation. (1 MARK)

c identify the strongest reducing agent in the reaction. (1 MARK)

Question 10 (5 MARKS)

Frodo was in a chemistry class studying redox reactions. He initially had a beaker with a 1.0 M blue solution of $Cu^{2+}{}_{(aq)}$ ions and accidentally put a strip of $Pb_{(s)}$ and $Fe_{(s)}$ in the beaker, instead of just $Pb_{(s)}$. However, Frodo predicted that the following reaction would still occur according to the electrochemical series because $Pb_{(s)}$ is a stronger reducing agent than $Fe_{(s)}$.

$Cu^{2+}{}_{(aq)} + Pb_{(s)} \rightarrow Cu_{(s)} + Pb^{2+}{}_{(aq)}$

a Comment on the accuracy of the student's prediction. If the student is incorrect, write the redox reaction that is occurring. (3 MARKS)

b Over time, what are two changes that the student could observe to the solution and strips of metal? (2 MARKS)

Multiple lessons

Question 11 (4 MARKS)

The following reaction is an example of a redox reaction.

$Na_{(s)} + Ag^{+}{}_{(aq)} \rightarrow Na^{+}{}_{(aq)} + Ag_{(s)}$

a Write the two half-equations of this redox reaction. (2 MARKS)

b Determine the conjugate redox pair for the oxidation process and for the reduction process. (2 MARKS)

Question 12 (5 MARKS)

Sulfur dioxide SO_2 gas can be produced in a reaction between sulfuric acid H_2SO_4 and nickel metal. A solution containing Ni^{2+} ions is formed.

a Write balanced oxidation and reduction half-equations for this process. (2 MARKS)

b Write a balanced overall reaction. (1 MARK)

c Sulfur dioxide can also be produced in a reaction between calcium sulfate, silicon dioxide from sand and pure carbon when heated together in a furnace according to the following equation.

$2CaSO_{4(s)} + 2SiO_{2(s)} + C_{(s)} \rightarrow 2CaSiO_{3(s)} + 2SO_{2(g)} + CO_{2(g)}$

Is this reaction an example of a redox reaction? Explain. (2 MARKS)

4C GALVANIC CELLS

In this lesson, we will learn about the construction and function of galvanic cells as well as the reactions occurring in galvanic cells.

4A Redox reactions	4B Writing equations for redox reactions	4C Galvanic cells	4D Designing galvanic cells	4E Direct and indirect redox reactions	4F Fuel cells

Study design dot points

- galvanic cells as primary cells and as portable or fixed chemical energy storage devices that can produce electricity (details of specific cells not required) including common design features (anode, cathode, electrolytes, salt bridge and separation of half-cells) and chemical processes (electron and ion flows, half-equations and overall equations)
- the use of the electrochemical series in designing and constructing galvanic cells and as a tool for predicting the products of redox reactions, deducing overall equations from redox half-equations and determining maximum cell voltage under standard conditions

Key knowledge units

Design of galvanic cells	3.1.11.1
Function of galvanic cells	3.1.11.2
Identifying half-reactions in galvanic cells	3.1.13.2.1

Key terms and definitions

- **Galvanic cell** electrochemical cell in which chemical energy from spontaneous redox reactions is converted into electrical energy
- **Anode** negatively charged electrode in a galvanic cell where oxidation occurs
- **Cathode** positively charged electrode in a galvanic cell where reduction occurs
- **Salt bridge** connection which allows the flow of ions between two half cells to maintain electrical neutrality of the cell
- **Electrode** electrical conductor that is either unreactive or involved in a reaction

Lesson links

This lesson builds on:

▶ 4A – Redox reactions

Redox reactions occur in galvanic cells.

▶ 4B – Writing equations for redox reactions

Writing balanced redox reactions is required to identify half-reactions and overall reactions in galvanic cells.

Design of galvanic cells 3.1.11.1

OVERVIEW

A galvanic cell consists of two separate half-cells that are connected to create a complete electric circuit.

THEORY DETAILS

Galvanic cells are found in the electronic devices we use everyday such as mobile phones, laptops, watches and calculators. Figure 1 shows the construction of a standard galvanic cell. A galvanic cell consists of two separate half-cells connected by a **salt bridge**. One of the most common salt bridges used is potassium nitrate (KNO_3) whose function will be discussed later in this lesson. Each half-cell includes a beaker with a specific solution and an **electrode** made of a material that is able to conduct electricity, often a metal or pure carbon rod. As shown in figure 1, the **anode**, a negatively charged electrode, is partially submerged in the solution of one half-cell and the **cathode,** a positively charged electrode, is partially submerged in the solution of the other half-cell. The anode and cathode are connected by a metal wire which allows the flow of electrons.

The metals and the solutions used in each half-cell vary. As can be seen in figure 2, the left half-cell consists of the zinc (Zn) electrode and zinc sulfate solution ($ZnSO_4$). In solution, $ZnSO_4$ exists as ions Zn^{2+} and SO_4^{2-}. Therefore, we call the left half-cell a Zn/Zn^{2+} half cell. The right half-cell consists of the copper (Cu) electrode and copper sulfate ($CuSO_4$). In solution, $CuSO_4$ exists as ions Cu^{2+} and SO_4^{2-}. Similarly, we call the right half-cell a Cu/Cu^{2+} half-cell.

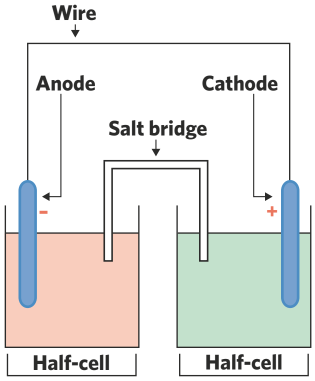


Figure 1 Simple structure of a galvanic cell

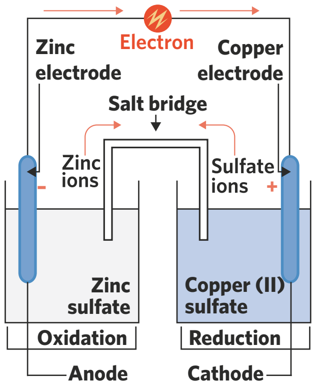


Figure 2 An example of the design of galvanic cells

Function of galvanic cells 3.1.11.2

OVERVIEW

Galvanic cells generate electrical energy for electronic devices from the redox reactions occurring in the half-cells.

THEORY DETAILS

In a galvanic cell, chemical energy is converted to electrical energy. The oxidation reaction always occurs at the anode, whilst the reduction reaction always occurs at the cathode. For the galvanic cell in figure 4, Zn is oxidised to Zn^{2+} at the anode and Cu^{2+} is reduced to Cu at the cathode. The redox reactions occurring at the half-cells of the galvanic cell in figure 4 are summarised as:

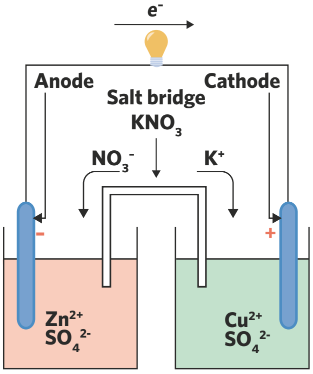


Figure 4 Illustration of a galvanic cell's function

Anode

Oxidation: $Zn_{(s)} \rightarrow Zn^{2+}{}_{(aq)} + 2e^-$

Cathode

Reduction: $Cu^{2+}{}_{(aq)} + 2e^- \rightarrow Cu_{(s)}$

Overall reaction

$Zn_{(s)} + Cu^{2+}{}_{(aq)} \rightarrow Zn^{2+}{}_{(aq)} + Cu_{(s)}$

The electrons produced from the oxidation reaction at the anode flow through the wire from the anode to the cathode providing electrical power to light up the bulb.

Tip In a galvanic cell, electrons always flow from the anode to the cathode.
'**Anox**' – **An**ode is where **ox**idation takes place.
'**Redcat**' – **Red**uction occurs at the **cat**hode.

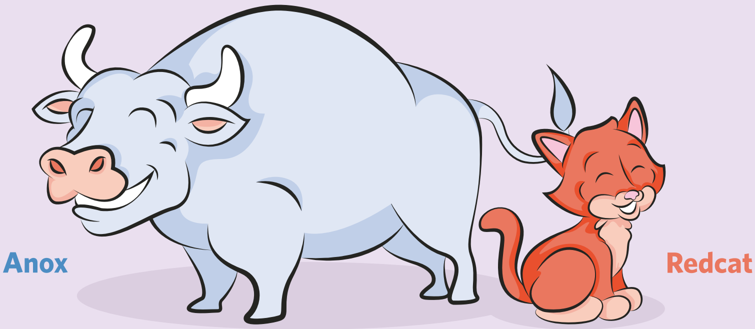


Figure 3 Mnemonic to remember 'Anox' and 'Redcat' for redox reactions

▶ **Important note**

In a galvanic cell, negative ions from the salt bridge migrate to the anode and positive ions from the salt bridge migrate to the cathode. Electrons never flow through the salt bridge.

In the Zn/Zn^{2+} half-cell, the oxidation of Zn causes the accumulation of Zn^{2+} ions in the half-cell, meaning that there is an excess amount of positively charged ions there. Therefore, it is important for the negative ions (such as NO_3^-) in the salt bridge to migrate to the Zn/Zn^{2+} half-cell (on left in diagram) to maintain electrical neutrality. On the other hand, Cu^{2+} ions are being consumed in the Cu/Cu^{2+} half-cell to form Cu meaning that there is only a small amount of positively charged ions there. Hence, the positive ions (such as K^+) of the salt bridge migrate to the Cu/Cu^{2+} half-cell (on the right in the diagram). The role of the salt bridge is to complete the circuit and maintain the overall electrical neutrality of the galvanic cell so that electricity can continue to be produced. There are several key requirements that need to be met with respect to the composition of the salt bridge. The ionic compound (salt) has to be very soluble in water, unreactive and not form an insoluble compound (precipitate) with any of the reactant species in either of the half-cells.

Identifying half-reactions in galvanic cells 3.1.13.2.1

OVERVIEW

Half-reactions in galvanic cells are determined based on the standard electrode potentials of the redox reactions occurring in the half-cells.

THEORY DETAILS

Redox reactions in galvanic cells are spontaneous. To determine which redox reaction occurs at each electrode, we need to consider the standard electrode potentials of the half-reactions of the half-cells. Standard electrode potentials can be found in the chemistry data book.

Consider the galvanic cell in figure 5.

From the chemistry databook, we know that Cu^{2+} is a stronger oxidising agent than Fe^{2+}. Therefore, Cu^{2+} will undergo reduction and Fe will undergo oxidation.

Reduction: $Cu^{2+}_{(aq)} + 2e^- \rightarrow Cu_{(s)} \quad +0.34V$

Oxidation: $Fe_{(s)} \rightarrow Fe^{2+}_{(aq)} + 2e^- \quad -0.44V$

The overall voltage of the redox reaction of the galvanic cell is calculated by the following equation : $E^0_{cell} = E^0_{reduction} - E^0_{oxidation}$

The overall reaction and its voltage is:

$Fe_{(s)} + Cu^{2+}_{(aq)} \rightarrow Fe^{2+}_{(aq)} + Cu_{(s)} \quad E^0 = +0.34V - (-0.44V) = 0.78\ V$

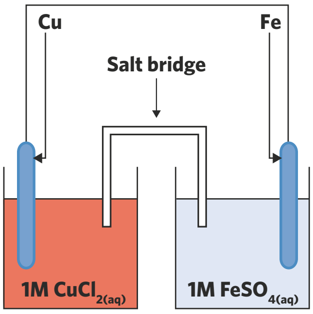
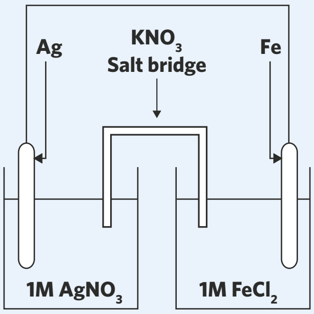


Figure 5 Copper (II) chloride and iron (II) sulphate galvanic cell

1 Worked example

Write balanced half equations occurring at each electrode and the overall reaction occurring in the given galvanic cell. On the given diagram, identify the anode and its charge, the cathode and its charge, the electron flow and the migration of the ions from the salt bridge.



What information is presented in the question?

Diagram of a galvanic cell

What is the question asking us to do?

Identify the half equations for the reaction occurring.

Determine the anode and its charge, the cathode and its charge, the electron flow and the migration of the ions from the salt bridge.

What strategy(ies) do we need in order to answer the question?

1. Determine which half-equations will give rise to a spontaneous reaction based on the standard electrode potentials found in the chemistry data book.
2. Write balanced half-equations.
3. Write the balanced overall reaction.
4. Determine the anode and its charge, the cathode and its charge, the electron flow and the migration of the ions from the salt bridge based on the reactions obtained in steps 2 and 3.

Answer

Anode

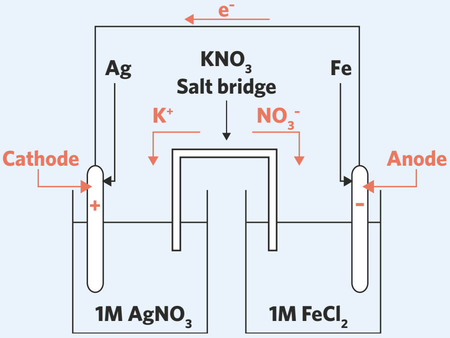
Oxidation: $Fe_{(s)} \rightarrow Fe^{2+}_{(aq)} + 2e^-$

Cathode

Reduction: $Ag^+_{(aq)} + e^- \rightarrow Ag_{(s)}$

Overall reaction:

$Fe_{(s)} + 2Ag^+_{(aq)} \rightarrow Fe^{2+}_{(aq)} + 2Ag_{(s)}$



Theory summary

- A galvanic cell consists of two separate half-cells where each half-cell consists of an electrode made of metal and a specific solution.
- The two electrodes in a galvanic cell are connected by a wire.
- The salt bridge plays an important role in completing the circuit and maintaining the charge neutrality of each half-cell.
- The electrons flowing through the wire from the anode to the cathode provide electrical power to devices.
- Half-equations and overall equations in galvanic cells are determined based on the standard electrode potentials.

4C QUESTIONS

Theory review questions

Question 1

Which of the following statements is correct about the set up of a galvanic cell?

A The solutions in two half-cells are connected by a wire.
B The two electrodes are connected by a salt bridge.
C The two half-cells are connected by a salt bridge.
D The anode and cathode are fully submerged in the solutions.

Question 2

Which of the following statements is **not** correct about the function of galvanic cells?

A Electrons migrate via a metal wire connecting the cathode and anode.
B Negative ions from the salt bridge migrate to the cathode.
C The salt bridge helps maintain the electrical neutrality of the half-cells.
D Negative ions from the salt bridge migrate to the anode.

Question 3

Which of the following statements is correct about the redox reactions in galvanic cells?

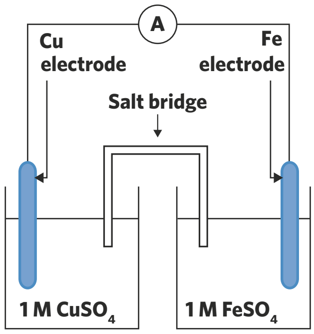
A Overall reaction is a non-spontaneous reaction.
B Oxidation reaction always occurs at the cathode
C Reduction reaction always occurs at the anode.
D Reduction reaction always occurs at the cathode.

Exam-style questions

Within lesson

Question 4 (1 MARK)

A galvanic cell's construction is shown.



When the given galvanic cell is operating, one thing that doesn't occur is

A electrons flow from the Fe electrode to the Cu electrode.
B the mass of the Fe electrode decreases.
C the mass of the Cu electrode increases.
D electrons flow from the Cu electrode to the Fe electrode.

Use the given galvanic cell to answer questions 5 and 6.

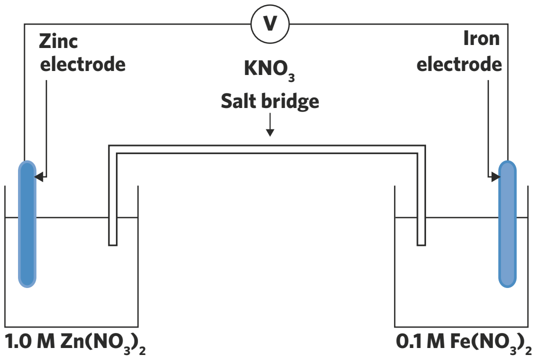


Image: VCAA 2014 Exam Section A Q27, 28

Question 5 (1 MARK)

Which of the following is correct about the given galvanic cell?

A Oxidation reaction occurs at the electrode on the right.

B Reduction reaction occurs at the electrode on the left.

C Electrons flow towards the iron electrode.

D The cell potential is 0.03 V

Question 6 (1 MARK)

Which of the following best describes what happens at the iron electrode?

A No change will be observed at this electrode.

B The electrode will become thicker.

C The electrode will become thinner.

D There will be a layer of zinc covering the iron electrode.

Question 7 (7 MARKS)

a On the given set up, identify the anode and the cathode. Explain your answers. (3 MARKS)

b On the given set up, identify the direction of the electron flow. (1 MARK)

c Write all possible reactions occurring at the anode and the cathode. (2 MARKS)

d Calculate the maximum voltage measured when the switch is closed. Justify your answer. (1 MARK)

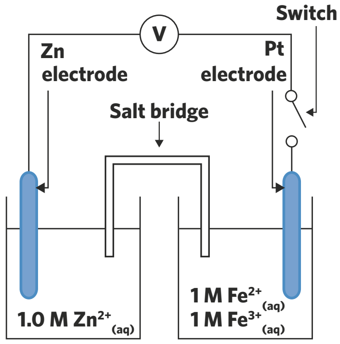


Image: VCAA 2015 Exam Section A Q26

Question 8 (5 MARKS)

The set up of a galvanic cell is provided:

The half-cell on the right is the standard hydrogen electrode (SHE) to which all standard redox potentials are compared.

a On the given set up, identify the anode and the cathode. (2 MARKS)

b Identify the type of redox reaction occurring at

  i the anode. (1 MARK)

  ii the cathode. (1 MARK)

c On the given set up, identify the direction of the electron flow. (1 MARK)

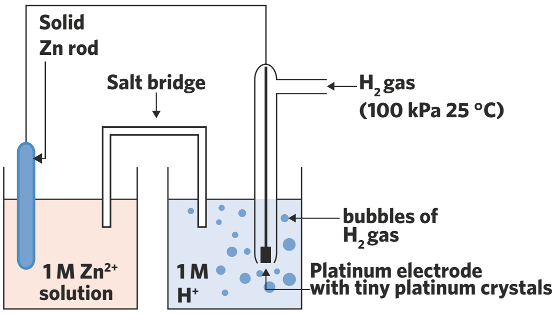


Image: VCAA 2016 Exam Section A Q29

Multiple lessons

Question 9 (8 MARKS)

a Determine the anode and the cathode of the galvanic cell. (2 MARKS)

b Write the balanced half-equations occurring at the:

  i anode and identify the type of redox reaction. (2 MARKS)

  ii cathode and identify the type of redox reaction. (2 MARKS)

c Write the balanced overall redox reaction occurring in the galvanic cell. (1 MARK)

d On the given diagram, draw the migration of the ions from the salt bridge. (1 MARK)

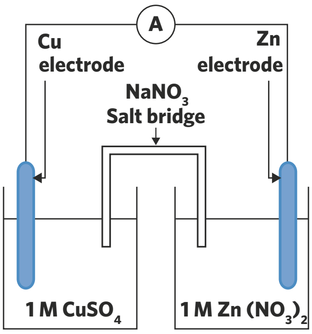
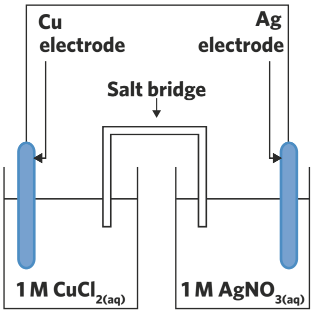


Image: VCAA 2018 Exam Section A Q11

Question 10 (8 MARKS)

Dora decided to create a galvanic cell as shown below.



She decided to use the salt sodium chloride as the salt bridge.

a After connecting the two half cells together with a wire, she soon discovered that the galvanic cell wasn't running that well and a solid was forming. Explain this observation with reference to the salt bridge. (2 MARKS)

b In light of this, she removed the salt bridge entirely but no electricity was generated. Why did this happen? (2 MARKS)

c She decided to use a salt bridge with potassium nitrate instead. Write out the equations occurring at the anode and cathode, the overall equation and the predicted voltage for the cell. (4 MARKS)

4D DESIGNING GALVANIC CELLS

In this lesson we will explore how to construct a galvanic cell based on standard half cells.

Study design dot point

- the use of the electrochemical series in designing and constructing galvanic cells and as a tool for predicting the products of redox reactions, deducing overall equations from redox half-equations and determining maximum cell voltage under standard conditions

Key knowledge units

Designing half cells	3.1.13.2.2
Constructing a complete galvanic cell	3.1.13.2.3

Key terms and definitions of this lesson

- **Standard half cell** cell consisting of both members of the conjugate redox pair and an electrode at standard conditions
- **Standard electrode potential** potential of the half reaction (reduction), given in volts, relative to the standard hydrogen electrode

Lesson links

This lesson builds on:

▶ 4A – Redox reactions

Redox reactions occur in galvanic cells.

▶ 4B – Writing equations for redox reactions

Equations can be written for the redox reactions occuring in galvanic cells.

Designing half cells 3.1.13.2.2

OVERVIEW

The half cells in a galvanic cell contain the necessary chemical species and electrode required for reduction or oxidation to occur.

THEORY DETAILS

Galvanic cells rely on spontaneous redox reactions in order to transfer chemical energy into electrical energy. In order for this to occur, each half cell needs to contain both of the following:

- Reducing/oxidising agent
- Electrode

Standard half cells are also constructed at the following standard (SLC) conditions:

- Gas pressure – 100 kPa
- Concentration – 1.0 M
- Temperature – 298 K

Whether reduction or oxidation is occurring in the half cell depends entirely on what the half cell is connected to. This is able to be determined by the use of the electrochemical series as we learned in lesson 4B.

There are 3 main types of standard galvanic half cells depending on whether the reducing/oxidising agent is a solid, an aqueous ion, liquid or a gas.

The first type of half cell is where the conjugate redox pair consists of a solid (usually a metal) and an aqueous ion. In this case, the electrode will consist of the metal (as metals can conduct electricity) and dissolved in the aqueous solution (the electrolyte) will be the ion of the metal. Figure 1 represents the typical set up of a metal/aqueous ion half cell using $Fe_{(s)}$ and $Fe^{2+}_{(aq)}$.

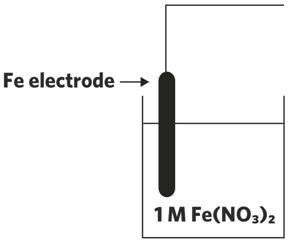


Figure 1 Metal/aqueous ion half cell

In this case, if reduction takes place in the half cell, the following reaction occurs:

$Fe^{2+}_{(aq)} + 2e^- \rightarrow Fe_{(s)}$

This means that aqueous ions are leaving the solution and are being reduced at the iron electrode, forming regions of solid iron on the electrode.

If oxidation takes place in the half cell, the following reaction occurs:

$Fe_{(s)} \rightarrow Fe^{2+}_{(aq)} + 2e^-$

In this case, the solid iron on the electrode is being oxidised to its aqueous ions which enter the solution. Therefore, the iron electrode will appear corroded as the solid piece of iron is oxidised.

Another type of half cell involves the conjugate redox pair consisting of both aqueous ions. In this case, since there is no solid present to make up the electrode, an inert (unreactive) electrode, like platinum or carbon, has to be used. An electrode is still required since it forms a site for the redox reactions to occur. It is important that a metal with the potential to undergo oxidation is not used because we do not want any other redox reactions to occur. For example, figure 2 represents the typical set up of a half cell involving multiple aqueous ions.

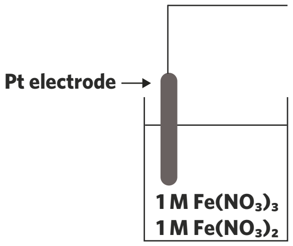


Figure 2 Aqueous ion/aqueous ion half cell

In this case, if reduction takes place in the half cell, the following reaction occurs:

$Fe^{3+}_{(aq)} + e^- \rightarrow Fe^{2+}_{(aq)}$

If oxidation takes place in the half cell, the following reaction occurs:

$Fe^{2+} \rightarrow Fe^{3+}_{(aq)} + e^-$

The final type of half cell involves a gas. In this case, a special half cell has to be used involving an inert electrode (platinum or carbon) and a glass tube to direct the movement of the gas. The half cell functions by gas being pumped into the glass tube at 100 kPa and onto the electrode so that it can undergo a spontaneous reaction. The most common gas half cell is the standard hydrogen electrode (SHE) and it is shown in figure 3.

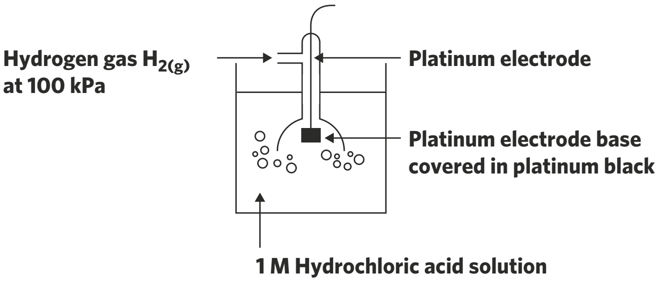


Figure 3 Standard hydrogen electrode

In this diagram, the bottom of the platinum electrode is covered in a substance known as platinum black. Platinum black is a fine powdery like substance which increases the surface area of the electrode and allows the hydrogen gas to cling to the electrode, meaning that it reacts at a higher rate.

In this case, if reduction takes place in the half cell, the following reaction occurs.

$2H^+_{(aq)} + 2e^- \rightarrow H_{2(g)}$

If oxidation takes place in the half cell, the following reaction occurs.

$H_{2(g)} \rightarrow 2H^+_{(aq)} + 2e^-$

You will not need to know each half cell type in detail, only that these are the possible types of half cells that can exist. The type of half cell constructed will depend on the species present in the reaction.

Constructing a galvanic cell 3.1.13.2.3

OVERVIEW

A complete galvanic cell can be constructed by connecting two half cells together with an electric wire and a salt bridge.

THEORY DETAILS

As we learned in lesson 4C, galvanic cells consist of two half cells connected together by an electric wire. The electric wire allows for the conduction of the flow of electrons between the two half cells. This is necessary in order for a spontaneous redox reaction to occur because the transfer of electrons is required.

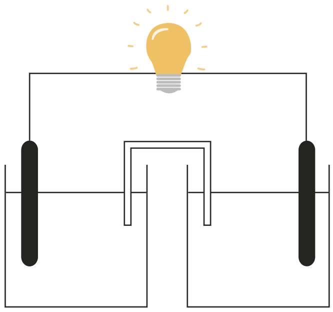


Figure 4 General diagram of a galvanic cell

However, one other component is necessary for a spontaneous redox reaction to occur and that is a salt bridge. As we learned previously, the salt bridge consists of soluble ions of positive and negative charges that migrate to the cathode and anode respectively to prevent the build up of excess charge hence maintaining electrical neutrality.

Once these requirements have been met, the galvanic cell can then be constructed as shown in figure 4.

One of the major benefits of connecting two standard half cells together to form a galvanic cell is to determine the relative strengths of oxidising and reducing agents. This was how the electrochemical series was created. Each of the standard half cells was connected to the standard hydrogen electrode and the potential difference was measured using a voltmeter. The potential difference is also known as the voltage.

Since it is impossible to measure the potential difference of a single half cell, chemists have created values called **standard electrode potentials** which are calculated with reference to the standard hydrogen electrode and are all calculated under SLC with 1 M concentrations of reducing/oxidising agents.

The standard hydrogen electrode is assigned a standard electrode potential value of 0.00 V. If a standard electrode potential value is positive, this means that the electrode connected to the standard hydrogen half cell was the cathode since it underwent reduction. If the standard electrode potential is negative, this means that the electrode connected to the standard hydrogen half cell was the anode since it underwent oxidation. Using this information, we can then determine what reaction is occurring in a galvanic cell involving any two individual half cells.

For a galvanic cell to function, a spontaneous redox reaction needs to occur. The electrochemical series is required so that we can determine, when we connect two half cells together with a salt bridge and a conducting wire, which electrode will be the cathode and which electrode will be the anode. The chemical species which is the strongest reducing agent will be oxidised at the anode and the chemical species which is the strongest oxidising agent will be reduced at the cathode.

1 Worked example

Draw a diagram of a $H_{2(g)}/H^+_{(aq)}$ standard half cell connected to a $Fe^{2+}_{(aq)}/Fe^{3+}_{(aq)}$ standard half cell with a $KNO_{3(aq)}$ salt bridge and label all key features including the voltage.

What information is presented in the question?

The following chemical species are present: $H_{2(g)}$, $H^+_{(aq)}$, $Fe^{2+}_{(aq)}$, $Fe^{3+}_{(aq)}$, $H_2O_{(l)}$

What is the question asking us to do?

Draw a labelled diagram of the galvanic cell

What strategy(ies) do we need in order to answer the question?

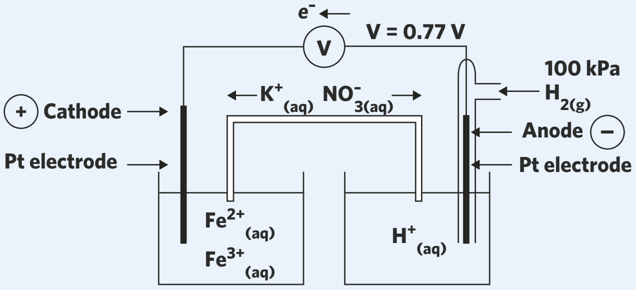
1. Use the electrochemical series to find the strongest reducing agent and the strongest oxidising agent.
2. Find the oxidation and reduction half equation.
3. Identify the anode and the cathode.
4. Draw the appropriate diagram including the anode, cathode, their composition and polarity, composition of salt bridge, flow of cations and anions, flow of electrons.

Answer

According to the electrochemical series, the strongest reducing agent present is $H_{2(g)}$ and the strongest oxidising agent present is $Fe^{3+}_{(aq)}$.

Therefore, the oxidation half-equation is $H_{2(g)} \rightarrow 2H^+_{(aq)} + 2e^-$ and the reduction half-equation is $Fe^{3+}_{(aq)} + e^- \rightarrow Fe^{2+}_{(aq)}$. This means that the platinum electrode in the standard hydrogen electrode is the anode and the platinum electrode in the $Fe^{2+}_{(aq)}/Fe^{3+}_{(aq)}$ half cell is the cathode.

The labelled diagram is shown below:



This is the fully labelled diagram.

It is important to note that the role of a galvanic cell is to convert chemical energy into usable electrical energy. Therefore, the current and the voltage of a galvanic cell are very important.

The voltage depends on how much energy is being released in the chemical reaction and can be determined according to the electrochemical series. The current depends on the rate of reaction, with a higher rate of reaction yielding a higher current because the transfer of electrons is occurring at a faster rate. Therefore, often galvanic cells are designed with really strong oxidising agents and reducing agents to maximise the voltage of the cell as well as redox reactions which occur very quickly to optimise the current.

Theory summary

- There are three different types of half cells depending on whether the oxidising/reducing agent is an aqueous ion, solid, gas or liquid.
- Constructing a galvanic cell requires two half cells to be joined together by a wire and a salt bridge.
- The anode, cathode and relevant oxidation and reduction equations can be determined by using the electrochemical series.

4D QUESTIONS

Theory review questions

Question 1

Which of the following represents standard conditions for a standard half cell?

A 1.0 M, 100 kPa and 298 K

B 1.0 M, 100 kPa and 273 K

C 1.0 M, 1 atm and 298 K

D 1.0 M, 1 atm and 273 K

Question 2

Which statement is incorrect?

A The strongest reducing agent will undergo oxidation at the anode.

B The strongest oxidising agent will undergo reduction at the cathode.

C In a standard half cell, the same reaction will always occur, no matter what other half cell it is attached to.

D All standard electrode potentials are measured with reference to the standard hydrogen electrode.

Exam-style questions

Within lesson

Question 3 (1 MARK)

What could be the suitable composition for the electrode in the $Fe^{2+}_{(aq)}/Fe^{3+}_{(aq)}$ standard half cell?

A $Fe_{(s)}$ **B** $Zn_{(s)}$ **C** $Pt_{(s)}$ **D** $Na_{(s)}$

Question 4 (1 MARK)

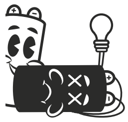
Which of the following represents the reduction half-equation that is occuring when the $Sn^{2+}_{(aq)}/Sn_{(s)}$ standard half cell is connected to the $Zn^{2+}_{(aq)}/Zn_{(s)}$standard half cell.

A $Sn^{2+}_{(aq)} + 2e^- \rightarrow Sn_{(s)}$

B $Sn_{(s)} \rightarrow Sn^{2+}_{(aq)} + 2e^-$

C $Zn_{(s)} \rightarrow Zn^{2+}_{(aq)} + 2e^-$

D $Zn^{2+}_{(aq)} + 2e^- \rightarrow Zn_{(s)}$



Question 5 (3 MARKS)

Emmanuel was creating a galvanic cell using platinum electrodes and a $KNO_{3(aq)}$ salt bridge in his laboratory when suddenly the air conditioner began to malfunction and the temperature of the room increased above 25 °C. The redox reaction that he thought would be occurring was $Fe_{(s)} + CuSO_{4\,(aq)} \rightarrow FeSO_{4\,(aq)} + Cu_{(s)}$ but in fact the opposite occurred even though he used standard concentrations and pressure.

a Suggest a reason for this inconsistency between the reaction predicted by the electrochemical series and his observations. (1 MARK)

b Over time, he noticed that the voltage was changing even though he had not disturbed the galvanic cell. Suggest a reason for this. (2 MARKS)

Question 6 (7 MARKS)

Mikayla wanted to make a galvanic cell. She reasoned that she could use an iron $Fe_{(s)}$ electrode for the $Sn^{4+}{}_{(aq)}/Sn^{2+}{}_{(aq)}$ half cell and use a zinc electrode for the $Zn^{2+}{}_{(aq)}/Zn_{(s)}$ standard half cell.

a Which of the half cells has been set up incorrectly? Why? (2 MARKS)

b How might the mistake be remedied? (1 MARK)

c Instead of the incorrectly constructed half cell, she decides to use a standard hydrogen electrode. Draw a diagram of the standard hydrogen electrode half cell, labelling all key features. (4 MARKS)

Question 7 (6 MARKS)

Construct a standard half cell for each of the following chemical species.

a $Cu^{2+}{}_{(aq)}/Cu_{(s)}$ (2 MARKS)

b $Fe^{2+}{}_{(aq)}/Fe^{3+}{}_{(aq)}$ (2 MARKS)

c $Cl_{2(g)}/Cl^{-}{}_{(aq)}$ (2 MARKS)

Question 8 (5 MARKS)

A common galvanic cell is the lithium-iodine battery. This battery produces a small current, a large voltage and is very reliable. Consequently, it is often used for medical devices such as pacemakers. No water is present in this cell and a metallic mesh allows for the flow of ions.

a Suggest a reason why there is no water present in this galvanic cell. (1 MARK)

b Why is lithium, which is a very strong reducing agent, a popular choice for this galvanic cell? (2 MARKS)

c Write out the complete redox equation that is occurring for this galvanic cell. (2 MARKS)

Multiple lessons

Question 9 (5 MARKS)

Dean wanted to create a galvanic cell by connecting the cadmium standard half cell to the lead standard half cell.

a Write the equation occurring at the anode. (1 MARK)

b Write the overall redox equation. (1 MARK)

c Draw a fully labelled diagram of the galvanic cell, labelling all key features including cathode, anode, voltage, direction of electron flow and direction of ion flow if a potassium nitrate salt bridge is used. (3 MARKS)

Question 10 (7 MARKS)

A VCE chemistry student, unsatisfied with the incomplete nature of VCAA's electrochemical series, wanted to find the relative oxidising and reducing agent strengths of more conjugate redox pairs. She was instructed by her teacher to set up the standard hydrogen electrode and then observe what happened when she connected 3 different standard half cells to the standard hydrogen electrode. She knows that the $Cr_2O_7{}^{2-}{}_{(aq)}$ ion turns a solution red and the $Cr^{3+}{}_{(aq)}$ ion turns a solution blue.
The following notes reveal her observations when each of the three half cells is connected to the standard hydrogen electrode under SLC:

Cell number	Conjugate redox pair	Observation
1	$Cr_2O_7{}^{2-}{}_{(aq)}/Cr^{3+}{}_{(aq)}$	Solution in the $Cr_2O_7{}^{2-}{}_{(aq)}/Cr^{3+}{}_{(aq)}$ half cell turns from red to blue
2	$Cr_{(s)}/Cr^{3+}{}_{(aq)}$	Chromium electrode appears corroded
3	$MnO_4{}^{-}{}_{(aq)}/Mn^{2+}{}_{(aq)}$	Solution turns from a lighter shade of red to yellow when methyl red universal indicator is placed in the standard hydrogen electrode half cell

a Outline what these observations indicate about the strengths of the oxidising and reducing agents found in cells 1, 2 and 3. (3 MARKS)

b Can the order of each of the three electrode potentials be determined based on the given data? (2 MARKS)

c Can the observations reveal any quantitative information about the standard electrode potentials? If not, explain how this could be done. (2 MARKS)

Question 11 (9 MARKS)

Samuel decided to replicate a historic galvanic cell called the Daniell cell which consists of a zinc standard half cell connected to a copper standard half cell, connected via a wire and salt bridge. Samuel also knows that the current is dependent on the rate of reaction.

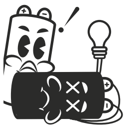
a Draw a fully labelled diagram of the galvanic cell, labelling all key features. (3 MARKS)

b What is the overall reaction occurring? (1 MARK)

c What is the purpose of the salt bridge in this galvanic cell? (1 MARK)

d Suggest two ways that Samuel could increase the current that this galvanic cell produces, excluding the use of a catalyst. (2 MARKS)

e How might these changes affect the predicted voltage of this galvanic cell according to the electrochemical series? (2 MARKS)



4E DIRECT AND INDIRECT REDOX REACTIONS

In this lesson, we will learn how energy transformations change depending on whether there is direct or indirect contact between reactants.

4A Redox reactions	4B Writing equations for redox reactions	4C Galvanic cells	4D Designing galvanic cells	4E Direct and indirect redox reactions	4F Fuel cells

Study design dot point

- the comparison of the energy transformations occurring in spontaneous exothermic redox reactions involving direct contact between reactants (transformation of chemical energy to heat energy) compared with those occurring when the reactants are separated in galvanic cells (transformation of chemical energy to electrical energy)

Key knowledge units

Direct and indirect redox reactions	3.1.12.1

Key terms and definitions of this lesson

- **Spontaneous reaction** reactions that occur in a set of conditions without being forced (without an external energy source)
- **Direct redox reaction** reactions where chemical species react in the same vessel
- **Indirect redox reaction** reactions where chemical species react together in separate vessels

Lesson links

This lesson builds on:

- 4B – Writing equations for redox reactions

Knowledge of redox reactions and the electrochemical series is able to predict the likelihood of a redox reaction occurring.

Direct and indirect redox reactions 3.1.12.1

OVERVIEW

The chemical reactions of reduction and oxidation can take place either directly in the same container or indirectly in separate half-cells.

THEORY DETAILS

Our understanding of the electrochemical series from lesson 4B can be used to predict the likelihood of a redox reaction occurring when certain chemical species are combined. When reactants are mixed directly in a single beaker, like if two chemicals were to react in nature, we say that the reaction is a **spontaneous reaction** as it has occurred in a situation without intervention such as providing an external energy source. In this case, a **direct redox reaction** has occurred as the reactants have reacted directly. This type of reaction generally results in the release of heat. An example of this is a bonfire, as only the reactants, oxygen and wood, are required for the reaction to occur. This particular reaction is exothermic, as energy in the form of heat is released into the surroundings.

Another example of a spontaneous direct redox reaction is the reaction of zinc in a copper sulfate solution.

$Zn_{(s)} \rightarrow Zn^{2+}{}_{(aq)} + 2e^-$

$Cu^{2+}{}_{(aq)} + 2e^- \rightarrow Cu_{(s)}$

From the above redox half-equations we can see that zinc undergoes oxidation, whilst copper undergoes reduction. The literature value for the enthalpy change of this reaction is $-217\,\text{kJ mol}^{-1}$ meaning that it releases heat during the reaction.

In 4B we also learnt that in galvanic cells, the oxidising agent (species on the left of the electrochemical series) must react with a reducing agent (species on the right of the electrochemical series), which is further down the electrochemical series than the oxidising agent. This is characteristic of all spontaneous redox reactions. We can use the electrochemical series to then predict the outcome of a spontaneous redox reaction and to determine whether a reaction will occur or not.

1 Worked example

Consider the following equations that appear in the electrochemical series.

$Ni^{2+}_{(aq)} + 2e^- \rightleftharpoons Ni_{(s)}$ $E^0 = -0.25\ V$

$Mg^{2+}_{(aq)} + 2e^- \rightleftharpoons Mg_{(s)}$ $E^0 = -2.37\ V$

Use the information given above to predict the effect of mixing $Mg^{2+}_{(aq)}$ and $Ni_{(s)}$.

What information is presented in the question?

The half-equations of $Mg^{2+}_{(aq)}$ and $Ni_{(s)}$ as given in the electrochemical series.

What is the question asking us to do?

Predict whether a reaction occurs or not.

What strategy(ies) do we need in order to answer the question?

Knowledge that an oxidising agent (chemical species on the left of the electrochemical series) reacts with a reducing agent (chemical species on the right of the electrochemical series) that is lower in the series.

Identify which species is the oxidising agent and which is the reducing agent.

Identify if the oxidising agent sits above or below the reducing agent in the electrochemical series.

Answer

$Mg^{2+}_{(aq)}$ is the oxidising agent (it sits on the left side of the reaction) and $Ni_{(s)}$ is the reducing agent (it sits on the right side of the reaction).

As $Mg^{2+}_{(aq)}$ is the oxidising agent and it sits below $Ni_{(s)}$ in the electrochemical series, no reaction will occur.

Alternatively, if a redox reaction occurs when the reactants are in two separate containers, like a galvanic cell, an **indirect redox reaction** occurs. This is because the two reactants are connected by a wire which facilitates the reaction, so the two reactants don't mix directly with each other. In this situation, energy is produced in the form of electrical energy, rather than the thermal energy that is produced in direct redox reactions, due to the transfer of electrons along the wire.

The key differences between direct and indirect redox reactions are summarised in table 1.

Table 1 Comparison between direct and indirect redox reactions.

Type of redox reaction	Contact between reactant	Energy conversion
Direct redox reaction	Reacting species are present in the same vessel	Chemical energy → Heat energy
Indirect redox reaction	Reacting species are kept separately in different vessels	Chemical energy → Electrical energy

Theory summary

- Direct redox reactions are spontaneous reactions where the reactants are mixed in the same reaction vessel.
- For a spontaneous reaction to occur, an oxidising agent must react with a reducing agent that is lower in the electrochemical series.
- Indirect redox reactions occur when the reactants are held in separate vessels.
- In direct redox reactions, chemical energy is transformed into heat energy, whilst in indirect redox reactions, chemical energy is transformed into electrical energy.

4E QUESTIONS

Theory review questions

Question 1

In a direct redox reaction

A the reactants can be kept in separate beakers depending on the reaction.

B the reactants are mixed in a single reaction vessel.

C reacting species lose and gain electrons in separate mediums.

D chemical energy is produced.

Question 2

In an indirect redox reaction

A reacting species are capable of losing and gaining electrons in the same vessel.

B reacting species must lose and gain electrons in the same medium.

C oxidation and reduction take place simultaneously in the same container.

D oxidation and reduction take place simultaneously in separate containers.

Question 3

A difference between direct and indirect redox reactions is

A chemical energy is transferred to heat energy in direct redox reactions, whereas it is transferred to electrical energy in indirect redox reactions.

B chemical energy is transferred to heat energy in indirect redox reactions, whereas it is transferred to electrical energy in direct redox reactions.

C chemical energy is transferred to potential energy in direct redox reaction, whereas it is transferred to electrical energy in indirect redox reactions.

D energy is transferred to chemical energy in indirect redox reactions, whereas it is transferred to heat energy in direct redox reactions.

Exam-style questions

Within lesson

Question 4 (2 MARKS)

Use the electrochemical series and the respective half-equations to predict whether a redox reaction will occur if chlorine gas is bubbled into water under standard conditions.

Question 5 (2 MARKS)

Use the electrochemical series and the respective half-equations to predict the effect of mixing $Br_{2(l)}$ and $Mg^{2+}{}_{(aq)}$.

Question 6 (5 MARKS)

Consider the following equations that appear in the order shown in the electrochemical series.

$Ni^{2+}{}_{(aq)} + 2e^- \rightleftharpoons Ni_{(s)}$ $E^0 = -0.23$ V

$Mg^{2+}{}_{(aq)} + 2e^- \rightleftharpoons Mg_{(s)}$ $E^0 = -2.37$ V

a Explain why if $Ni^{2+}{}_{(aq)}$ is mixed with $Mg_{(s)}$ in a beaker, a redox reaction will occur. (2 MARKS)

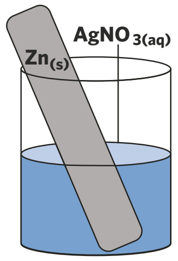
b Write the overall redox reaction that occurs. (1 MARK)

c Is this considered a direct or indirect redox reaction? Suggest why. (2 MARKS)

Multiple lessons

Question 7 (4 MARKS)

In the given experiment, a piece of solid zinc is dropped into a beaker containing silver nitrate solution.



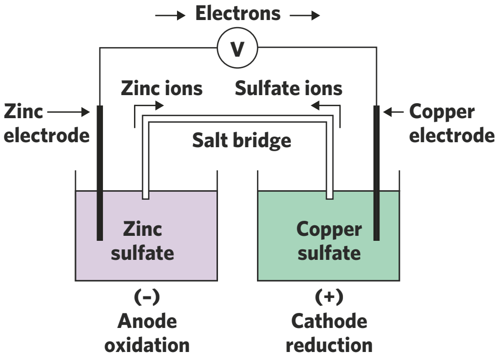
a Write the oxidation and reduction half-equations of this reaction. (2 MARKS)

b Write the overall reaction. (1 MARK)

c Describe the energy change that takes place in this reaction. (1 MARK)

Question 8 (5 MARKS)

A student set up a simple galvanic cell with copper and zinc electrodes as shown.



a Write the two redox half-reactions. (2 MARKS)

b Identify the oxidising agent and the reducing agent. (1 MARK)

c Is this reaction an example of a direct or indirect redox reaction? Support your answer. (2 MARKS)

Question 9 (5 MARKS)

The following are the half-equations of $Pb^{2+}_{(aq)}$, $Al_{(s)}$ and $Cu_{(s)}$, in the order that they appear in the electrochemical series.

$Cu^{2+}_{(aq)} + 2e^- \rightleftharpoons Cu_{(s)}$ $E^0 = +0.34$ V

$Pb^{2+}_{(aq)} + 2e^- \rightleftharpoons Pb_{(s)}$ $E^0 = -0.13$ V

$Al^{3+}_{(aq)} + 3e^- \rightleftharpoons Al_{(s)}$ $E^0 = -1.66$ V

a Predict whether $Pb^{2+}_{(aq)}$ will oxidise $Al_{(s)}$or $Cu_{(s)}$ spontaneously under standard laboratory conditions. Give reasons for your answer. (3 MARKS)

b Write the balanced overall redox reaction for the reaction identified in a. that occurs spontaneously. (1 MARK)

c Calculate the cell potential for the above reaction. (1 MARK)

4F FUEL CELLS

In this lesson, we will cover the structure and function of fuel cells, and compare their ability to generate electricity with combustion reactions and galvanic cells.

4A Redox reactions	4B Writing equations for redox reactions	4C Galvanic cells	4D Designing galvanic cells	4E Direct and indirect redox reactions	4F Fuel cells

Study design dot points

- the common design features of fuel cells including use of porous electrodes for gaseous reactants to increase cell efficiency (details of specific cells not required)
- the comparison of the use of fuel cells and combustion of fuels to supply energy with reference to their energy efficiencies (qualitative), safety, fuel supply (including the storage of hydrogen), production of greenhouse gases and applications
- the comparison of fuel cells and galvanic cells with reference to their definitions, functions, design features, energy transformations, energy efficiencies (qualitative) and applications

Key knowledge units

Structure of fuel cells	3.1.14.1
Function of fuel cells	3.1.14.2
Comparison of fuel cells and combustion of fuels	3.1.15.1
Comparison of fuel cells and galvanic cells	3.1.16.1

Key terms and definitions

- **Fuel cell** electrochemical cell that continuously converts chemical energy into electrical energy by a redox reaction
- **Porous electrode** material with many holes (pores) which is used in a fuel cell to maximise the ability for gaseous reactants to come into contact with the electrolyte

Lesson links

This lesson builds on:

▶ 3A – Combustion reactions

We will compare combustion reactions and fuel cells in terms of energy transformations, efficiency, safety and environmental impact.

▶ 4C – Galvanic cells

We will compare galvanic cells and fuel cells in terms of energy transformations, efficiency, function and applications.

Structure of fuel cells 3.1.14.1

OVERVIEW

Fuel cells are a type of galvanic cell consisting of an anode, a cathode and an electrolyte.

THEORY DETAILS

A fuel cell is a type of galvanic cell that converts chemical energy from a fuel to electrical energy. However, fuel cells differ from the galvanic cells that we have studied in 4C. In a fuel cell, a fuel is continuously pumped in and electricity continuously generated. However, in a galvanic cell, a fixed quantity of fuel is used to generate a finite quantity of electricity.

Figure 1 shows a typical example of a fuel cell, using hydrogen as an energy source.

In this set-up, hydrogen gas is used as a fuel and pumped in, with oxygen required as well. This fuel cell has two redox reactions occurring simultaneously, as shown in figure 2.

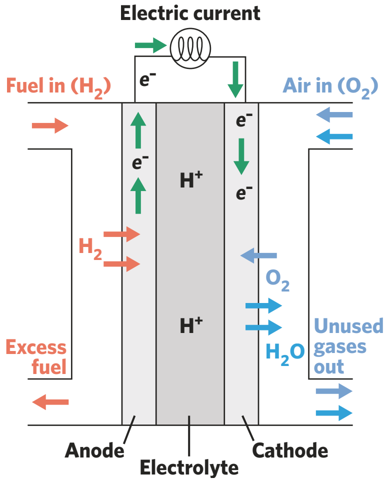


Figure 1 A hydrogen fuel cell under acidic conditions

Oxidation

$H_{2(g)} \rightarrow 2H^+_{(aq)} + 2e^-$

and

Reduction

$O_{2(g)} + 4H^+_{(aq)} + 4e^- \rightarrow 2H_2O_{(g)}$

Figure 2 The redox reactions occurring in a hydrogen fuel cell

The electrons from the oxidation of hydrogen gas travel towards the oxygen electrode. Here, the electrons are used to reduce oxygen. As the reaction of hydrogen gas is an oxidation reaction, we label the electrode where this takes place the anode. Similarly, as the reaction of oxygen is a reduction reaction, we label this electrode the cathode.

Tip if oxygen is being used, it will always react at the cathode and the fuel will react at the anode.

The electrolyte is situated between the two electrodes and is a very important part of the fuel cell. It can be acidic (source of $H^+_{(aq)}$ ions), basic (source of $OH^-_{(aq)}$ ions) as well as some more unusual versions which involve other ions such as the molten carbonate ion ($CO_3{}^{2-}{}_{(l)}$) and the oxide ion ($O^{2-}{}_{(s)}$).

NOTE: The reactions involving a complex electrolyte (i.e. an electrolyte that is not a source of $H^+_{(aq)}$ ions or $OH^-_{(aq)}$ ions) are not required knowledge as the necessary information will be supplied to you in the question.

Function of fuel cells 3.1.14.2

OVERVIEW

Fuel cells are electrochemical cells that can be used to convert chemical energy into electrical energy continuously given a constant supply of fuel.

THEORY DETAILS

The two main distinguishing components of a fuel cell which govern its function are the electrolyte and the electrodes.

Electrolyte

The electrolyte, shown between the two electrodes in figure 1, plays a crucial role in the function of the fuel cell. It only allows the movement of charged ions in order for a redox reaction to occur. It is also essential that the reactant species have access to the electrolyte as it is a crucial source of ions which are needed in order for the reaction to proceed.

If the reaction is under acidic conditions, H^+ ions need to be transferred through the electrolyte (as shown in figure 1). If the reaction is under alkaline conditions, OH^- ions need to be transferred through the electrolyte.

Electrodes

Electrodes also play an important role in the function of a fuel cell.

The electrode provides a surface for the oxidation/reduction reaction to occur. Many fuel cells make use of **porous electrodes**. These electrodes are composed of a material with many holes, or pores, that allow a greater surface area for reactions to take place. A greater surface area means the reaction can occur at a faster rate than if a solid electrode such as graphite were used. The electrode may also contain a catalyst that aids in maximising the speed of the reaction. Another function of the pores is allow the reacting gases to access the electrolyte. This enables the reaction to proceed.

Comparison of fuel cells and combustion of fuels 3.1.15.1

OVERVIEW

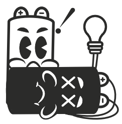
Fuel cells and combustion reactions both make use of fuels to produce usable energy. However, they differ in their efficiency, cost and impact on the environment.

THEORY DETAILS

Recall from 3A that a combustion reaction involves the burning of a fuel in the presence of excess oxygen to produce carbon dioxide and water.

Combustion of fuels and fuel cells differ in their efficiency. Coal-fired power stations make use of the combustion of coal to produce electrical energy. This process involves many intermediate steps as chemical energy is converted to thermal energy, then to mechanical energy and finally into electrical energy, with energy lost at each step resulting in an overall energy efficiency of around 30%. A fuel cell however converts the chemical energy from a fuel directly into electrical energy. Since there are fewer steps than a combustion reaction to produce electricity, fuel cells lose less energy, and are more efficient with an energy efficiency of around 60%.

Fuel cells are also generally more expensive to operate than traditional combustion-based set-ups. This is because porous electrodes are expensive to produce, a fuel cell has to run at very high temperatures and pure hydrogen fuel is also difficult to obtain. Hydrogen is also very expensive to store due to its highly flammable nature and the need for it to be carefully monitored for leaks.



Additionally, combustion of fuels and fuel cells can have different impacts on the environment. For fuel cells, the impact varies depending on the fuel used. A hydrogen fuel cell produces only water as a product, and so has a much smaller impact on the environment compared to a combustion reaction of a fossil fuel, which may release greenhouse gases such as CO_2, CO, and NO_2.

Table 1 Comparison of fuel cells and combustion reactions

Fuel cell (redox reaction)	**Combustion reaction**
Higher efficiency	Lower efficiency
More expensive	Cheaper
Pollutants depend on fuel used	Pollutants can include CO_2, CO, NO_2
One energy transformation (chemical → electrical)	Many energy transformations
Quieter	Noisier

Comparison of fuel cells and galvanic cells 3.1.16.1

OVERVIEW

Fuel cells and galvanic cells both make use of fuels to produce usable energy, however differ in their function, design, energy transformations and efficiency.

THEORY DETAILS

Fuel cells and galvanic cells both convert chemical energy to electrical energy by the use of redox reactions, however do so in different ways.

Structurally, a fuel cell and galvanic cell are similar, as seen in figure 3.

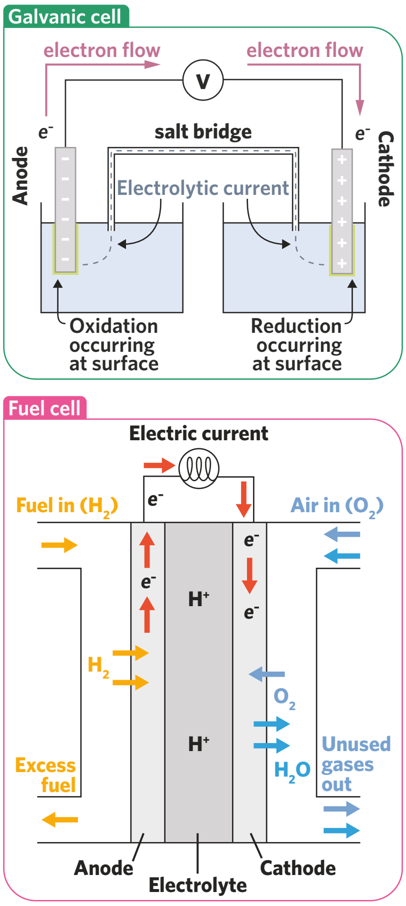


Figure 3 Structural comparison of fuel cells and galvanic cells

However, a fuel cell contains porous electrodes often containing catalysts, opposed to the non-porous electrode of a galvanic cell that does not contain catalysts. Additionally, electrodes in a fuel cell are separated within the same vessel whereas electrodes in galvanic cells are in separate vessels.

In terms of reactants, a fuel cell requires a continuous supply of reactants which are pumped into the cell, whereas a galvanic cell contains all the reactants required for the reaction within each half-cell. This also means a galvanic cell can only generate a finite amount of electrical energy. This is a useful property of fuel cells, as operation does not cease, allowing a continuous energy supply. In terms of products, fuel cells are continuously releasing products, whereas a galvanic cell will store its products.

Table 2 summarises the similarities and differences between fuel cells and galvanic cells.

Table 2 Comparison of fuel cells and galvanic cells

Fuel cell	**Galvanic cell**
Chemical energy → electrical energy	Chemical energy → electrical energy
Porous electrodes	Electrodes are inert, or contain reactants/products
Requires ongoing supply of reactants (open system)	Contains reactants and products (closed system)
Normally uses fuels such as methane or hydrogen gas	Normally uses solid or aqueous ion chemical species as reactants
Normally used in submarines and some transport vehicles	Normally used as batteries for portable devices
Usually operate at very high temperatures	Operate at lower temperatures
Half cells separated within the same vessel	Half cells in separate vessels

NOTE: fuel cells are a type of galvanic cell.

Theory summary

- Fuel cells:
  - convert chemical energy to electrical energy via a redox reaction.
  - require a continuous supply of reactants.
  - use porous electrodes.
  - are much more efficient compared to combustion reactions.
  - are a type of galvanic cell.

4F QUESTIONS

Theory review questions

Question 1

Fill in the blanks in the description on fuel cells below.

Fuel cells convert __________ energy to electrical energy by two simultaneous reactions, an __________ reaction and a __________ reaction.

Question 2

Fuel cells

A facilitate redox reactions.

B are rechargeable.

C primarily convert chemical energy to thermal energy

D are cheaper than galvanic cells.

Question 3

Which of the following statements is true in a fuel cell?

I The anode is always positive.

II Reduction reactions occur at the cathode.

III Electrons travel across the electrolyte.

A I only

B II only

C I and II only

D I, II and III

Exam-style questions

Within lesson

Question 4 (1 MARK)

Which of the following statements is most correct?

A All fuel cells are electrolytic cells.

B All galvanic cells are fuel cells.

C The electrodes of a fuel cell are always separated.

D The required reactants for a fuel cell are stored within the cell.

Question 5 (1 MARK)

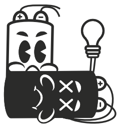
Fuel cells

A are more efficient than combustion reactions.

B are less expensive than combustion reaction systems.

C always produce less pollutants than combustion reactions.

D have more energy transformations than combustion reactions.



Question 6 (9 MARKS)

An environmental engineer is researching new options for energy production, and decides to investigate the use of a fuel cell to power a factory. This fuel cell uses hydrogen gas and oxygen to produce steam and electricity under acidic conditions.

a Write the equation for the reaction occurring in the fuel cell. (1 MARK)
b Name the type of reaction occurring. (1 MARK)
c Draw a diagram of the fuel cell, labelling the reactants, products, flow of electrons and electrolyte. (4 MARKS)
d What is the purpose of the electrolyte? (1 MARK)
e Write a balanced half equation for the reaction occurring at the anode. (1 MARK)
f Would you expect the cathode of the fuel cell to be positive or negative? (1 MARK)

Question 7 (6 MARKS)

A commercial vehicle company is looking to upgrade their newest models by switching from petrol-fuelled cars to those powered by fuel cells. The proposed model would incorporate a tank of hydrogen gas stored within the car to provide a continual source of fuel to the cell, which would provide electricity for the motor.

a Name the type of reaction occurring in the original petrol-fuelled models. (1 MARK)
b Explain the difference in efficiency between the original and new model, referring to energy transformations in your answer. (2 MARKS)
c Identify an issue with the storage of hydrogen gas. (1 MARK)
d Compare the original and new models in terms of the impact of their products on the environment. (2 MARKS)

Question 8 (4 MARKS)

Justine is tasked with constructing a report outlining the differences between galvanic cells and fuel cells for her company, which is interested in optimising their current method of energy production. Fill in the relevant sections of her report plan below.

Comparison of galvanic cells and fuel cells

a Fuel cells are __________ expensive than galvanic cells because __________. (2 MARKS)
b The products of the reaction build up in a __________ cell. (1 MARK)
c A __________ cell requires porous electrodes. (1 MARK)

Question 9 (4 MARKS)

Consider a hydrogen/oxygen fuel cell under alkaline conditions.

a Write the half-equation for the reaction occurring at the cathode and circle the species that is transferred through the electrolyte. (2 MARKS)
b In which direction do electrons travel in a fuel cell? (1 MARK)
c Calculate the voltage that the fuel cell outputs. (1 MARK)

Multiple lessons

Question 10 (10 MARKS)

Natural gas fuel cells are a particularly useful type of cell that can make use of methane as a fuel source to produce energy. This cell operates at high temperatures and uses porous electrodes, under acidic conditions to convert methane and oxygen into water and carbon dioxide.

a What energy transformation is occurring within the cell? (1 MARK)
b Construct a balanced equation for the overall reaction occurring within the fuel cell. (1 MARK)
c Write the half-equation for the reaction occurring at the anode, and identify the polarity of this electrode. (2 MARKS)
d Write the half-equation for the reaction occurring at the cathode. (1 MARK)
e Identify the reducing agent in this reaction. (1 MARK)
f List one advantage and one disadvantage of the use of porous electrodes. (2 MARKS)
g Would this process be considered renewable? Justify your answer. (2 MARKS)

Question 11 (10 MARKS)

A company is interested in creating a new power generator that is reliable and efficient. They decided to use a ceramic oxide fuel cell which uses methane from natural gas as a fuel source and a solid ceramic electrolyte which allows oxide ions to move through it.

The overall reaction occurring in the fuel cell is: $CH_{4(g)} + 2O_{2(g)} \rightarrow CO_{2(g)} + 2H_2O_{(g)}$

The reaction at the cathode is: $O_{2(g)} + 4e^- \rightarrow 2O^{2-}{}_{(s)}$

a Deduce from the overall equation and the half-equation at the cathode, the reaction occurring at the anode. (1 MARK)

b Draw a diagram of this fuel cell, labelling the anode, cathode, electrolyte, reactants entering the cell and the products leaving. (4 MARKS)

c Since this fuel cell operates at high temperatures, water vapour is produced. Suggest a possible use for this steam. (1 MARK)

d A contractor for the company says that this method of generating electricity from methane is less efficient than combusting methane in a normal combustion power station. Comment on the accuracy of this statement with respect to energy transformations. (3 MARKS)

e Suggest how methane could be sourced in a renewable manner. (1 MARK)

EXPERIMENT

CONSTRUCTION OF A GALVANIC CELL

Through the principles of redox reactions, galvanic cells are able to convert chemical energy to electrical energy. The voltage that can be produced from these electrochemical cells depends on the reactants used to construct the cell.

Materials

(per group)

- 100 mL 0.50 M $CuSO_4$
- 100 mL 0.50 M $ZnSO_4$
- Cu and Zn metal strip
- 2 × alligator clips
- Paper towel
- Voltmeter
- 2 × 250 mL beakers
- 1.0 M KCl solution

Method

1. Label both beakers 'beaker A & B'.
2. In beaker A, add 100 mL of a 0.50 M $CuSO_4$ solution.
3. In beaker A, place a strip of Cu metal, making sure that it comes into contact with the $CuSO_4$ solution.
4. In beaker B, add 100 mL of 0.50 M of $ZnSO_4$ solution.
5. In beaker B, place a strip of Zn metal, making sure that it comes into contact with the $ZnSO_4$ solution.
6. Connect an alligator clip to the strip of Cu and connect it to the negative (black) terminal of the voltmeter.
7. Connect an alligator clip to the strip of Zn and connect it to the positive (red) terminal of the voltmeter.
8. Soak a small sample of paper towel in KCl solution. Slightly twist the paper towel sample to remove some of the solution and place one end of the sample into beaker A and the other end into beaker B. Make sure that both ends are submerged into the corresponding solutions.

QUESTIONS

Question 1 (1 MARK)

Write a balanced equation to show the reaction occurring at the anode and cathode.

Question 2 (1 MARK)

Describe the purpose of the KCl solution.

Question 3 (1 MARK)

Identify the dependent variable in this experiment.

Question 4 (1 MARK)

It has been identified that copper ions exhibit a light blue colour. Describe the qualitative changes that would occur during the operation of the galvanic cell.

ANSWERS

1 Anode: $Zn_{(s)} \rightarrow Zn^{2+}_{(aq)} + 2e^-$

Cathode: $Cu^{2+}_{(aq)} + 2e^- \rightarrow Cu_{(s)}$

2 [The purpose of the KCl solution is to act as a salt bridge,[1]][and thus provides charged ions to the two half cells to maintain electrical neutrality within the whole galvanic cell.[2]]

✓ ✗ I have identified the purpose of KCl.[1]

✓ ✗ I have described how KCl functions with respect to electrical neutrality.[2]

3 Dependent variable – the voltage produced

4 [As copper ions are being reduced to produce copper solid, the solution in the copper half cell would get lighter as the reaction proceeds.[1]] [Also, it would be observed that a layer of solid material is developed on the Cu electrode during the course of the reaction.[2]]

✓ ✗ I have described the colour change in the solution of the copper half cell.[1]

✓ ✗ I have identified the change occurring on the copper electrode.[2]

CHAPTER 4 QUESTIONS

MULTIPLE CHOICE (10 MARKS)

Question 1 (1 MARK)

Which of the following is a redox reaction?

A $2HI_{(aq)} + H_2SO_{4(aq)} \rightarrow I_{2(s)} + SO_{2(g)} + 2H_2O_{(l)}$

B $H_2SO_{4(aq)} + Ba(OH)_{2(aq)} \rightarrow BaSO_{4(s)} + 2H_2O_{(l)}$

C $H_2SO_{4(aq)} + CaO_{(s)} \rightarrow CaSO_{4(s)} + H_2O_{(l)}$

D $H_2SO_{4(aq)} + Na_2CO_{3(aq)} \rightarrow Na_2SO_{4(aq)} + CO_{2(g)} + H_2O_{(l)}$

Question 2 (1 MARK)

Some pieces of tin (Sn), cobalt (Co), iron (Fe) and copper (Cu) are placed in four separate beakers. Each beaker contains 1.5 M lead (II) sulfate $PbSO_4$ dissolved in water.

What will occur over time?

A A reaction will occur only in the beaker containing Fe.

B A reaction will occur only in the beaker containing Co and Sn.

C A reaction will occur only in the beaker containing Cu.

D A reaction will occur only in the beaker containing Sn, Co and Fe.

Question 3 (1 MARK)

A strip of aluminium (Al) is placed into a solution of $CuSO_4$ which is blue due to the presence of copper ions. What would you expect to occur over time?

A Nothing will occur because redox reactions cannot occur between Al and Cu.

B The solution will lose its blue colour.

C The Al metal will look corroded.

D Both B and C are correct.

Question 4 (1 MARK)

The reaction between HNO_2 and the ion $Cr_2O_7^{2-}$ in an aqueous solution is presented by the reaction below.

$Cr_2O_7{}^{2-}{}_{(aq)} + 3HNO_{2(aq)} + 5H^+{}_{(aq)} \rightarrow 2Cr^{3+}{}_{(aq)} + 3NO_3{}^-{}_{(aq)} + 4H_2O_{(l)}$

Which of the following is the correct half-equation for the oxidation reaction?

A $HNO_{2(aq)} + H_2O_{(l)} \rightarrow 5H^+{}_{(aq)} + NO_3{}^-{}_{(aq)} + 3e^-$

B $HNO_{2(aq)} + H_2O_{(l)} \rightarrow 3H^+{}_{(aq)} + NO^-{}_{3(aq)} + 2e^-$

C $Cr_2O_7{}^{2-}{}_{(aq)} + 6e^- + 14H^+{}_{(aq)} \rightarrow 2Cr^{3+}{}_{(aq)} + 7H_2O_{(l)}$

D $Cr_2O_7{}^{2-}{}_{(aq)} + 6e^- + 14H^+{}_{(aq)} \rightarrow 2Cr^{3+}{}_{(aq)} + 6H_2O_{(l)}$

Question 5 (1 MARK)

An unbalanced overall redox reaction is shown below.

$Fe^{2+}{}_{(aq)} + MnO_4{}^-{}_{(aq)} + H^+{}_{(aq)} \rightarrow Mn^{2+}{}_{(aq)} + Fe^{3+}{}_{(aq)} + H_2O_{(l)}$

What is the coefficient of $Fe^{3+}{}_{(aq)}$ when the given equation is completely balanced?

A 4

B 6

C 5

D 2

Question 6 (1 MARK)

Consider the following beakers under standard conditions.

Beaker I: A strip of gold is placed into a 1.0 M hydrochloric acid solution.

Beaker II: A strip of Zn is placed into a 1.0 M copper (II) sulfate solution.

Beaker III: Bromine gas is bubbled through a 1.0 M sodium nitrate solution.

Beaker IV: A piece of cadmium oxide is placed into a 1.0 M zinc sulfate solution.

In which beaker will a reaction occur?

A I, II and III

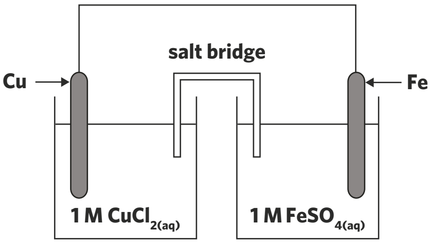
B I and II only

C II only

D All beakers

Question 7 (1 MARK)

A galvanic cell set up is shown in the diagram.



Which statement is incorrect regarding the given galvanic cell?

A The cell potential is 0.78 V.

B Over time, the iron electrode will increase in mass.

C The iron electrode is the anode.

D The copper electrode is the cathode.

Question 8 (1 MARK)

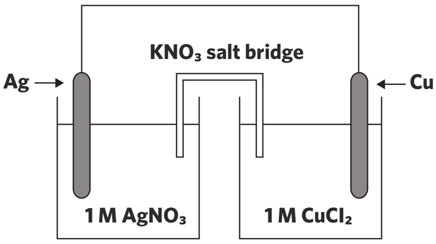
Place the following galvanic cells into the order of increasing cell potential.

Cell 1	Ni electrode with $NiSO_4$	Zn electrode with $ZnCl_2$
Cell 2	Pb electrode with $Pb(NO_3)_2$	Fe electrode with $FeSO_4$
Cell 3	Ag electrode with $AgNO_3$	Cu electrode with $CuSO_4$

A Cell 1, cell 3, cell 2 **B** Cell 3, cell 1, cell 2 **C** Cell 3, cell 2, cell 1 **D** Cell 2, cell 3, cell 1

Question 9 (1 MARK)

The set up of a galvanic cell is shown.

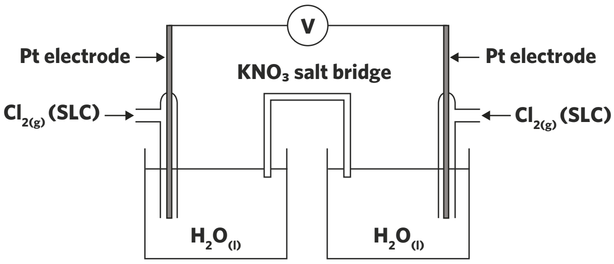


Which of the following best describes the direction of electron flow in the external wire and the direction of migration of the ions from the salt bridge?

	Direction of electron flow	Migration of the ions from the salt bridge
A	Towards the Ag electrode	K^+ will migrate to the Cu^{2+}/Cu half-cell
B	Towards the Cu electrode	K^+ will migrate to the Cu^{2+}/Cu half-cell
C	Towards the Ag electrode	K^+ will migrate to the Ag^+/Ag half-cell
D	Towards the Cu electrode	K^+ will migrate to the Ag^+/Ag half-cell

Question 10 (1 MARK)

A group of Chemistry students constructed the galvanic cell shown.



A student predicted that no reaction would occur because Cl_2 is in both half-cells.

Is the student's prediction correct or incorrect?

A Correct, because the reaction rate was too slow.

B Incorrect, because Cl_2 gas reduced water.

C Incorrect, because Cl_2 gas oxidised water.

D Correct, because the students did not construct the galvanic cell correctly.

SHORT ANSWER (35 MARKS)

Question 11 (6 MARKS)

Consider the following reactions between Ge^{2+} and various reagents carried out under standard conditions:

$Ge^{2+}{}_{(aq)} + Zn^{2+}{}_{(aq)} \rightarrow$ no observed reaction

$Ge^{2+}{}_{(aq)} + Pb_{(s)} \rightarrow Ge_{(s)} + Pb^{2+}{}_{(aq)}$

$Ge^{2+}{}_{(aq)} + Cu_{(s)} \rightarrow$ no observed reaction

$Ge^{2+}{}_{(aq)} + Sn^{2+}{}_{(aq)} \rightarrow Ge_{(s)} + Sn^{4+}{}_{(aq)}$

A Chemistry student concluded that the reaction $Ge^{2+}{}_{(aq)} + 2e^- \rightarrow Ge_{(s)}$ would have an electrode potential between +0.40 V and –0.73 V under standard conditions.

a Is the student's conclusion correct? Justify your answer. (3 MARKS)

b State the correct range of electrode potential values for the reaction $Ge^{2+}{}_{(aq)} + 2e^- \rightarrow Ge_{(s)}$. Justify your answer. (3 MARKS)

Question 12 (11 MARKS)

A student is given the following half-equations. The student also knows that the three standard electrode potential values are +0.30 V, +0.50 V and –2.9 V but does not know to which half-equation each value belongs.

Half-equations

$CaSO_{4(aq)} + 2e^- \rightleftharpoons Ca_{(s)} + SO_4^{2-}{}_{(aq)}$

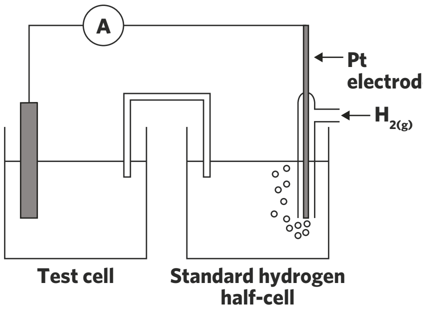
$CuCl_{2(aq)} + 2e^- \rightleftharpoons Cu_{(s)} + 2Cl^-{}_{(aq)}$

$AgNO_{3(aq)} + e^- \rightleftharpoons Ag_{(s)} + NO_3^-{}_{(aq)}$

To identify the cell potential values of each equation, the student constructs standard half-cells for each of the given half-equations and connects these half-cells one at a time to a standard hydrogen half-cell as shown in the diagram.

The student noted the following observations over several minutes.

Half-equations	Experimental notes
$CaSO_{4(aq)} + 2e^- \rightleftharpoons Ca_{(s)} + SO_4^{2-}{}_{(aq)}$	The pH of the solution in the standard hydrogen half-cell increased
$CuCl_{2(aq)} + 2e^- \rightleftharpoons Cu_{(s)} + 2Cl^-{}_{(aq)}$	Electron flow passed from the standard hydrogen half-cell to the half-cell containing the copper electrode
$AgNO_{3(aq)} + e^- \rightleftharpoons Ag_{(s)} + NO_3^-{}_{(aq)}$	The mass of the silver electrode increased



Adapted from VCAA 2012 Exam MCQ6

a Provide an explanation for each of the following observations:

i The pH of the solution in the standard hydrogen half-cell connected with the Ca/Ca^{2+} half-cell increased. (2 MARKS) ii Electron flow passed from the standard hydrogen half-cell to the half-cell containing the copper electrode. (2 MARKS)

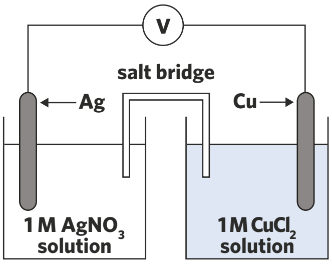
 iii The mass of the silver electrode increased. (2 MARK)

b The experimental notes can only be used to determine the cell potential value of one half-cell. Identify this half-equation and its cell potential value. Justify your answer. (2 MARKS)

c Explain why the cell potential values of the other two equations cannot be determined. (3 MARKS)

Question 13 (10 MARKS)

The diagram of a galvanic cell is shown.



a Determine the anode and the cathode of the galvanic cell. (2 MARKS)

b Write the balanced half-equations occurring at the

 i anode and identify the type of redox reaction. (2 MARKS)

 ii cathode and identify the type of redox reaction. (2 MARKS)

c Write the balanced overall redox reaction occurring in the galvanic cell. (1 MARK)

d A Chemistry student Mia shows her calculation of the cell potential as below:

$V_{cell} = 2 \times 0.8 - 0.34 = 1.26$ V

She explains that 0.8 was multiplied by 2 because she multiplied half-equations by 2 to obtain the balanced overall redox reaction. Is Mia's calculation of the cell potential correct? Justify your answer. (3 MARKS)

KEY SCIENCE SKILLS QUESTION

Question 14 (9 MARKS)

Sulfur dioxide has been widely used as a preservative in the food industry. A food brand has claimed that their peanuts contain 1.3% of sulfur dioxide per 10.00 g. Giao and Jasmine used gravimetric analysis to test the sulfur dioxide content in the brand's dried peanuts. During this experiment, a redox reaction occurred.

Procedure:

- A sample of the dried peanuts weighing 60.00 g was put into a conical flask containing 150 mL of de-ionised water.
- A 3% solution of hydrogen peroxide was added to convert the dissolved sulfur dioxide to sulfate ions.
- An excess of calcium chloride was then added. The calcium sulfate precipitate was filtered off, dried and weighed.

The students recorded the following results:

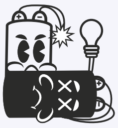
Mass of dry filter paper	0.735 g
Mass of dry filter paper and $CaSO_4$	1.500 g

a Write a balanced reaction to convert sulfur dioxide into sulfate ions when the peanuts were placed into water containing protons. Identify the type of this reaction. (2 MARKS)

b What is the role of hydrogen peroxide in this procedure? (1 MARK)

c Calculate the percentage, by mass, of sulfur dioxide in the peanut sample. (4 MARKS)

d Giao and Jasmine noticed that the percentage of sulfur dioxide they determined was lower than the percentage the company has claimed. Explain why this is the case and describe what they could have done to get a higher percentage of sulfur dioxide. (2 MARKS)



UNIT 3

AOS2

How can the yield of a chemical product be optimised?

In this area of study students explore the factors that increase the efficiency and percentage yield of a chemical manufacturing process while reducing the energy demand and associated costs.

Students investigate how the rate of a reaction can be controlled so that it occurs at the optimum rate while avoiding unwanted side reactions and by-products. They explain reactions with reference to the collision theory including reference to Maxwell-Boltzmann distribution curves. The progression of exothermic and endothermic reactions, including the use of a catalyst, is represented using energy profile diagrams.

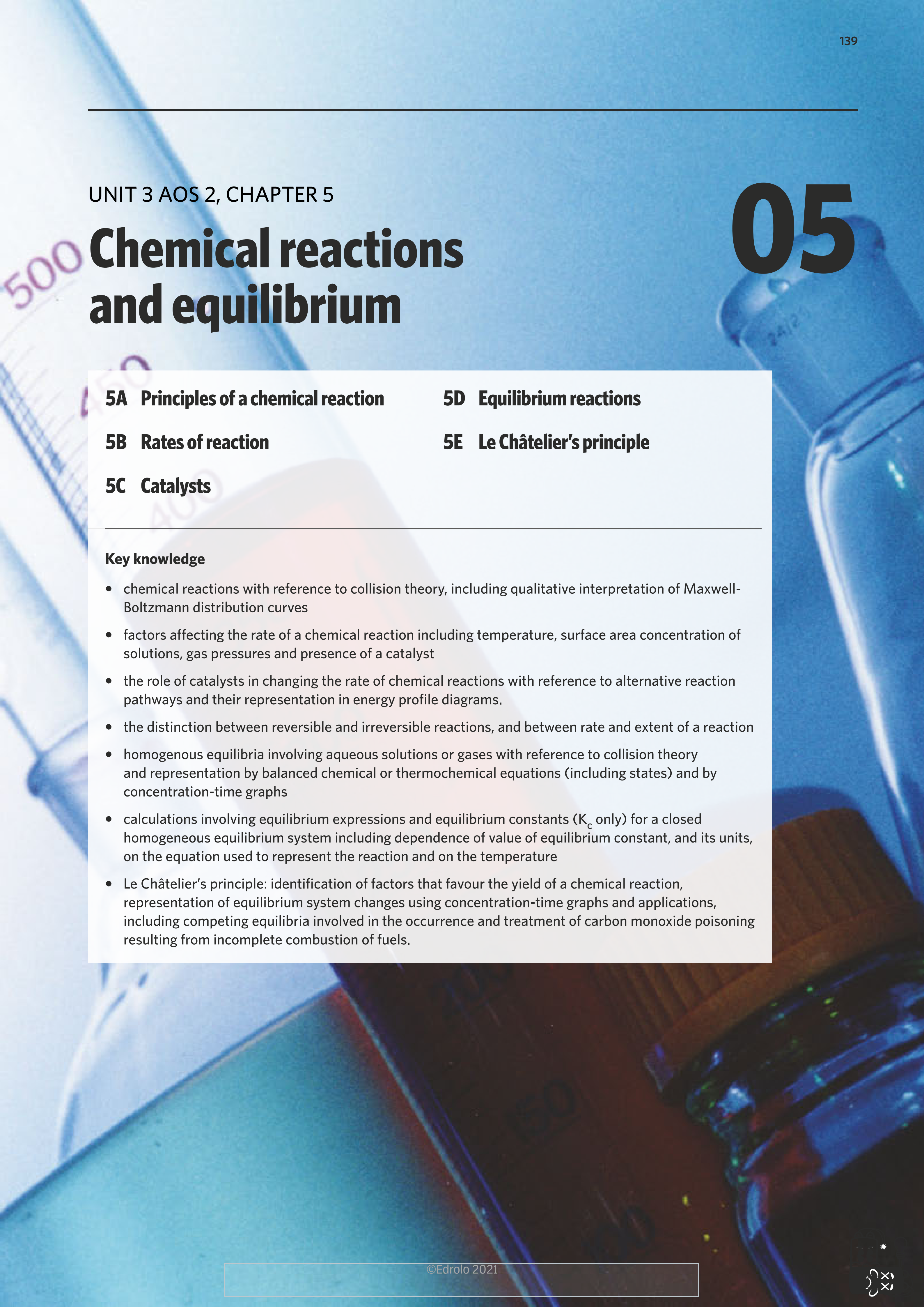
Students explore homogeneous equilibrium systems and apply the equilibrium law to calculate equilibrium constants and concentrations of reactants and products. They investigate Le Châtelier's principle and the effect of different changes on an equilibrium system and make predictions about the optimum conditions for the production of chemicals, taking into account rate and yield considerations.

Students represent the establishment of equilibrium and the effect of changes to an equilibrium system using concentration-time graphs.

Students investigate a range of electrolytic cells with reference to their basic design features and purpose, their operating principles and the energy transformations that occur. They examine the discharging and recharging processes in rechargeable cells, and apply Faraday's laws to calculate quantities in electrochemistry and to determine cell efficiencies.

Outcome 2

On completion of this unit the student should be able to apply rate and equilibrium principles to predict how the rate and extent of reactions can be optimised, and explain how electrolysis is involved in the production of chemicals and in the recharging of batteries.



UNIT 3 AOS 2, CHAPTER 5

05

Chemical reactions and equilibrium

Key knowledge

- chemical reactions with reference to collision theory, including qualitative interpretation of Maxwell-Boltzmann distribution curves
- factors affecting the rate of a chemical reaction including temperature, surface area concentration of solutions, gas pressures and presence of a catalyst
- the role of catalysts in changing the rate of chemical reactions with reference to alternative reaction pathways and their representation in energy profile diagrams.
- the distinction between reversible and irreversible reactions, and between rate and extent of a reaction
- homogenous equilibria involving aqueous solutions or gases with reference to collision theory and representation by balanced chemical or thermochemical equations (including states) and by concentration-time graphs
- calculations involving equilibrium expressions and equilibrium constants (K_c only) for a closed homogeneous equilibrium system including dependence of value of equilibrium constant, and its units, on the equation used to represent the reaction and on the temperature
- Le Châtelier's principle: identification of factors that favour the yield of a chemical reaction, representation of equilibrium system changes using concentration-time graphs and applications, including competing equilibria involved in the occurrence and treatment of carbon monoxide poisoning resulting from incomplete combustion of fuels.

5A PRINCIPLES OF A CHEMICAL REACTION

In this lesson we will learn about the underlying mechanisms of a chemical reaction as well as how to interpret a graph depicting the kinetic energy of particles in a reaction.

5A Principles of a chemical reaction	5B Rates of reaction	5C Catalysts	5D Equilibrium reactions	5E Le Châtelier's principle

Study design dot point

- chemical reactions with reference to collision theory, including qualitative interpretation of Maxwell-Boltzmann distribution curves

Key knowledge units

Collision theory	3.2.1.1
Maxwell-Boltzman distribution curve	3.2.1.2

Key terms and definitions of this lesson

- **Collision theory** theory which states that for a chemical reaction to occur, the reactant particles have to collide with sufficient energy and with the correct orientation
- **Maxwell-Boltzman distribution curve** graph which shows the kinetic energy distribution of particles

Lesson links

This lesson builds on:

- 3B – Energy changes during combustion

Activation energy can be shown on an energy profile diagram to indicate the minimum amount of energy needed to initiate a chemical reaction.

Collision theory 3.2.1.1

OVERVIEW

For a chemical reaction to occur, the reactant particles must collide with each other.

THEORY DETAILS

Chemical reactions are happening all around us and there are certain factors that must be satisfied for these reactions to occur. **Collision theory** requires that for a chemical reaction to occur, the reacting particles must collide. These collisions must occur with sufficient energy and at the correct orientation. The three conditions in collision theory that must be met for a chemical reaction to occur are summarised below:

1. The reactant molecules must collide with each other.
2. The reactant molecules must collide with sufficient energy to break the bonds within the reactants.
3. The reactant molecules must collide with the correct orientation to break the bonds within the reactants.

If these conditions aren't met, then a chemical reaction cannot occur.

The first rule is fundamental as in order for the reactants to react they must come into contact with each other. The second rule refers to a concept known as activation energy (E_a). Collisions must have sufficient energy to overcome the activation energy barrier when they collide. If the particles collide and haven't reached this activation energy level, then the particles will rebound and move away from each other without reacting. In lesson 3B we saw how activation energy can be represented on an energy profile diagram to show the minimum energy that a collision needs to initiate a reaction. When the energy of a collision is equal to the activation energy, or greater than, a reaction can occur.

The last rule highlights the importance of collision orientation in initiating a chemical reaction. A reaction is more likely to proceed if the orientation of the collision is favourable in certain reactions. For example, in the formation of CO_2, for the reaction to proceed, the carbon atom in CO must be facing the oxygen atom in O_2 for the reaction to occur. As shown in figure 1, if the oxygen atom in CO is facing one of the oxygen atoms in O_2 then the reaction will not occur.

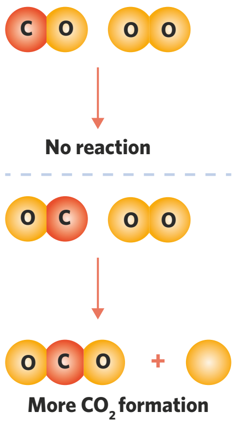


Figure 1 Effect of collision orientation on the initiation of a reaction

Maxwell-Boltzman distribution curve 3.2.1.2

OVERVIEW

Maxwell-Boltzmann distribution curves represent the range of kinetic energies of particles in a reaction and show the proportion of particles that can overcome the activation energy barrier.

THEORY DETAILS

The range of energies of particles can be represented by a **Maxwell-Boltzmann distribution curve**, which shows the distribution of kinetic energies of particles, as shown in figure 2.

Particles to the left have relatively low kinetic energies compared to the particles on the right, which have higher kinetic energies. The peak of the graph represents the kinetic energy of most of the particles in the sample. The area under the curve is equal to the total number of particles in the sample. The area can therefore be used to find the proportion of particles which are above or below a particular energy level. For example, the Maxwell-Boltzmann distribution curve can indicate which particles have enough kinetic energy to overcome the activation energy barrier, as shown in figure 3.

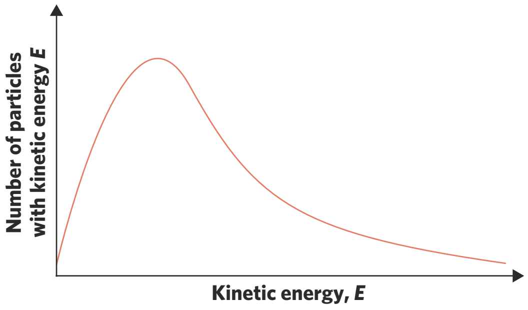
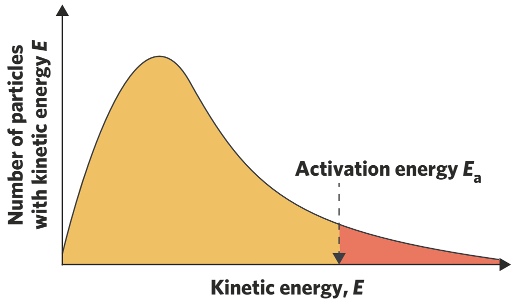


Figure 2 Maxwell-Boltzmann distribution curve showing the distribution of energies of particles in a sample



● This area corresponds to all the particles which do not have sufficient energy to overcome the activation energy barrier.

● This area corresponds to all the particles with sufficient energy to overcome the activation energy barrier and therefore react.

Tip No particles have a kinetic energy of 0 as indicated by the curve not starting at 0 on the *x*-axis.

Figure 3 Maxwell-Boltzmann distribution curve showing the number of particles with enough kinetic energy to overcome the activation energy barrier

Maxwell-Boltzmann distribution curves can also be used to show the range of kinetic energies of particles at different temperatures. The curves themselves can vary significantly, as shown in figure 4, because as the temperature of a system increases, the average kinetic energy of the particles increases and so the speed of the particles increases as well.

As can be seen, the curves become flatter at higher temperatures as the average kinetic energy of the particles increases, shifting the graph to the right. However, it is important to remember that although the shape of the curves change with temperature, the area under the curve representing the number of particles does not change.

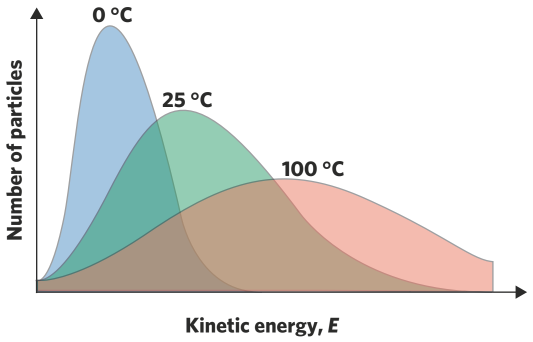


Figure 4 Maxwell-Boltzmann distribution curves at different temperatures

Theory summary

- Collision theory is a model that outlines three conditions that must be satisfied for a chemical reaction to proceed – reacting particles must collide (1) with sufficient energy (2) at the correct orientation (3).
- Maxwell-Boltzmann distribution curves show the distribution of kinetic energies of particles in a system.
- Maxwell-Boltzmann distribution curves can be used to show the number of particles in the system that have enough kinetic energy to overcome the activation energy barrier, as well as the effect of temperature on the kinetic energies of particles in a system.

5A QUESTIONS

Theory review questions

Question 1

Which of the following statements is true of collision theory?

A Whenever two particles collide, a reaction will occur.

B It is based on the assumption that for a reaction to occur it is necessary for the reacting species to collide with one another.

C It provides a quantitative explanation of chemical reactions.

D It determines how a reaction takes place.

Question 2

Increasing the temperature of a system will

A not change the average kinetic energy of the particles.

B decrease the average kinetic energy of the particles.

C increase the average kinetic energy of the particles.

D shift the Maxwell-Boltzmann distribution curve to the left.

Question 3

A Maxwell-Boltzmann distribution curve can be used to

A show the specific kinetic energy of a single particle.

B determine the activation energy of a reaction.

C show the effect of temperature on the average kinetic energy of particles in a reaction system.

D illustrate the rate of reaction.

Question 4

Which of the following statements is a result of increasing the number of particles reacting at a constant temperature?

I An increase in the frequency of collisions between reactants

II An increase in the proportion of successful collisions

III A decrease in the frequency of collisions between reactants

A I only **B** I and II **C** II and III **D** All of the above

Exam-style questions

Within lesson

Question 5 (1 MARK)

Which of the following will increase the average kinetic energy of the particles in the system?

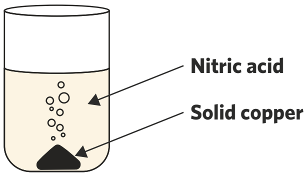
$Cu_{(s)} + 4HNO_{3(aq)} \rightarrow Cu(NO_3)_{2(aq)} + 2NO_{2(g)} + 2H_2O_{(l)}$

A Allowing NO_2 gas to escape

B Increasing the temperature of HNO_3

C Decreasing the temperature of HNO_3

D Increasing the size of the copper particles

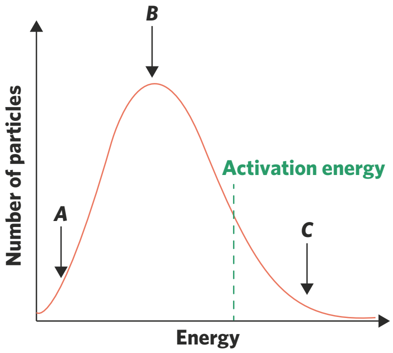


Question 6 (2 MARKS)

A chemist mixed two substances together and found that the molecules were having difficulties reacting. Explain why this could occur, referring to collision theory with specific reference to temperature and collision orientation.

Question 7 (4 MARKS)

A Maxwell-Boltzmann distribution for a reaction is shown.

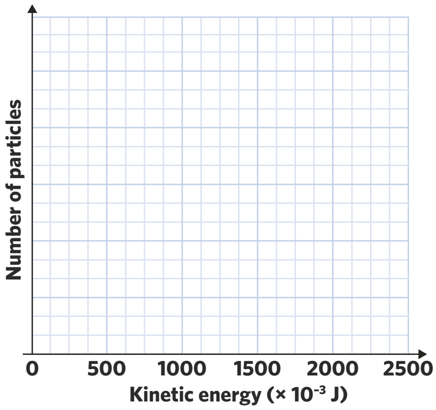


a Compare the kinetic energy of the particles that sit in the areas labelled *A*, *B* and *C*. (3 MARKS)

b In which area(s) would the particles be able to overcome the activation energy barrier? (1 MARK)

Question 8 (5 MARKS)

Julia performs an experiment at four different temperatures.



a On the graph given, sketch the curve at four different temperatures ranging from low to high, taking into consideration the effect of temperature on a Maxwell-Boltzmann distribution curve. (4 MARKS)

b Given that the activation energy for the reaction is 1000 × 10^{-3} J, shade the proportion of particles which have sufficient activation energy at the highest temperature. (1 MARK)

Multiple lessons

Question 9 (5 MARKS)

Abby calculated the activation energy of a reaction to be 50 kJ mol^{-1} and the enthalpy change, ΔH, to be −100 kJ mol^{-1}.

a Draw the energy profile diagram for this reaction, labelling the activation energy and enthalpy change. (3 MARKS)

b What type of reaction is occurring? (1 MARK)

c What is the activation energy for the reverse reaction? (1 MARK)

Question 10 (7 MARKS)

A scientist reacts 1 mol of methane gas in an unlimited supply of oxygen in a combustion reaction. To break the bonds of the methane molecules, 3380 kJ of energy is used, and when the products of the combustion reaction are formed, 4270 kJ of energy is released.

a Write a complete balanced thermochemical equation for the combustion of methane. (2 MARKS)

b What type of reaction is occurring in the formation of the products? (1 MARK)

c Draw and label a diagram to show the energy changes during the course of the reaction. (4 MARKS)

5B RATES OF REACTION

In this lesson, we will learn about the different methods of measuring the rate of a reaction, and the effect of temperature, surface area, pressure and concentration on the rate of a chemical reaction.

5A Principles of a chemical reaction	5B Rates of reaction	5C Catalysts	5D Equilibrium reactions	5E Le Châtelier's principle

Study design dot point

- factors affecting the rate of a chemical reaction including temperature, surface area concentration of solutions, gas pressures and presence of a catalyst

Key knowledge units

Measuring the rate of a reaction	3.2.3.1
Effect of temperature on reaction rate	3.2.3.2.1
Effect of surface area on reaction rate	3.2.3.2.2
Effect of concentration on reaction rate	3.2.3.2.4
Effect of pressure on reaction rate	3.2.3.2.3

Key terms and definitions

- **Gradient** extent of steepness of a graph
- **Surface area** amount of a material or compound in contact with the surroundings
- **Precipitate** substance formed as a solid from a solution

Measuring the rate of a reaction 3.2.3.1

OVERVIEW

We can use a range of different techniques to experimentally determine how fast a reaction is occurring, and we can represent these with rate versus time graphs.

THEORY DETAILS

There are a number of ways we can measure how fast a reaction is happening.

For example, if a reaction produces a gas, we can measure the rate of gas production by collecting this gas in a graduated cylinder and by recording the change in volume over time. This experimental setup is shown in figure 1.

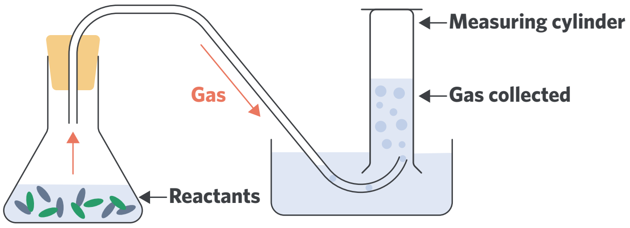
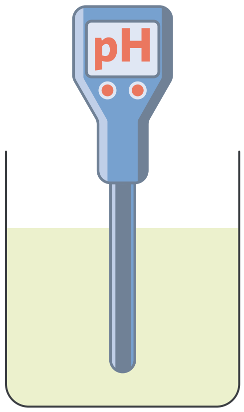


Figure 1 The collection of gas in a graduated cylinder

We can also use the change in pH over time as an indicator of the rate of a reaction. An example of this is the reaction of hydrochloric acid with copper oxide (CuO) given in figure 2. In this reaction, as hydrochloric acid is used up in the reaction, the pH of the reaction mixture will increase due to a decrease in the hydrogen ion concentration. Therefore, we can measure the rate of the reaction by measuring the change in pH over a certain period of time as the reaction progresses.

If a reaction produces a **precipitate** (an insoluble solid), the rate of the reaction can be measured by assessing the time taken for a solution to become cloudy. This is because a precipitate is a solid which causes a solution to become cloudy.



$2HCl_{(aq)} + CuO_{(s)} \rightarrow CuCl_{2(aq)} + H_2O_{(l)}$

Figure 2 The reaction of hydrochloric acid with copper oxide

For example, take the reaction:

$AgNO_{3(aq)} + KCl_{(aq)} \rightarrow AgCl_{(s)} + KNO_{3(aq)}$

Here, the product $AgCl_{(s)}$ is a solid, and so can be observed in the solution as a cloudy precipitate. We can establish the rate of the reaction by measuring the time taken for the cross below the beaker to no longer be visible. If the cross is no longer visible after a short period of time, we know that the reaction has proceeded relatively quickly. However, if the cross remains visible for a longer period of time, we can conclude that the rate of reaction was relatively slow. It is important to note that the point at which the cross is no longer visible would be quite a subjective judgement (it depends on who is looking at the cross). This would mean that a well-designed experiment would be sure to have only one person judging when the cross disappears.

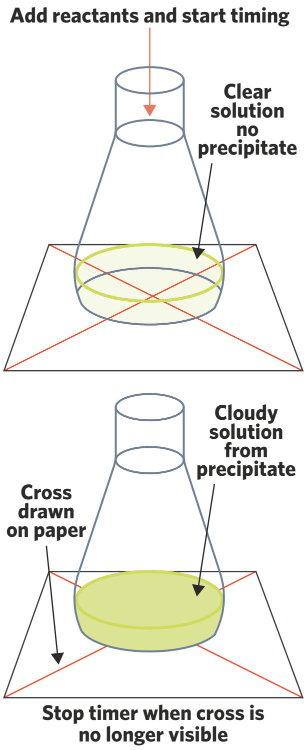


Figure 3 Measuring the rate of a reaction via precipitate formation

Another way of measuring the rate of the reaction is to observe the rate of colour change of a reaction.

We know that different compounds in chemistry have different colours, and so in some reactions, the reactants will be a different colour to the products. As a result, we can use the rate at which the colour changes to observe how fast a reaction is happening.

Take for example, the displacement reaction between copper sulfate and iron.

A beaker is filled with copper sulfate, and a piece of solid iron added, as shown in figure 4.

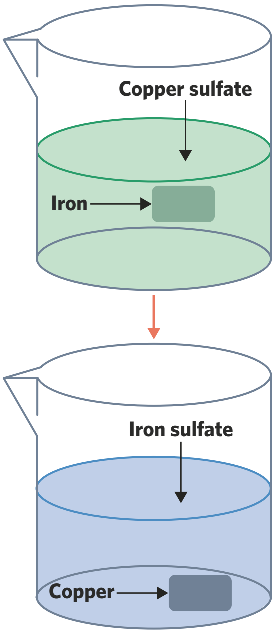


Figure 4 The displacement reaction of copper sulfate and iron sulfate

Similar to a reaction producing a precipitate, the rate of two reactions involving a colour change can be compared by assessing the time taken to complete the colour change, with a smaller time required indicating a faster rate of reaction.

We can use the experimental data collected using the methods outlined above to construct a graph of the rate of the reaction over time.

We can see an example of a concentration against time graph in figure 5.

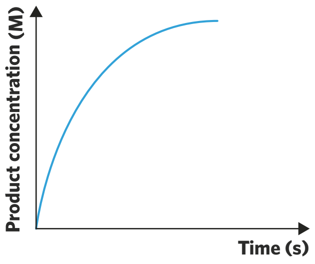


Figure 5 Concentration vs time graph

The rate of reaction is the **gradient** (slope) of this graph as this is the change in a chemical species' concentration per unit of time, the definition of the rate of reaction. Figure 6 illustrates this process.

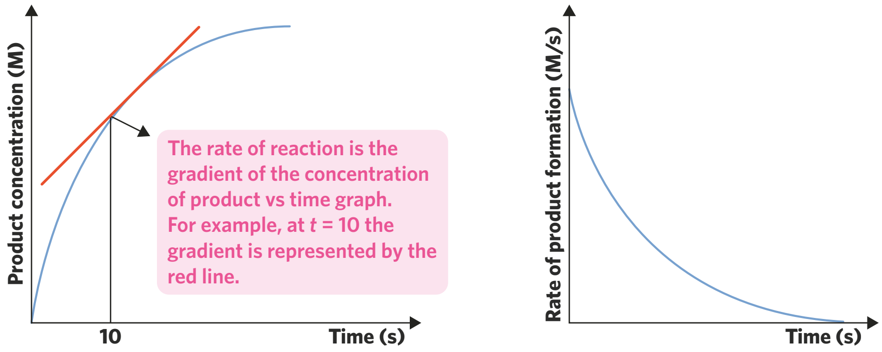


Figure 6 Process for the determination of the rate of reaction

Figure 6 shows that for this particular reaction, the rate is greatest at the start, and begins to plateau, reaching a point where no product is being formed – this is when all the reactant has been used up for an irreversible reaction. We can use graphs such as this to represent the effect of changing conditions on the rate of a reaction.

Effect of temperature on reaction rate 3.2.3.2.1

OVERVIEW

We can apply collision theory to reactions with changing temperature to determine the effect on the rate of reaction.

THEORY DETAILS

The temperature of a substance is representative of the average kinetic energy of the particles within the substance. When a substance is at a high temperature, particles on average have more energy than those at a lower temperature, as we observed in the Maxwell-Boltzmann distribution curves we studied in lesson 5A.

We can observe the distinction between low temperature and high temperature reactions in figure 7.

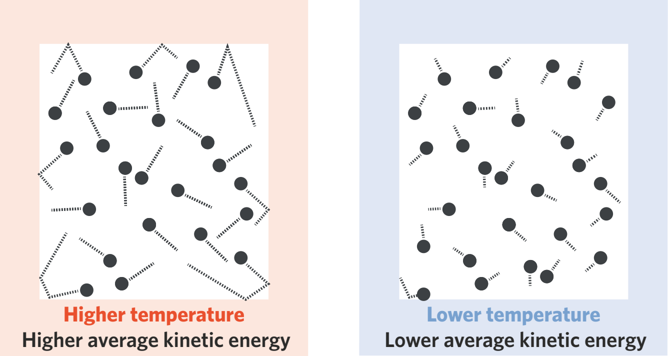


Figure 7 Comparison of average kinetic energy of particles in low temperature and high temperature substances

As the temperature of a reaction increases, the rate of the reaction increases, as there is a an increase in the:

- frequency of collisions due to the increase in average kinetic energy of the particles.
- number of successful collisions in a given amount of time.
- proportion of collisions with an energy equal to or greater than the E_a.
- higher chance of a successful collision when particles collide and the particles are colliding more often in a given amount of time.

This can be represented in figures 8a & 8b, which show the graphs of concentration of product over time and rate of reaction at two different temperatures, respectively. Compared to a reaction at a lower temperature, the concentration of products is greater in a reaction with a higher temperature at any given point in time, as illustrated in figure 8a. After a certain period of time however, the concentration of products of reactions at both higher and lower temperatures are equal to each other. This means that the overall total amount of product produced in a reaction is the same at both temperatures (given that there were no other changes to the reaction) however there is more product being produced in the earlier stages of reactions at higher temperatures than at lower temperatures. As seen in figure 8b, the rate of product formation (and thereby the rate of a reaction) starts much higher for reactions occurring at higher temperatures however decreases much quicker than that of reactions occurring at lower temperatures. Although starting at a slower rate, the rate of product formation reactions occurring at lower temperatures decreases much less over time, resulting in a reaction that would occur over a longer period of time.

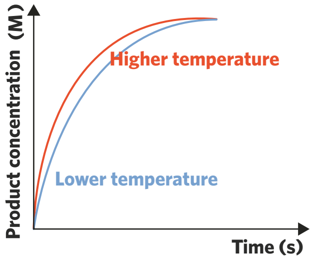


Figure 8a Concentration of product vs time graph for higher and lower temperatures

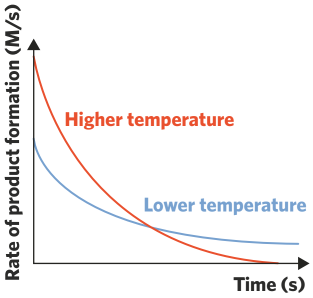


Figure 8b Rate of product formation vs time graph for higher and lower temperatures

For irreversible reactions, it is important to note that at higher temperatures, the maximum concentration of product is still the same because the amount in moles of the limiting reactant has stayed the same, but the maximum concentration of product is just reached faster.

NOTE: When dealing with reactants in the form of gases, we recall from lesson 3C that a change in temperature affects the pressure and/or volume of a gas, and so for the purposes of VCE Chemistry, we generally assume these remain constant when considering the effect on reaction rate.

Effect of surface area on reaction rate 3.2.3.2.2

OVERVIEW

We can apply collision theory to a change in surface area to determine its effect on the rate of a chemical reaction.

THEORY DETAILS

We recall from lesson 5A that collision theory requires reactant particles to come into contact with each other for a successful reaction to occur.

The **surface area** of a reactant refers to how much of a reactant's surface is exposed and free to collide with other reactant particles. Surface area dictates how many particles come into contact with each other.

As a result, when the surface area of a reactant increases, the proportion of reactant particles that are able to come into contact with one another increases, increasing the frequency of collisions and subsequently the number of successful collisions in a given amount of time.

We can increase the surface area of a substance by crushing it (if the reactant can be made into a powder or by cutting the substance into smaller pieces). Sometimes stirring increases the surface area by agitating the particles in a solution.

We can construct a graph to compare the effect of surface area on the rate of a reaction. We know that a larger surface area results in a faster rate of reaction, and so we can represent this as shown in figure 10. Here, the experiment utilising reacting species with a larger surface area has a steeper curve compared with the experiment with species with a decreased surface area. This means that the reaction with the steeper curve had a faster reaction rate than reaction with a more gradual gradient.

Just like a change in temperature, the amount of the limiting reagent has not changed and therefore, increasing the surface area only causes the maximum product concentration to be achieved more quickly.

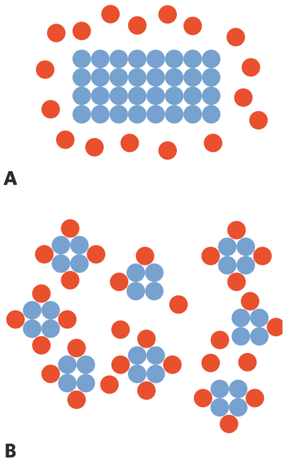


Figure 9 Comparison of reactants with low (A) and high (B) surface areas

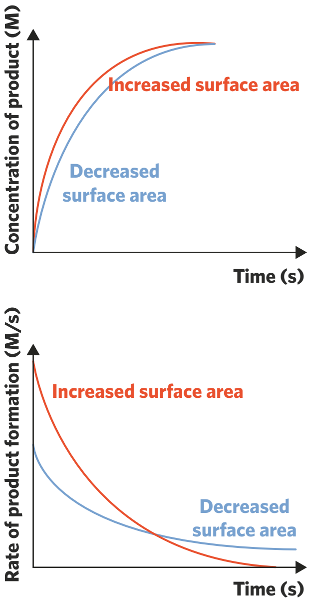


Figure 10 The effect of the surface area of a reactant on the rate of a reaction

Effect of concentration on reaction rate 3.2.3.2.4

OVERVIEW

We can apply collision theory to determine the effect of altering concentration on reaction rate.

THEORY DETAILS

For a reaction to occur, reactant particles must come into contact with one another. The frequency of these reactions depends on the concentration of the reactant(s) present.

When the concentration of a reactant is increased, there are more reactant particles present in the system per unit of volume, and so the collision frequency and therefore the number of successful collisions in a given amount of time increases, increasing the rate of the reaction. Figure 11 illustrates the effect of concentration on reaction rate.

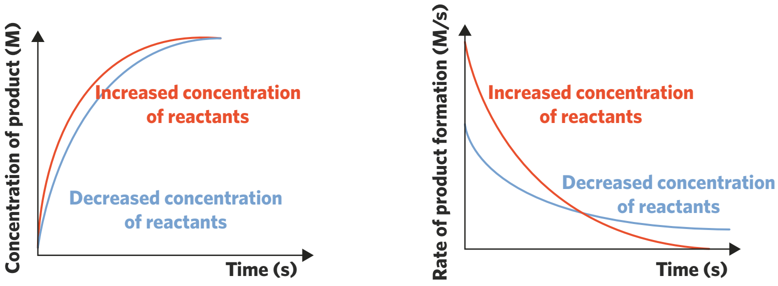


Figure 11 The effect of concentration on the rate of a reaction

Effect of pressure on reaction rate 3.2.3.2.3

OVERVIEW

We can apply collision theory to establish the effect of changing pressure on reaction rate.

THEORY DETAILS

Recall from lesson 3C on gases that pressure is related to the number of moles of gas, temperature, and volume through the universal gas equation, $PV = nRT$.

As a result, a change in pressure will affect one or more of these variables, an assumption usually highlighted in the question stem.

If the number of moles and temperature are constant, when pressure is changed, the volume will also change. From the universal gas equation, we can see that pressure and volume are inversely proportional, and so an increase in pressure results in a decrease in volume.

A decrease in volume means particles are in a smaller space, resulting in an increase in the number of collisions between particles thereby increasing the rate of the reaction.

If the volume and temperature are both constant and more moles of reactant have been injected into the system, the pressure will change. As we have explored earlier in this lesson, when more molecules are present in the same volume, there are more collisions, and so the rate of the reaction is increased.

If the volume and the number of moles are both constant, then when pressure changes, the temperature will change. From the universal gas equation, we know that pressure and temperature are directly proportional, and so an increase in pressure will increase the temperature of the system.

The pressure may also be changed by the addition of an inert gas. These are a group of gases, known as noble gases, found in the rightmost column of the periodic table (group 18), that are unreactive. If an inert gas such as argon, helium, or neon, is added at constant volume and temperature, the pressure increases but the concentration of reactants stays the same. As we have specified constant volume and temperature, there is no change in the rate of reaction.

Tip Always read the question carefully to identify what conditions are kept constant and which change during a reaction.

Theory summary

- The rate of a reaction can be measured by
  - the rate of production of a gas.
  - the rate of pH change.
  - the rate of production of a precipitate.
  - the rate of change in colour.
- An increase in the temperature of a reaction increases the rate of a reaction by increasing
  - collision frequency.
  - number of successful collisions in a given amount of time.
  - proportion of collisions with sufficient energy to overcome E_a.
- An increase in the surface area increases the rate of a reaction by increasing
  - frequency of collisions.
  - number of successful collisions in a given time.
- An increase in the concentration of the reactants increases the rate of a reaction.
- An increase in pressure decreases volume and thereby increases concentration. This results in an increase in
  - frequency of collisions.
  - number of successful collisions in a given time.

5B QUESTIONS

Theory review questions

Question 1

At lower temperatures, a reaction will occur more slowly because the

A reactant particles collide more frequently.
B reactant particles collide in the incorrect orientation.
C reactant particles have a lower average kinetic energy.
D the reaction has a lower activation energy.

Question 2

Which of the following changes could be implemented to decrease the rate of a reaction?

A Increasing the concentration of reactants
B Decreasing the surface area of the reactants
C Adding an inert gas at constant volume and temperature
D Increasing the temperature of the reaction

Question 3

Fill in the blanks in the sentences below.

Consider the reaction of a solution of hydrochloric acid with a solution of 25 °C sodium hydroxide.

If sodium hydroxide at 50 °C was added instead, the rate of the reaction would ___________.

If hydrochloric acid of half the original concentration was used, the rate of the reaction would ___________.

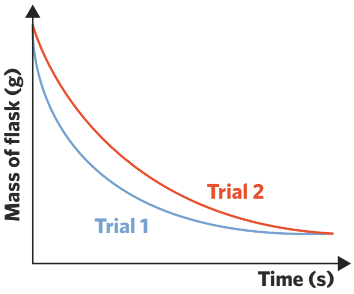
If the mixture were stirred, the rate of the reaction would ___________.

Exam-style questions

Within lesson

Question 4 (1 MARK)

A student decided to measure the rate of reaction by constantly weighing a flask sitting on a scale. Throughout the reaction, a gas was evolved. What would have caused the change seen in trial 2, when compared to trial 1?

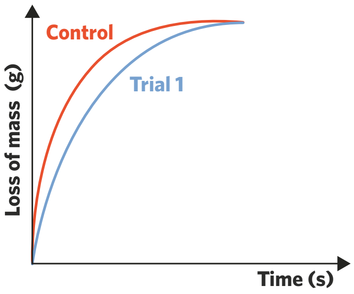


- **A** An increase in temperature
- **B** An increase in concentration of reactants
- **C** A decrease in surface area of reactants
- **D** An increase in surface area of reactants

Question 5 (1 MARK)

Strips of zinc metal are added to a solution of sulfuric acid (in excess) yielding hydrogen gas and zinc sulphate under SLC. The loss of mass is plotted against the time, and the trial is repeated with a single factor changed. Assume the reaction goes to completion.

Which of the following changes implemented in trial 1 could explain the loss of mass vs time graph given?

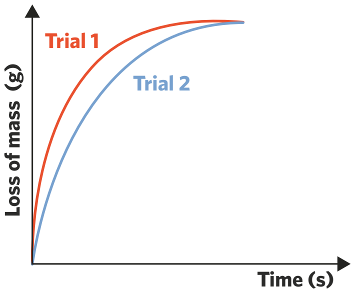


- **A** adding 20 g of zinc sulphate
- **B** decreasing the temperature
- **C** cutting the same amount of zinc into finer pieces
- **D** adding more strips of zinc metal

Question 6 (8 MARKS)

An excess amount of powdered sodium bicarbonate ($NaHCO_3$) and 10 mL of 5.0 M hydrochloric acid are added to an open flask. The mass of the flask is monitored over a period of time, and the results presented as trial 1 in the diagram given. Assume that the reaction is irreversible.

A second trial is now conducted, with the same reaction, and only a single variable changed.



- **a** Write a balanced equation for the reaction occurring in the beaker. (1 MARK)
- **b** With reference to the equation determined in part a, explain why the mass of the flask is changing. (1 MARK)
- **c** A student conducting the experiment claims that the variable changed may have been the mass of sodium bicarbonate. Explain whether the mass added would need to be increased or decreased. (2 MARKS)
- **d** A third trial is now conducted with the same reaction conditions as trial 1, but with sodium bicarbonate crushed into a finer powder. Draw a rate vs time graph to compare trial 1 with the expected rate of this new trial (trial 3), assuming both approach the same final loss of mass. (2 MARKS)
- **e** Explain, with reference to collision theory, the effect of the change implemented in part d. (2 MARKS)

Question 7 (8 MARKS)

Adam is building a fishing boat and is looking for a material to use that experiences minimal rusting when in contact with water. To investigate which materials would be suitable, Adam exposes a range of different types of metal screws and nails to water and the air.

It is noted that iron nails react more quickly with oxygen from the air and water than those that are coated with a protective layer of zinc.

a A new set of iron nails are broken into smaller pieces and exposed to the same conditions. Would you expect rusting to occur faster or slower than the full sized nails? Justify your answer. (2 MARKS)

b After construction, Adam tests the boat on the water. On the side of the boat exposed to the sun, it is observed that the nails rust much faster than those on the shaded side. Explain this observation, using collision theory to support your answer. (3 MARKS)

c Adam is looking to slow down the rate at which the nails rust, and proposes a test conducted in a higher pressure oxygen environment (at the same temperature as before), to observe the rate of the reaction. Adam hypothesises the nails will not rust at all, because the oxygen molecules will have too much energy at high pressure to react.

Evaluate this statement. (3 MARKS)

Multiple lessons

Question 8 (11 MARKS)

Dr Lan is investigating the reaction of copper with nitric acid. An empty 100 mL flask is placed on a set of scales and a 5.0 g piece of copper is added. 10 mL of 5.0 M nitric acid is then poured into the flask, and the rate of the reaction measured across a period of 5 minutes. This process is then repeated with 6.0 M, 7.0 M, 8.0 M and 9.0 M concentrations of nitric acid.

The equation for the reaction occurring in the flask is given below. Assume SLC.

$Cu_{(s)} + 4HNO_{3(aq)} \rightarrow Cu(NO_3)_{2(aq)} + 2NO_{2(g)} + 2H_2O_{(l)}$

a Explain how Dr Lan could best measure the rate of the reaction with the use of the electronic scales. (2 MARKS)

b Identify the independent and dependent variables, using your answer to part a. (2 MARKS)

c After the experiment, Dr Lan notes the electronic scales used to measure the weight of the copper pieces were not calibrated before use. Would this be considered a systematic or random error? Explain your answer. (2 MARKS)

d Dr Lan hypothesises that trials with a greater concentration of nitric acid will occur at a slower rate than those with smaller concentrations. Evaluate this statement with reference to collision theory. (3 MARKS)

e The reactions in the flasks are now carried out in a water bath at 50 °C. How would you expect the concentration of copper to change over time as compared to the trial conducted at SLC? (2 MARKS)

Question 9 (7 MARKS)

A tank of natural gas is used as a fuel source for a combustion engine. The gas enters a chamber and reacts according to the equation given.

$CH_{4(g)} + O_{2(g)} \rightarrow CO_{2(g)} + H_2O_{(g)}$

a Rewrite the above reaction as a balanced equation. (1 MARK)

b How much energy, in kilojoules, would be released by the combustion of two mol of methane? (1 MARK)

c 500 mL of neon gas is now added to the reaction chamber at constant temperature and volume. How would you expect the rate of production of carbon dioxide to be affected? Justify your answer with reference to collision theory. (3 MARKS)

d The original system is kept at constant pressure and volume, and 2 mol of CO_2 is removed. Using the universal gas equation, explain the effect this change has on the rate of the reaction. (2 MARKS)

5C CATALYSTS

In this lesson, we will learn about the function of catalysts and how they can affect the rate of a reaction.

5A Principles of a chemical reaction	5B Rates of reaction	5C Catalysts	5D Equilibrium reactions	5E Le Châtelier's principle

Study design dot points

- factors affecting the rate of a chemical reaction including temperature, surface area concentration of solutions, gas pressures and presence of a catalyst
- the role of catalysts in changing the rate of chemical reactions with reference to alternative reaction pathways and their representation in energy profile diagrams.

Key knowledge units

Effects of catalysts on the reaction rate	3.2.3.2.5
Representing catalysed reactions	3.2.4.1

Key terms and definitions

- **Catalyst** substance that increases the reaction rate without itself being consumed or permanently changed
- **Heterogeneous catalyst** catalyst whose physical state differs from the phase of the reactants
- **Homogeneous catalyst** catalyst whose physical state is the same as the phase of the reactants
- **Activation energy** minimum amount of energy required for a chemical reaction to occur
- **Energy profile diagram** diagram of how energy changes during a chemical reaction
- **Transition state** state corresponding to the highest energy point in the energy profile diagram of a reaction during which bond breaking and forming is occurring

Lesson links

This lesson builds on:

▶ 5B – Rates of reaction

Catalysts affect the rate of reaction.

Effects of catalysts on the reaction rate 3.2.3.2.5

OVERVIEW

Catalysts can increase the reaction rate by decreasing the activation energy of the reaction.

THEORY DETAILS

As we learned in lesson 5B, a high temperature increases the reaction rate by increasing kinetic energy of reactant particles. Using **catalysts** is another way to speed up the reaction rate. What is special about catalysts is that they are neither chemically nor quantitatively changed during the reaction. This means that after the reaction has finished, both the chemical structure of the catalyst(s) and the amount of catalyst(s) remain the same as before the reaction occurs.

As shown in figure 1, the initial state and the final state of a reaction have different energy levels. The **transition state** is the maximum energy level in the **energy profile diagram** in a reaction. **Activation energy** (E_a) is the minimum amount of energy required for a chemical reaction to occur. More specifically, it is the minimum amount of energy required to go from the initial state to the transition state. A reaction only occurs when the activation energy is achieved.

The energy profile diagrams differ in endothermic reactions and exothermic reactions. As shown in figure 2, in an endothermic reaction, the energy of the reactants is lower than the energy of the products because energy is absorbed. In an exothermic reaction, the reactants have a higher energy level than the products because energy is released. However, the activation energy is always the amount of energy required to go from the initial state to the transition state.

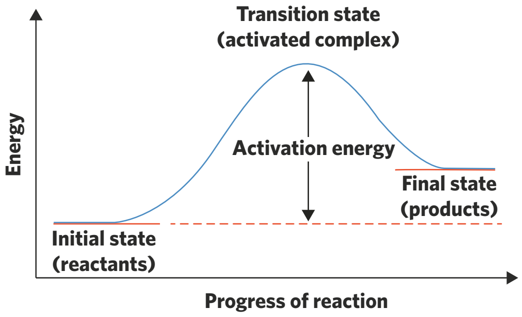
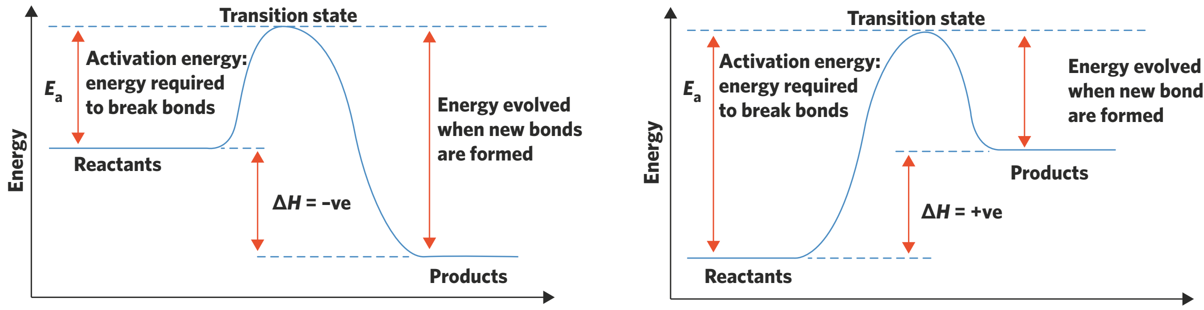


Figure 1 Simple energy profile diagram of a chemical reaction



Energy diagram for an exothermic reaction **Energy diagram for an endothermic reaction**

Figure 2 Energy profile diagrams of an exothermic reaction and an endothermic reaction

Catalysts increase the reaction rate by lowering the activation energy of the reaction. The activation energy is lowered by the catalyst providing an alternative reaction pathway with a lower activation energy, as shown in figure 3. It can be seen that without a catalyst, the activation energy is relatively high, meaning that fewer reactant particles have enough energy to reach the transition state, and so the reaction rate is low. On the other hand, in the presence of a catalyst, the alternative reaction pathway with a lower activation energy occurs faster because more reactant particles have enough energy to reach the transition state. This alternative reaction pathway generates the same products as the uncatalysed reaction.

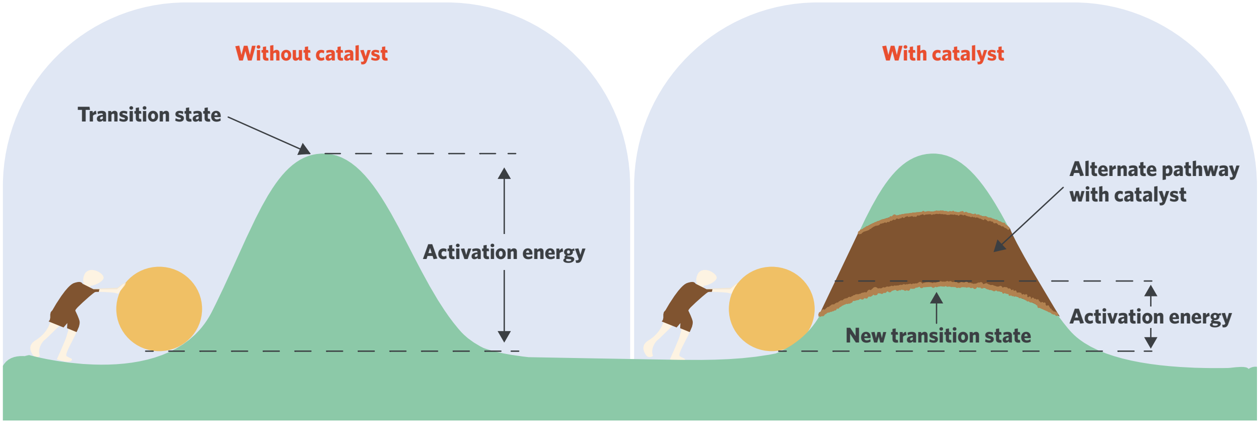


Figure 3 Illustration of how a catalyst creates alternative pathways of a reaction

Depending on the physical state of the catalyst and its reactants, catalysts can be classified into two main categories. **Homogeneous catalysts** are catalysts that have the same physical state as the reactants. For example, $NO_{(g)}$ is a gaseous catalyst of the reaction between two gases SO_2 and O_2 to produce SO_3, which is another gas.

$$2SO_{2(g)} + O_{2(g)} \overset{NO_{(g)}}{\rightarrow} 2SO_{3(g)}$$

Heterogeneous catalysts are catalysts that have different physical states from the reactants in a reaction. For example, $Fe_{(s)}$ is a solid catalyst for the reaction between two gases N_2 and H_2 to produce ammonia NH_3.

$$N_{2(g)} + 3H_{2(g)} \overset{Fe_{(s)}}{\rightarrow} 2NH_{3(g)}$$

Representing catalysed reactions 3.2.4.1

OVERVIEW

Uncatalysed and catalysed reactions can be represented by energy profile diagrams and by the Maxwell-Boltzmann curve.

THEORY DETAILS

Figure 4 shows the difference in the energy profile diagram between a catalysed reaction and an uncatalysed reaction. It can be clearly seen that the activation energy of a catalysed reaction is lower than the activation energy of an uncatalysed reaction. It is important to know how to draw this diagram.

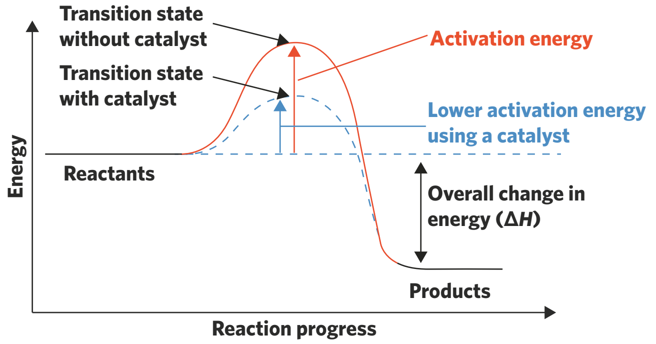


Figure 4 Energy profile diagram with and without a catalyst

As we learned in 5A, a reaction only occurs when there are successful collisions between the particles of the reactants. In the presence of a catalyst, as the activation energy is lower, an increased proportion of reactant particles are able to reach the energy level that allows for successful collisions. This is depicted in the Maxwell-Boltzmann curve in figure 5. The shaded area under the curve of a catalysed reaction (green and blue area), to the right of the identified E_a, is larger than that of an uncatalysed reaction (blue area).

▶ Important note

Students sometimes misinterpret the Maxwell-Boltzmann curve, thinking that it shows that the activation energy of a catalysed reaction is higher than that of an uncatalysed reaction since the height of the curve is greater at the energy level of the catalysed reaction. Therefore, it is important to notice that the vertical axis in the Maxwell-Boltzmann curve represents the number of particles with a specific kinetic energy, not the value of the energy itself. Therefore, what we focus on here is the area under the curve.

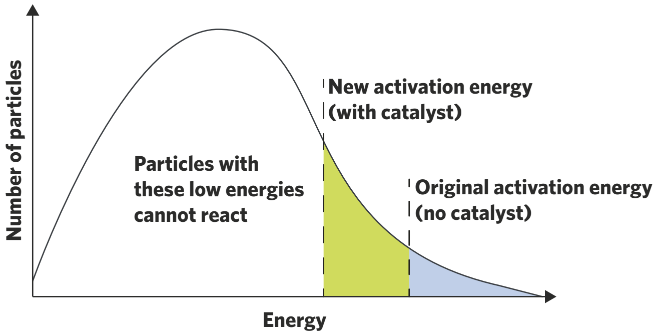


Figure 5 Maxwell-Boltzmann curve of a catalysed reaction and uncatalysed reaction

Theory summary

- Catalysts are substances that increase the reaction rate without being consumed or chemically changed.
- Catalysts increase the reaction rate by creating an alternate reaction pathway with a lower activation energy.
- Energy profile programs differ between endothermic and exothermic reactions.
- There are two types of catalysts: homogeneous catalysts and heterogeneous catalysts.
- Uncatalysed and catalysed reactions can be represented by energy profile diagrams and the Maxwell-Boltzmann curve.

5C QUESTIONS

Theory review questions

Question 1

A catalyst is

A a substance that decreases the reaction rate.

B a substance that is consumed during a chemical reaction.

C a substance that increases the reaction rate without being consumed or changed.

D a substance that increases the reaction rate with its chemical structure being changed after the reaction is finished.

Question 2

What is the activation energy of a chemical reaction?

A The highest point in the energy profile diagram of a chemical reaction

B The minimum amount of energy required for a reaction to occur

C The maximum amount of energy required for a reaction to occur

D The point in the energy profile diagram where the transition state occurs

Question 3

A catalyst increases the reaction rate by

A creating an alternative pathway that requires a lower activation energy.

B increasing the amount of energy used during the reaction.

C decreasing the amount of energy released during the reaction.

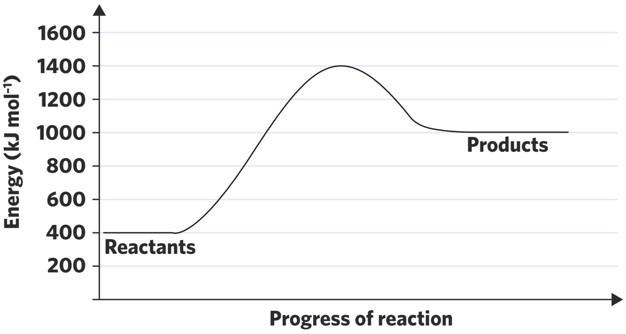
D increasing the surface area of contact between reactants.

Exam-style questions

Within lesson

Use the following information to answer questions 4 and 5.

An uncatalysed chemical reaction has the energy profile diagram.



Question 4 (1 MARK)

The activation energy of the forward uncatalysed reaction is

A 1400 kJ mol^{-1}

B 1000 kJ mol^{-1}

C 600 kJ mol^{-1}

D 800 kJ mol^{-1}

Question 5 (1 MARK)

A catalyst decreases the activation energy by 380 kJ mol^{-1}.

The enthalpy change of the catalysed reaction is

A +220 kJ mol^{-1}

B –620 kJ mol^{-1}

C +600 kJ mol^{-1}

D –600 kJ mol^{-1}

Question 6 (3 MARKS)

Ozone, O_3, has detrimental effects on our health. Chlorine is often used as a catalyst to convert ozone to oxygen according to the following reaction: $2O_3 \rightarrow 3O_2$

Activation energy 1 406 kJ mol^{-1}

Activation energy 2 520 kJ mol^{-1}

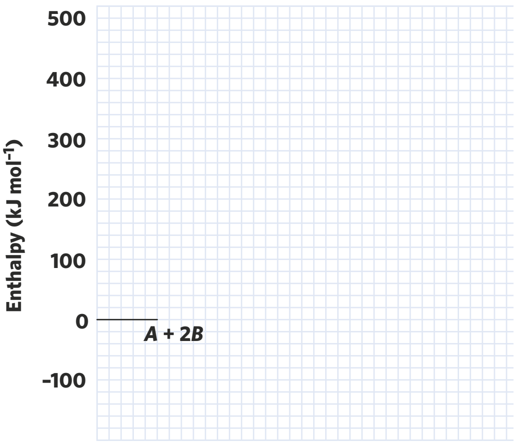
a Which activation energy represents the catalysed reaction? (1 MARK)

b Explain your choice above. (2 MARKS)

Question 7 (5 MARKS)

A reaction between two reactants, A and B, is represented as:

$A + 2B \rightarrow C$ $\Delta H = +85\ \text{kJ mol}^{-1}$



a The activation energy for the uncatalysed reaction is 345 kJ mol^{-1}. The activation energy for the reaction when a catalyst, X, is used is 152 kJ mol^{-1}.

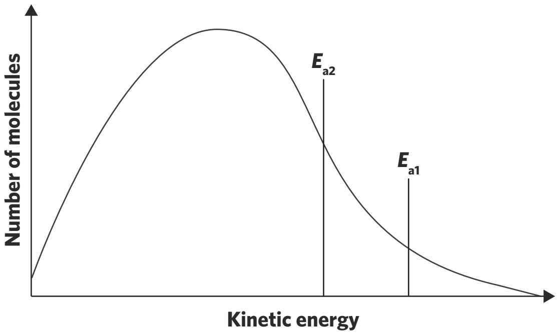
Draw a labelled energy profile diagram for the uncatalysed and catalysed reaction on the given grid. (3 MARKS)

b The activation energy for the reaction when a different catalyst Y is used is 170 kJ mol^{-1}. Which catalyst, X or Y, will cause the reaction to occur slower? Justify your answer. (2 MARKS)

Question 8 (6 MARKS)

The distribution of kinetic energy in a sample of gaseous reactant molecules is represented by the given Maxwell-Boltzmann curve.

The activation energy E_{a1} is changed to activation energy E_{a2} in the presence of a catalyst.



a Explain why this change will increase the reaction rate between the reactant molecules. (3 MARKS)

b A student suggests that the reaction rate will decrease because the number of molecules at E_{a2} is higher than at E_{a1}. Explain why this student's conclusion is incorrect based on the given curve. (3 MARKS)

Multiple lessons

Question 9 (5 MARKS)

$S_{(s)} + \frac{3}{2}O_{2(g)} \rightarrow SO_{3(g)}$ $\Delta H = -395.2\ \text{kJ mol}^{-1}$

$2SO_{2(g)} + O_{2(g)} \rightarrow 2SO_{3(g)}$ $\Delta H = -198.2\ \text{kJ mol}^{-1}$

a Calculate ΔH for the reaction $S_{(s)} + O_{2(g)} \rightarrow SO_{2(g)}$.
Identify whether it is an endothermic or exothermic reaction. Explain your answer. (3 MARKS)

b Predict how the reaction rate of the reaction in question **a** will change if a catalyst is added. Justify your answer. (2 MARKS)

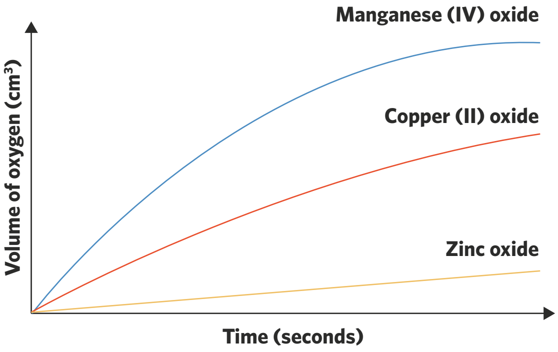
Question 10 (5 MARKS)

Different catalysts can be used for the same reaction, however it's important to be able to select the best catalyst for a particular type of reaction.

The decomposition of hydrogen peroxide can be catalysed by a variety of different catalysts.

$2H_2O_{2(aq)} \rightarrow 2H_2O_{(l)} + O_{2(g)}$

The graph shows the beginning stages of the decomposition of hydrogen peroxide using different catalysts. (Note: This graph does not represent the decomposition reaction going to completion.)



a Which catalyst would increase the rate of reaction the most? (1 MARK)

b Justify your answer above. (2 MARKS)

c Xue decided to use Copper (II) oxide as the catalyst for her reaction. Given that she did not add any extra catalyst to her reaction, what effect would doubling the amount of hydrogen peroxide in the reaction have on the rate of the reaction? (2 MARKS)

5D EQUILIBRIUM REACTIONS

In this lesson we will be learning about the theory of equilibrium reactions, how to represent them and calculations involving systems in dynamic equilibrium.

5A Principles of a chemical reaction	5B Rates of reaction	5C Catalysts	5D Equilibrium reactions	5E Le Châtelier's principle

Study design dot points

- the distinction between reversible and irreversible reactions, and between rate and extent of a reaction
- homogenous equilibria involving aqueous solutions or gases with reference to collision theory and representation by balanced chemical or thermochemical equations (including states) and by concentration-time graphs
- calculations involving equilibrium expressions and equilibrium constants (K_c only) for a closed homogeneous equilibrium system including dependence of value of equilibrium constant, and its units, on the equation used to represent the reaction and on the temperature

Key knowledge units

Reversible and irreversible reactions	3.2.5.1
Rate vs extent of reaction	3.2.5.2
Equilibrium reactions	3.2.6.1
Representing equilibrium reactions	3.2.6.2
Equilibrium law & equilibrium constant	3.2.7.1
Calculations involving equilibrium reactions	3.2.7.2

Key terms and definitions

- **Reversible reaction** chemical reaction that can go backwards and forwards
- **Irreversible reaction** chemical reaction that can only go in one direction
- **Extent of reaction** how far the chemical reaction proceeds
- **Equilibrium system** reaction in which reactants and products are constantly being formed
- **Dynamic equilibrium** system in which the forwards and backwards reaction are occurring at the same rate with reactants and products continuously being formed and used up
- **Equilibrium constant (K_c)** expression or value involving the concentrations of the reactants and products of a system in dynamic equilibrium
- **Reaction quotient (Q_c)** expression or value involving the concentrations of the reactants and products of a system that is not at equilibrium
- **Homogenous** describes a system where all chemical species are in the same physical state
- **Rate-time graph** representation of the rate of the forward and backward reaction over time
- **Concentration-time graph** representation of the concentration of reactants and products over time

Reversible and irreversible reactions 3.2.5.1

OVERVIEW

Chemical reactions can be classified as either reversible or irreversible depending on whether products formed can be converted back to reactants.

THEORY DETAILS

An **irreversible** chemical reaction is one where the products of the reaction cannot be returned to the reactants. Once the reaction occurs, the reactants can never be recovered in their initial states. A common irreversible reaction we have investigated is a combustion reaction, where fuel is burnt in the presence of oxygen. For the combustion of methane shown in figure 1, for example, we cannot recover the oxygen and fuel used up in the reaction. For such reactions, we use a 'unidirectional arrow' (→) to represent how the reaction only proceeds in the 'forward' direction.

$CH_{4(g)} + 2O_{2(g)} \rightarrow CO_{2(g)} + 2H_2O_{(g)}$

The opposite of an irreversible chemical reaction is a **reversible** one. A basic example of a reversible chemical reaction is a physical state change. For example, when water melts from solid (ice) to liquid (water), as shown in figure 2, we can easily restore it to its solid state by cooling the system down until it refreezes. The system can be returned to its initial state, as shown by the reactions below.

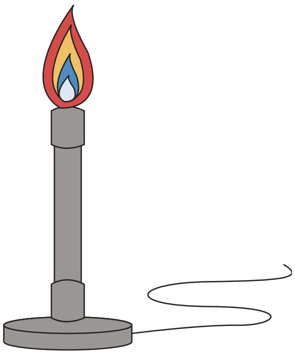


Figure 1 A Bunsen burner using methane as a fuel source is an example of an irreversible reaction

$H_2O_{(s)} \rightarrow H_2O_{(l)}$

$H_2O_{(l)} \rightarrow H_2O_{(s)}$

For reactions that can be reversed (that is, they can go both 'backwards' and 'forwards') we can use 'bidirectional harpoons' or 'equilibrium arrows' ($\rightleftharpoons$) as a shorthand to represent this. An alternate way of expressing this is by saying that the reaction can go 'to the left,' which forms reactants or 'to the right,' which forms products.

$H_2O_{(s)} \rightleftharpoons H_2O_{(l)}$

We will explore how this concept of reversible reactions extends well beyond simple changes in physical state and actually applies to the majority of all chemical reactions. Perhaps the most famous example of a reversible reaction is the production of ammonia NH_3 from the combination of nitrogen N_2 and hydrogen H_2 – a reaction known as the Haber process.

$N_{2(g)} + 3H_{2(g)} \rightleftharpoons 2NH_{3(g)}$

As denoted by the arrows, this is a reversible reaction. This means that the reaction can proceed forwards to form ammonia through the combination of nitrogen and hydrogen, or it can proceed backwards and form nitrogen and hydrogen via the decomposition of ammonia. What we will discover is that the balance between these two reactions can be quantified and influenced through different changes to the reaction vessel.

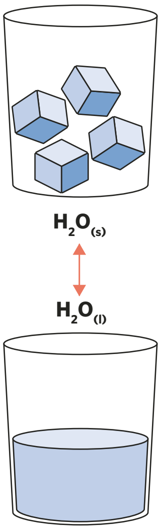


Figure 2 Ice melting into water is an example of a reversible reaction

Rate vs extent of reaction 3.2.5.2

OVERVIEW

Chemical reactions can be analysed by measuring both the speed of the reaction (its rate) and how far 'forward' the reaction proceeds to form products.

THEORY DETAILS

We have already established that in a reaction such as the Haber process, both the forward and backward reaction can occur.

$N_{2(g)} + 3H_{2(g)} \rightleftharpoons 2NH_{3(g)}$

The rate of a chemical reaction determines how fast the reactants are being converted into products. As we learned in lessons 5B and 5C, there are many factors that can influence the rate of reaction: concentration, pressure, volume, temperature or the addition of a catalyst. For example, an iron catalyst is used in the Haber process to greatly increase the rate of formation of ammonia. The difference in the rate of reaction as a plot of concentration against time with the addition of a catalyst is summarised in figure 3, where the black line represents the uncatalysed pathway and the dotted orange line represents the catalysed pathway.

The addition of a catalyst, as we learned in lesson 5C, will increase the rate of reaction, but will not change the **extent of reaction**. This means that even if we waited for an incredibly long time, the amount of reactants and products present at the end of the reaction will be the same whether we used a catalyst or not.

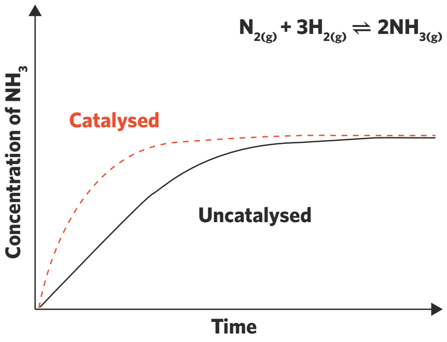


Figure 3 The difference in the rate of reaction in the catalysed and uncatalysed reaction pathway of the Haber process. The final concentration is the same in both cases.

The extent of a reaction is determined by how much of a reactant or product is present. If all of the reactants are converted to products, we say that the reaction has gone to completion. If instead there are both reactants and products present in the system, then the reaction is said to be incomplete. Some reactions will tend towards products being formed in large amounts, whereas others will greatly resist the forward reaction and instead remain with a large amount of reactants still present in the system. We will investigate the chemistry behind this observation in the next section.

Equilibrium reactions 3.2.6.1

OVERVIEW

Reversible reactions that have both the forward and backward reactions occurring simultaneously are known as equilibrium reactions.

THEORY DETAILS

For the Haber process, if we look at the stoichiometric ratios of the products and reactants, it would seem that for every 1 mol of nitrogen and 3 mol of hydrogen that is put into the system, 2 mol of ammonia will be formed.

$N_{2(g)} + 3H_{2(g)} \rightleftharpoons 2NH_{3(g)}$

This is the assumption that we have so far made when conducting calculations in stoichiometry. For irreversible reactions, such as combustion reactions, this assumption is almost always accurate since the extent of the reaction is so high. That is, almost all of the reactants are converted into products.

However, for a chemical reaction like the Haber process, any experiment that puts 1 mol of nitrogen and 3 mol of hydrogen into a reaction vessel will reveal that an amount much lower than 2 mol of ammonia is produced. In fact, if the concentrations of all three species are measured over time, we will observe that while the concentrations of the reactants will decrease initially to form ammonia as a product, they will eventually reach some constant non-zero amount and never deviate from it unless the system is disturbed.

A potential 'final state' for the amounts with these initial conditions could be 0.6 mol of N_2, 1.8 mol of H_2 and 0.8 mol of NH_3 present in the reaction vessel. It is important to note that the laws of stoichiometry and reacting amounts still apply, so in this case 0.4 mol of N_2 and 1.2 mol of H_2 reacts and 0.8 mol of NH_3 is produced, which retains the ratio of 1:3:2. This scenario is depicted in figure 4.

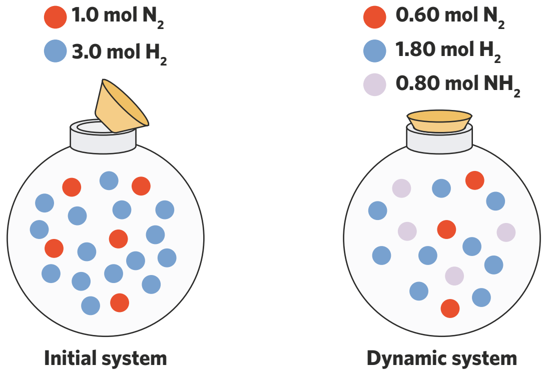


Figure 4 A reaction vessel for the reaction $N_{2(g)} + 3H_{2(g)} \rightleftharpoons 2NH_{3(g)}$ reaches dynamic equilibrium. Both reactants and products are present during dynamic equilibrium.

To an observer, it would appear as if the reaction has stopped at some 'middle ground' since all the concentrations of both reactants and products are constant but are still both present in the reaction vessel.

To a chemist, however, it is known that while no large scale change is observed, at a microscopic level the forward and backward reactions are still occurring, with products and reactants still being formed, only they are being formed and lost at the same rate. This state of the forward and backward reactions occurring at the same, constant rate is known as **dynamic equilibrium**.

That is, for a system in dynamic equilibrium

- the amounts of reactants and products are constant.
- the concentrations of reactants and products are constant.
- the pressure of the system is constant.
- the temperature of the system is constant.
- the forward and backward reactions are occurring at the same, constant rate.

We will only consider equilibrium reactions that have all reactants and products in the same physical state. These are known as **homogenous** equilibria and we will further confine our discussion to equilibria involving aqueous solutions or gases, like the Haber process.

Representing equilibrium reactions 3.2.6.2

OVERVIEW

A system reaching equilibrium can be represented graphically by either a concentration-time graph or a rate-time graph.

THEORY DETAILS

Representing a system as it moves towards equilibrium and what occurs when it reaches it is a key aspect of understanding the mechanism behind equilibrium reactions.

Again, we will examine the Haber process reaction and investigate how both the rate of the forward and backward reactions and concentration of reactants and products change over time.

$N_{2(g)} + 3H_{2(g)} \rightleftharpoons 2NH_{3(g)}$

In the previous section, we noticed that for every 1.0 mol of N_2 and 3.0 mol of H_2 that we put into the system, we did not actually get 2.0 mol of NH_3 since the reaction did not proceed to completion, and instead reached a state of dynamic equilibrium. However, for every 0.4 mol of N_2 that reacted, we did indeed have the correct ratio of 1:3:2, with 1.2 mol of H_2 consumed and 0.8 mol of NH_3 produced.

This means that while a certain amount of reactants and products remain 'unreacted' as the system reaches equilibrium, every time the reaction occurs, the predicted stoichiometric amounts are retained. We can then track how these concentrations change over time, keeping in mind this ratio.

For simplicity, let's use a reaction vessel with a volume of 1.0 L so that each chemical's concentration has the same magnitude as its molar amount. We can then represent how the concentrations of the reactants and products change over time on what is known as a **concentration-time graph**. An example of a concentration-time graph for the scenario depicted above is shown in figure 5.

In figure 5, we can see that the system starts with the concentrations of $[H_2]$ = 3.0 M and $[N_2]$ = 1.0 M since those were the two reactants we start with at the time t_0. The initial concentration of NH_3 is, as we expect, 0 M as we don't start with any NH_3 in the system.

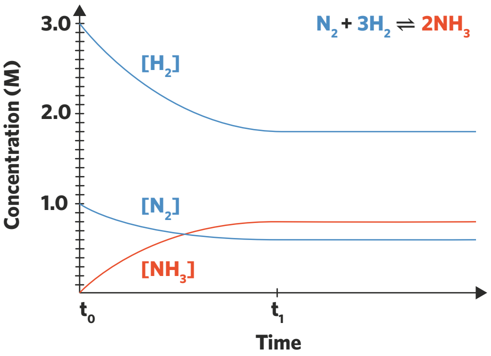


Figure 5 Concentration-time graph of $N_{2(g)} + 3H_{2(g)} \rightleftharpoons 2NH_{3(g)}$ as the system reaches equilibrium

As the reaction proceeds, we can see that the concentration of H_2 has changed to 1.8 M (a 1.2 M decrease), the concentration of N_2 has changed to 0.6 M (a 0.4 M decrease) and the concentration of NH_3 has changed to 0.8 M (a 0.8 M increase). Graphically, this means that the amount each curve moves (up or down) from its initial concentration is equal to its stoichiometric ratio. This means that the $[H_2]$ curve decreased by 3 times as much as the N_2 curve and the $[NH_3]$ curve increased by 2 times as much as the $[N_2]$ curve decreased. The stoichiometric ratios are preserved in the ratio of the concentration changes.

By analysing the concentration-time graph, we also know that the system has reached dynamic equilibrium by the time t_1 because at this point all of the concentration curves are horizontal, meaning that they have reached a constant concentration.

We also know that at dynamic equilibrium, not only are all the concentrations of reactants and products constant, but the rate of the forward and backward reactions are equal. However, we also have to consider what happens to the rates of forward and backward reactions before the system reaches equilibrium. Similarly to mapping the concentrations over time, we can express this process on what is known as a **rate-time graph**. An example of a rate-time graph for $N_{2(g)} + 3H_{2(g)} \rightleftharpoons 2NH_{3(g)}$ with the same initial concentrations of $[H_2]$ = 3.0 M and $[N_2]$ = 1.0 M is shown in figure 6.

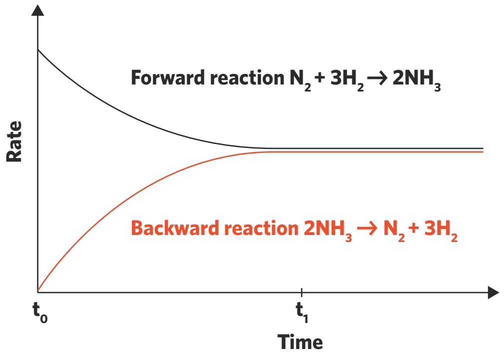
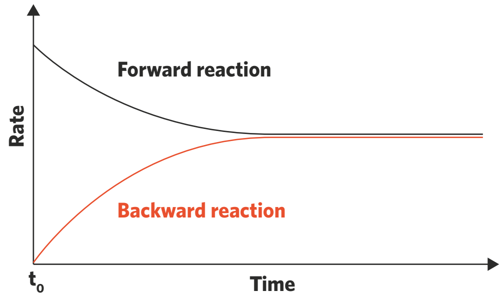


Figure 6 Rate-time graph for the reaction $N_{2(g)} + 3H_{2(g)} \rightleftharpoons 2NH_{3(g)}$

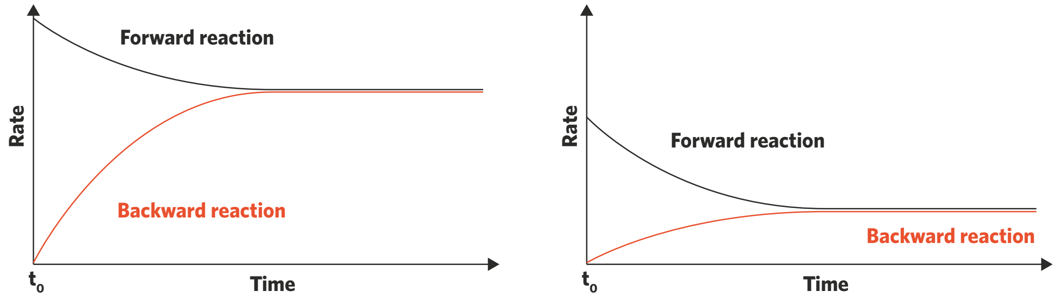
Since the only molecules present initially in the reaction vessel are N_2 and H_2, at time t_0 there is only one way that the reaction can go – forwards. Since no products have been formed yet, the rate of the backward reaction must be zero. This means that the rate of the forward reaction (the black line) starts quite high, whereas the rate of the backward reaction (the red line) begins at zero. As the reaction proceeds, N_2 and H_2 are being converted into NH_3, which increases the concentration of NH_3 present in the reaction vessel. As the concentration of NH_3 increases, the rate of the backward reaction increases also, since the rate of reaction is proportional to concentration. However, since N_2 and H_2 are being consumed, their concentrations are simultaneously decreasing, lowering the rate of the forward reaction.

What we can see on the graph is that as the rate of the forward reaction decreases, the rate of the backward reaction increases until they are equal. At this point, given by the time t_1 on the graph, the system has reached dynamic equilibrium, where the ratio of the concentrations of reactants and products allow for the system to maintain constant and equal rates of the forward and backward reactions.

The ultimate value of the rate of reaction that the system reaches will depend on the environmental conditions inside the reaction vessel, following the same trends we have learned in lessons 5A, 5B and 5C. A summary of how these conditions affect the rate-time graph of an equilibrium reaction is given in figure 7. All rate-time graphs are given for a system that initially only contains reactants and track the reaction as it reaches equilibrium. Note that these graphs are purely qualitative, as the degree of the changes will also depend on how much each condition is altered (for example, whether the volume increased was increased by a factor of 2 or 200). The important elements are what the rates of reaction are at equilibrium and how quickly equilibrium is established.

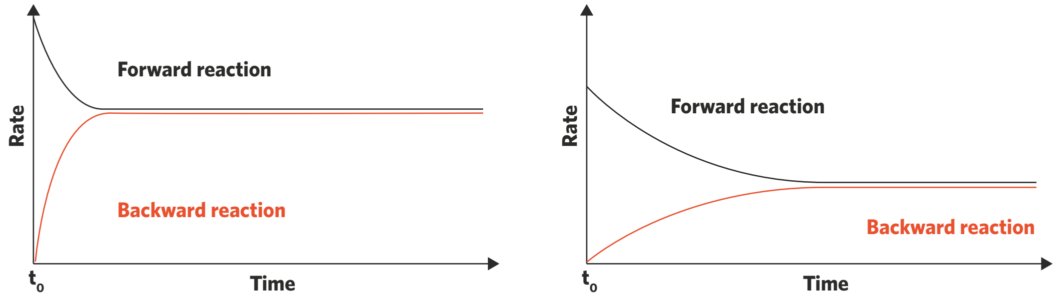


Generic reaction rate-time graph



Increased concentrations or decreased volume

Decreased concentrations or increased volume



Increased temperature or with catalyst

Decreased catalyst or without catalyst

Figure 7 Rate-time graphs showing the general trends for changes in experimental conditions

1 Worked example

Phosphorous pentachloride decomposes according to the following equilibrium reaction.

$PCl_{5(g)} \rightleftharpoons PCl_{3(g)} + Cl_{2(g)}$

For a reaction vessel with volume 3.0 L, 4.0 mol of PCl_5 was initially the only species present at a time t_0. If equilibrium is established at a time t_1 and the final concentration of Cl_2 is 0.50 M, draw a concentration-time graph showing how the concentrations of all species change over time.

What information is presented in the question?

The balanced reaction for the decomposition of phosphorous pentachloride.

The volume of the reaction vessel.

The initial amount of PCl_5 present.

The final concentration of Cl_2 once equilibrium was established .

What is the question asking us to do?

Draw a concentration-time graph for the reaction system.

What strategy(ies) do we need in order to answer the question?

1. Calculate the initial concentration of PCl_5.
2. Determine the concentration change of PCl_5.
3. Determine the concentration change of PCl_3 and Cl_2 by considering the molar ratios of the reaction.
4. Graph the change over time of these concentrations.

Answer

$[PCl_5]$ initial $= \frac{n}{V} = \frac{4.0}{3.0} = 1.33$ M

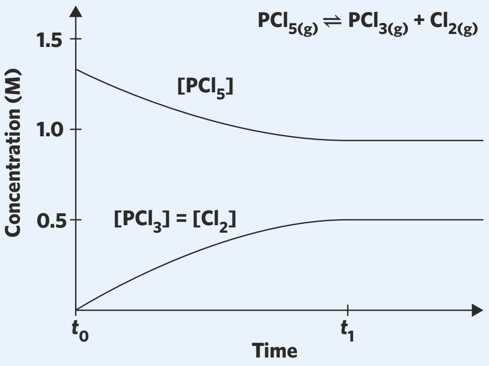
$[PCl_3]$ initial and $[Cl_2]$ initial are both equal to 0.

For every 1 mol of PCl_5 that reacts, 1 mol of Cl_2 is produced, so if $[Cl_2]$ at equilibrium has increased from 0 M to 0.50 M, then $[PCl_5]$ has decreased by 0.50 M.

This gives an equilibrium concentration of PCl_5 of 1.33 – 0.50 = 0.83 M.

Since the mole ratio of Cl_2 and PCl_3 is 1:1, the concentration of PCl_3 at equilibrium must also have increased from 0 M to be equal to 0.50 M.

All of these initial and final concentrations can be graphed on a concentration-time graph. Since equilibrium is established at a time t_1, at this point all concentrations must be constant.



Equilibrium law & equilibrium constant 3.2.7.1

OVERVIEW

The ratios of concentrations of reactants and products of a certain chemical reaction provide insight into the dynamics of an equilibrium system. This is given a specific value, known as the equilibrium constant.

THEORY DETAILS

We have established so far that if a mixture of reactants and products are put into a system and allowed to react, they will reach a middle-ground with their concentrations constant, which we have defined as a state of dynamic equilibrium. Importantly, the concentrations of reactants and products present when the system reaches dynamic equilibrium, although they are constant, will depend entirely on the amounts of reactants and products that were initially present in the reaction vessel.

In previous sections we have been using the scenario in which 3.0 mol of H_2 and 1.0 mol of N_2 are placed into a 1.0 L reaction vessel and allowed to reach dynamic equilibrium. We considered the result that the final equilibrium concentrations were $[H_2] = 1.8$ M, $[N_2] = 0.6$ M and $[NH_3] = 0.8$ M. We will see that the final state of the system once it reaches equilibrium can have very different final concentrations of reactants and products depending on these initial concentrations.

However, since a system in dynamic equilibrium always has reactants and products at constant concentrations, it would make sense that there is some constant specific to the reaction to describe this. This constant is known as the **equilibrium constant**, with the symbol K_c (the c denotes 'concentration').

For the general reaction $aA + bB \rightleftharpoons cC + dD$ it has the value:

$$K_c = \frac{[C]^c[D]^d}{[A]^a[B]^b}$$

The expression for K_c has the product of the concentrations of the products divided by the product of the concentrations of the reactants – i.e. $K_c \sim \frac{[\text{products}]}{[\text{reactants}]}$ and the coefficients of the equilibrium reaction become the indices for each of their respective species. This would mean that if '$2NO_2$' appears in the reaction, then it would be represented as $[NO_2]^2$ in the equilibrium expression.

The value of K_c is specific only to a given temperature at which the reaction is occurring. The relationship between K_c and temperature depends on whether the reaction is exothermic or endothermic.

For forward endothermic reactions, an increase in temperature will lead to an increase in the value of K_c. For forward exothermic reactions, an increase in temperature will lead to a decrease in the value of K_c.

Tip Temperature is the only factor that can affect the value of K_c.

Since temperature is the only variable that can affect the value of K_c, any changes in pressure, volume, reactant or product amounts or the addition of a catalyst will not change the measured value of K_c. Adding or removing products will, of course, change the concentrations of the reactants and products but the system will move towards new equilibrium concentrations that still keep the expression for K_c balanced. A more detailed discussion of the mechanism behind this 'rebalancing', as well as the dependence of K_c on the temperature of the reaction, can be found in the next lesson (5E).

For the Haber process, the reaction would have the expression for its equilibrium constant given by:

$$1N_{2(g)} + 3H_{2(g)} \rightleftharpoons 2NH_{3(g)}$$

$$K_c = \frac{[NH_3]^2}{[N_2]^1[H_2]^3}$$

If we substitute in the concentrations present at equilibrium above (assuming the reaction was performed at constant temperature), we can calculate the value for the equilibrium constant as:

$$K_c = \frac{(0.8)^2}{(0.6) \times (1.8)^3} \approx 0.183$$

We also have to consider the units for the equilibrium constant.
Since each concentration is measured in M or mol L^{-1}, the units of the equilibrium constant can be calculated by:

$$\frac{M^2}{M \times M^3} = \frac{M^2}{M^4} = M^{2-4} = M^{-2}$$

or $(\text{mol}\,L^{-1})^{-2} = \text{mol}^{-2}\,L^2$

This gives us an overall value of the equilibrium constant as $K_c = 0.183\ M^{-2}$.

It is quite difficult to give any real physical meaning to a unit such as $\text{mol}^{-2}\,L^2$, but the convention is still to list any value with its units. Substituting M or mol L^{-1} for the concentrations in the equilibrium expression allows the units for the equilibrium constant to be determined for any reaction.

An interesting situation occurs when calculating the units for a reaction with an equal number of reactants and products. For example, in the reaction $H_{2(g)} + I_{2(g)} \rightleftharpoons 2HI_{(g)}$, the equilibrium constant is given by $K_c = \frac{[HI]^2}{[H_2][I_2]}$ and would have the units $\frac{M^2}{M \times M} = \frac{M^2}{M^2} = 1$.
For this reaction, we would say that the equilibrium constant has no units.

For the initial concentrations we have been using throughout this lesson, we have determined that the equilibrium constant was approximately equal to 0.183 M^{-2}. If we had instead considered a different set of initial concentrations, we would find that the value of the equilibrium expression does not change. The following table gives a few examples of different initial concentrations and the concentrations present in the system once equilibrium has been established. All these values are given for the same temperature as the reaction vessel above.

Table 1 Initial and equilibrium concentrations for the reaction $N_{2(g)} + 3H_{2(g)} \rightleftharpoons 2NH_{3(g)}$ at constant temperature

Initial			**Equilibrium**			K_c	
$[N_2]$	$[H_2]$	$[NH_3]$	$[N_2]$	$[H_2]$	$[NH_3]$		
1.00	3.00	0.00	0.60	1.80	0.80	$\frac{(0.8)^2}{(0.6) \times (1.8)^3}$	0.183
2.00	6.00	0.00	0.965	2.895	2.070	$\frac{(2.070)^2}{(0.965) \times (2.895)^3}$	0.183
1.00	1.00	1.00	1.129	1.387	0.742	$\frac{(0.742)^2}{(1.129) \times (1.387)^3}$	0.183
0.00	0.00	10.0	1.719	5.156	6.563	$\frac{(6.563)^2}{(1.719) \times (5.156)^3}$	0.183

Any time the system is not at equilibrium, the number calculated from the expression above is known as the **reaction quotient** with the symbol Q_c. Unlike K_c, Q_c can take any positive or zero value (except that of K_c) for a given temperature.

If, instead of the concentrations at equilibrium, we had taken the concentrations of the reactants and products at the beginning of the reaction, we could calculate the value of Q_c as:

$$Q_c = \frac{(0)^2}{(1.0) \times (3.0)^3} = 0 \text{ M}^{-2}$$

The value of Q_c can give us valuable information about what is occurring inside the reaction vessel at that time. For the Haber process example, the value of K_c (0.183) is greater than that of Q_c (0). Recall that the equilibrium constant can be thought of as some value that involves the concentrations of the products being divided by the concentrations of the reactants – with $K_c \sim \frac{[\text{products}]}{[\text{reactants}]}$. In this situation, the value for Q_c is 'too small.' The only way to increase it is to increase the numerator of our 'concentration fraction' and decrease the denominator. That is, we have to convert more reactants to products. At this point in time, the forward reaction has to be favoured. This does not mean that the backward reaction is not occurring at all, just that it is occurring at a lower rate, so the overall shift is towards the formation of products.

This would make sense as the reaction vessel only contained reactants – it can only go forward. In fact, the forward reaction will be favoured, gradually increasing Q_c until it reaches the value of K_c, at which point the system is at equilibrium.

If the value of Q_c had been greater than that of K_c, we would need to decrease its value by converting products to reactants. Therefore, as the system reached equilibrium, the reverse reaction would be favoured. This situation is explored in worked example 2.

In figure 8 we can see that the way the system moves to establish equilibrium depends on the value of Q_c. This concept can be compared to a boulder on the incline of one of two separate hills – the boulder will roll either forward or backward depending on its position relative to the system's equilibrium (represented here by the valley between the two hills).

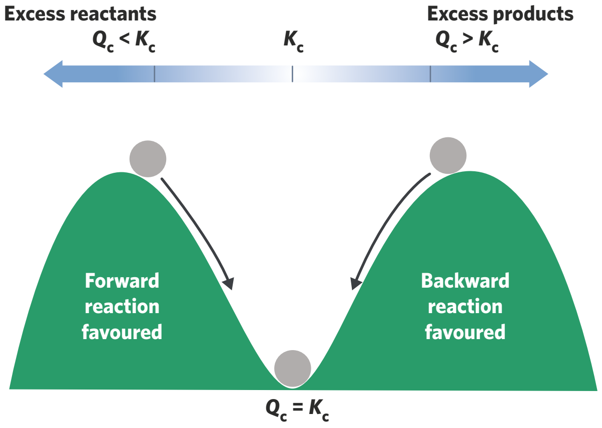


Figure 8 The system will move to establish equilibrium either by favouring the forward or backward reaction. The value of Q_c relative to K_c will determine the direction in which the overall reaction proceeds until it reaches equilibrium.

2 Worked example

At a particular temperature, the value of K_c for the reaction

$CO_{(g)} + Cl_{2(g)} \rightleftharpoons COCl_{2(g)}$

is equal to $4.3\ M^{-1}$. A 2.00 L reaction vessel contains 0.060 mol of CO, 0.50 mol of Cl_2 and 0.34 mol of $COCl_2$.

a. Write the equilibrium expression for the reaction.

b. Calculate the value of Q_c and hence determine whether the reaction vessel is in dynamic equilibrium. If not, how will the system act to establish equilibrium?

---

a. Write the equilibrium expression for the reaction.

What information is presented in the question?

The balanced equilibrium reaction equation.

What is the question asking us to do?

Give the equilibrium expression for the reaction given.

What strategy(ies) do we need in order to answer the question?

1. Take into account the coefficients of the reactants and products, which will become indices.
2. Remember that the equilibrium expression involves the reactants divided by the products.

Answers

$$K_c = \frac{[COCl_2]^1}{[CO]^1 \times [Cl_2]^1}$$

$$K_c = \frac{[COCl_2]}{[CO][Cl_2]}$$

---

b. Calculate the value of Q_c and hence determine whether the reaction vessel is in dynamic equilibrium. If not, how will the system act to establish equilibrium?

What information is presented in the question?

The amounts of reactants and products.

The volume of the reaction vessel.

The value of the equilibrium constant K_c.

The balanced equilibrium reaction equation.

What is the question asking us to do?

Calculate Q_c and use it to determine how the system will re-establish equilibrium.

What strategy(ies) do we need in order to answer the question?

1. Calculate the concentrations of the reactants and products.
2. Calculate the value of Q_c and compare it to the value of K_c.
3. Use this to determine how the system will move to restore equilibrium with reference to the rate of the forward and backward reactions.

Answers

$$[CO] = \frac{0.060}{2.00} = 0.030\ M$$

$$[Cl_2] = \frac{0.50}{2.00} = 0.25\ M$$

$$[COCl_2] = \frac{0.34}{2.00} = 0.17\ M$$

The expression for Q_c is the same as K_c, so:

$$Q_c = \frac{[COCl_2]}{[CO][Cl_2]}$$

$$Q_c = \frac{(0.17)}{(0.030) \times (0.25)}$$

$$Q_c = 22.67 = 23\ M^{-1}$$

Since $Q_c \neq K_c$, the system is **not** at equilibrium. In fact, $Q_c > K_c$ which means that the relative concentration of the products is too high. As a result, the system will favour the backward reaction until it has re-established equilibrium.

The value of K_c can also give an indication of the extent of the reaction. Similar to the logic we used to investigate Q_c, which was the fact that $K_c \sim \frac{[\text{products}]}{[\text{reactants}]}$, the magnitude of K_c is an approximate measure of the ratio of products to reactants. If there are significantly greater quantities of products than reactants present at equilibrium, then the reaction will have a high value for K_c. If instead there are significantly greater quantities of reactants than products still present in the reaction vessel at equilibrium, then the value of K_c will be very low. The standard boundaries for what is considered to be a ‘high’ or ‘low’ value of K_c are approximately 10^4 and 10^{-4} respectively. Any reaction with a K_c value between these two boundaries is usually considered to have a mixture of both reactants and products.

A reaction with a K_c value greater than 10^4 is almost a complete reaction (i.e. nearly all reactants are converted to products). On the other hand, a reaction with a K_c value less than 10^{-4} only occurs to a negligible extent (i.e. only a small quantity of reactants are converted to products). This information is summarised in figure 9.

An example of an equilibrium reaction with an exceptionally high value of K_c is the reaction $2H_{(g)} \rightleftharpoons H_{2(g)}$, which has the equilibrium constant $K_c = 10^{36}$ at 25 °C. Although this reaction can technically be reversed, when K_c is so large, such reactions are considered to be effectively irreversible.

Figure 9 The magnitude of K_c is an indicator of the ratio of reactants to products present at equilibrium

Calculations involving equilibrium reactions 3.2.7.2

OVERVIEW

Calculations with reactions involved in equilibrium systems can be understood through stoichiometry and the expression for the equilibrium constant.

THEORY DETAILS

As we discovered in previous sections, although reactants in an equilibrium system will not react completely until there are none left, the amounts that do react do so in the stoichiometric ratios predicted by the equation. This gives us a large amount of insight in predicting amounts and concentrations of reactants and products present in an equilibrium system. We can combine these stoichiometric principles with our new knowledge of the equilibrium constant to calculate what is happening to concentrations for an equilibrium reaction.

One tool that is useful in analysing equilibrium reactions is what is known as an 'ICE table', which allows us to visualise the changes in concentrations or amounts of reactants and products. The acronym refers to the amounts present at the **I**nitial, **C**hanging and **E**quilibrium stages in the reaction. We can also specify whether we are dealing with molar amounts, concentrations, or in the case of a gaseous equilibrium reaction, volumes. Remember that in all these situations, the stoichiometric rules that our calculations follow will be the same. An example of an ICE table is shown in table 2 for the Haber process reaction with the same initial and final amounts described above.

Table 2 ICE table representing the reaction $N_{2\,(g)} + 3H_{2\,(g)} \rightleftharpoons 2NH_{3\,(g)}$ with given starting amounts

Molar amount (mol)	$N_{2(g)}$	$3H_{2(g)} \rightleftharpoons$	$2NH_{3(g)}$
n	1	3	2
Initial	1.00	3.00	0.00
Change	- 0.40	- 1.20	+ 0.80
Equilibrium	0.60	1.80	0.80

We can generalise the table so that it can represent this reaction for any combination of initial reactant and product concentrations. As shown in table 3, all our values are given as concentrations, not molar amounts since they are easier to work with when we consider the equilibrium constant in our calculations as well.

Notice how the values listed in 'Change' are negative on the reactants' side, as they are being consumed, and positive on the products' side, as they are being produced. This is because a net forward reaction has occurred to establish equilibrium. For a net backward reaction, the amount of reactants changing would be positive and the amount of products would decrease, making it negative. For this reaction, the values also appear in the correct stoichiometric ratio of 1:3:2. We can use both these pieces of information and the other rows in our table to solve for unknown values in equilibrium reactions. One such problem is explored in worked example 3.

Table 3 ICE table representing the reaction $N_{2(g)} + 3H_{2(g)} \rightleftharpoons 2NH_{3(g)}$ with unknown starting concentrations

Concentration (mol L^{-1})	$N_{2(g)}$	$3H_{2(g)} \rightleftharpoons$	$2NH_{3(g)}$
n	1	3	2
Initial	a	b	c
Change	$-x$	$-3x$	$+2x$
Equilibrium	$a-x$	$b-3x$	$c+2x$

3 Worked example

Hydrogen and iodine gas react together to form hydrogen iodide according to the following equilibrium reaction.

$H_{2(g)} + I_{2(g)} \rightleftharpoons 2HI_{(g)}$

For a reaction vessel with volume 5.0 L, 0.40 mol of H_2, 0.70 mol of I_2 and 0.10 mol of HI was present initially, and the mixture was allowed to reach equilibrium at constant temperature. At equilibrium, the concentration of HI was determined to be 0.14 M.

a. Calculate the amount of H_2, in mol, that reacted as the system reached equilibrium.

b. Calculate the value of the equilibrium constant for this reaction.

---

a. Calculate the amount of H_2, in mol, that reacted as the system reached equilibrium.

What information is presented in the question?

The balanced equilibrium reaction equation.

The amounts, in mol, of reactants and products present initially.

The concentration of HI that is present at equilibrium.

What is the question asking us to do?

Determine how much H_2, in mol, reacted.

What strategy(ies) do we need in order to answer the question?

1. Take into account the coefficients of the reactants and products, which will become indices.
2. Remember that the equilibrium expression involves the reactants divided by the products.

Answer

Since the majority of values we are given are in mol and the question is asking for an answer in mol, we will use an ICE table with molar amounts. For the initial molar amounts, we are given that $n(H_2) = 0.40$, $n(I_2) = 0.70$ and we can calculate $n(HI) = 0.14\ M \times 5.0\ L = 0.70$ mol. Since the amount of HI has increased from its initial amount, we know that there has been a net forward reaction.

We can put all this information, along with the amounts that will be 'changing' in their correct ratios. The pronumeral *x* represents the unknown reacting amount and this amount depends on the mol ratios. Remember also that for a net forward reaction, the amount changing for a reactant is negative and is positive for a product.

Molar amount (mol)	$H_{2(g)}$	$H_{2(g)} \rightleftharpoons$	$2HI_{2(g)}$
n	1	1	2
Initial	0.40	0.70	0.10
Change	$-x$	$-x$	$+2x$
Equilibrium	$0.40 - x$	$0.70 - x$	$0.10 + 2x = 0.70$

Looking at the equilibrium cell for HI, we know that we started with 0.10 mol, that for every 1 mol of *x* that reacted, 2*x* mol of HI was produced, and also that the final amount of HI was 0.70 mol. This gives us the equation:

$0.10 + 2x = 0.70$

Solving for *x* gives us $x = 0.30$ mol.

Therefore, the amount of H_2 that reacted as the system reached equilibrium was 0.30 mol.

---

b. Calculate the value of the equilibrium constant for this reaction.

What information is presented in the question?

The volume of the reaction vessel.

The balanced equilibrium reaction equation.

Some of the molar amounts of reactants and products present at equilibrium.

What is the question asking us to do?

Calculate K_c.

What strategy(ies) do we need in order to answer the question?

1. Calculate the amounts, then the concentrations of the reactants and products present at equilibrium.
2. Determine the expression for the equilibrium constant.
3. Substitute in the calculated equilibrium concentrations.

Answer

We have already calculated in **a.** that the amount of H_2 and I_2 that reacted was equal to 0.30 mol. Therefore, we can fill out the rest of the ICE table with the true values. Since concentrations are required for calculating the equilibrium constant, we will also include an extra row in the table to represent these amounts converted back to concentrations.

The volume of the reaction vessel is given as 5.0 L.

We can put all this information, along with the amounts that will be 'changing' in their correct ratios. The pronumeral *x* represents the unknown reacting amount and this amount depends on the mol ratios. Remember also that for a net forward reaction, the amount changing for a reactant is negative and is positive for a product.

Molar amount (mol)	**$H_{2(g)}$**	**$H_{2(g)} \rightleftharpoons$**	**$2HI_{2(g)}$**
n	1	1	2
Initial	0.40	0.70	0.10
Change	$-x$	$-x$	$+2x$
Equilibrium	$0.40 - x$	$0.70 - x$	$0.10 + 2x = 0.70$
Concentration **[ ]**	$\frac{0.10}{5.0} = 0.020$	$\frac{0.40}{5.0} = 0.080$	$\frac{0.70}{5.0} = 0.14$

The equilibrium expression for this reaction is $K_c = \frac{[HI]^2}{[H_2][I_2]}$

We have calculated that at equilibrium $[H_2] = 0.020$ M, $[I_2] = 0.080$ M and $[HI] = 0.14$ M.

Therefore, the value of the equilibrium constant is given by:

$K_c = \frac{(0.14)^2}{(0.02) \times (0.08)} = 12.25$ (no units).

Dependance of K_c on the equation used to represent the reaction

In previous sections, we noted that the equilibrium expression depends not only on the concentrations of reactants and products, but also the coefficients or the stoichiometric ratio of the reaction. We will now explore the effect of changing the mole ratios and direction of equilibrium reactions on the value of the equilibrium constant.

Remember that for the Haber process $N_{2(g)} + 3H_{2(g)} \rightleftharpoons 2NH_{3(g)}$, we discovered that:

$$K_1 = \frac{[NH_3]^2}{[N_2][H_2]^3}$$

If instead we had considered the reaction $2N_{2(g)} + 6H_{2(g)} \rightleftharpoons 4NH_{3(g),}$ it would have the equilibrium expression $K_2 = \frac{[NH_3]^4}{[N_2]^2[H_2]^6}$.

This expression can be rewritten as $K_2 = \frac{([NH_3]^2)^2}{([N_2])^2([H_2]^3)^2} = \left(\frac{[NH_3]^2}{[N_2][H_2]^3}\right)^2 = (K_1)^2$

So, by multiplying all the coefficients of the first reaction by 2, we have obtained an equilibrium constant for the second reaction that is the square of the first reaction – it was raised to the power of 2.

In general, for a reaction with the equilibrium constant K_1 that has been multiplied by some factor *n*, the value for the new equilibrium constant K_2 is given by:

$$K_2 = (K_1)^n$$

We can also determine the value of the equilibrium constant for reactions that have been 'reversed' or 'flipped'. For the reverse reaction in the Haber process $2NH_{3(g)} \rightleftharpoons N_{2(g)} + 3H_{2(g)}$, the equilibrium expression can be calculated as:

$$K_{-1} = \frac{[N_2][H_2]^3}{[NH_3]^2}$$

This is very similar to K_1, but the fraction has been 'flipped.' In fact, this expression can be rewritten as $K_{-1} = \frac{1}{\frac{[NH_3]^2}{[N_2][H_2]^3}} = \frac{1}{K_1} = (K_1)^{-1}$

This would make sense as a forward reaction that has a very high value of K_c strongly favours the formation of products. If K_c is very large, then $\frac{1}{K_1}$ is very small, meaning that the reverse reaction is not favoured.

In summary, this means that if we consider reversing the direction of an equilibrium reaction as 'multiplying by –1,' our result $K_2 = (K_1)^n$ still holds true.

More complicated calculations with equilibrium constants can occur when we add multiple reactions together. We have already explored this situation in Chapter 3 when we calculated enthalpy changes in reactions that had been combined in some way. Here, let's consider the reactions:

1 $2NO_{(g)} \rightleftharpoons N_{2(g)} + O_{2(g)}$ $\quad K_1$

2 $2CO_{(g)} + O_{2(g)} \rightleftharpoons 2CO_{2(g)}$ $\quad K_2$

We can quite easily determine the equilibrium expressions for K_1 and K_2:

$$K_1 = \frac{[O_2][N_2]}{[NO]^2} \text{ and } K_2 = \frac{[CO_2]^2}{[CO]^2[O_2]}$$

However, if we wanted to calculate the value of the equilibrium expression for the reaction:

3 $2NO_{(g)} + 2CO_{(g)} \rightleftharpoons N_{2(g)} + 2CO_{2(g)} \qquad K_3$

it would appear to be much more difficult. The first step would be to recognise that this third reaction can be obtained by adding the first and second one together, with the $O_{2(g)}$ removed since it will appear on both sides of the equation. What we can also do is derive an expression for K_3 as if it were simply a reaction on its own: $K_3 = \frac{[N_2][CO_2]^2}{[NO]^2[CO]^2}$

If we consider the $O_{2(g)}$ that was removed on both sides of equation (3), this expression can be rewritten as $K_3 = \frac{[O_2][N_2][CO_2]^2}{[NO]^2[CO]^2[O_2]} = \frac{[O_2][N_2]}{[NO]^2} \times \frac{[CO_2]^2}{[CO]^2[O_2]} = K_1 \times K_2$

A third reaction formed from adding two reactions has its equilibrium constant given by the product of the equilibrium constants of the reactions that formed it.

Calculations involved in manipulating reactions and the value of equilibrium constants are explored in worked example 4.

4 Worked example

The equilibrium reaction for the formation of sulfur trioxide is given by:

1 $2SO_{2(g)} + O_{2(g)} \rightleftharpoons 2SO_{3(g)}$

It has the equilibrium constant $K_c = 1600\ M^{-1}$ at a certain temperature.

Calculate the value of the equilibrium constant for the reaction:

2 $SO_{3(g)} \rightleftharpoons SO_{2(g)} + \frac{1}{2}O_{2(g)}$

given that it occurs at the same temperature.

What information is presented in the question?

The balanced reaction for the formation of sulfur trioxide.

The equilibrium constant for this reaction at a certain temperature.

A version of this equilibrium reaction that contains the same chemical species but in different ratios and that has been reversed.

Both reactions are occurring at the same temperature.

What is the question asking us to do?

Calculate the value of the equilibrium constant for reaction 2.

What strategy(ies) do we need in order to answer the question?

1. Determine how to express reaction 2 in terms of reaction 1.
2. Determine how this affects the value of the equilibrium constant for reaction 1.
3. Use the formula $K_2 = (K_1)^n$ to calculate the equilibrium constant for reaction 2.

Answer

Reaction 2 can be formed by reversing reaction 1 and multiplying the mole ratios by a factor of $\frac{1}{2}$ (the order does not matter).

This means that we will have to raise the equilibrium constant for reaction 1 to the power of –1 and also to the power of $\frac{1}{2}$.

Applying the formula $K_2 = ((K_1)^{-1})^{\frac{1}{2}} = (K_1)^{-\frac{1}{2}}$, we can substitute in the given value for $K_1 = 1600\ M^{-1}$ and calculate:

$K_2 = ((1600\ M^{-1})^{-1})^{\frac{1}{2}} = \frac{1}{\sqrt{1600}} = 0.025\ M^{\frac{1}{2}}$

Theory summary

- Chemical reactions are classified as either ‘reversible’ or ‘irreversible’ depending on whether they can be returned to their initial state.
- Reversible reactions can also be described as equilibrium reactions and use ‘bidirectional harpoons’ $\rightleftharpoons$ to represent how the reaction can proceed both forwards and backwards.
- Reactions can be described both by their rate, which defines how quickly the reaction proceeds and by their extent, which defines how far the reaction proceeds and depends on the final concentrations of reactants and products.
- A homogenous equilibrium is one in which all reactants and products are in the same physical state (solid, liquid or gas).

- A system in dynamic equilibrium has
  - constant concentrations and amounts of reactants and products.
  - constant pressure.
  - constant temperature.
  - the forward and backward reactions occurring at the same rate.
- Equilibrium systems can be graphically represented as they establish equilibrium on both concentration-time graphs and rate-time graphs.
- The equilibrium constant for the reaction $aA + bB \rightleftharpoons cC + dD$ has the expression $K_c = \frac{[C]^c[D]^d}{[A]^a[B]^b}$. It represents the ratio of the concentrations of reactants and products that are present during dynamic equilibrium.
- The units of K_c can be calculated by substituting M or $mol\,L^{-1}$ for each concentration in the equilibrium expression.
- The value of K_c can only be affected by a change in temperature.
  - An increase in temperature will decrease the value of K_c for an exothermic reaction and increase its value for an endothermic reaction.
  - A decrease in temperature will increase the value of K_c for an exothermic reaction and decrease its value for an endothermic reaction.
- If a system is not at equilibrium, the equilibrium expression, K_c, is instead known as the reaction quotient, Q_c, which will dictate whether a net forward or backward reaction occurs to establish equilibrium.
- The concentrations of reactants and products in equilibrium reactions can be modeled using an ICE table to solve calculations involving unknown concentrations.
- A reaction with equilibrium constant K_1, if multiplied by some number n, will have the new equilibrium constant $K_2 = (K_1)^n$
  - For such calculations, reversing the reaction can be considered as multiplying it by –1.

5D QUESTIONS

Theory review questions

Question 1

Which of the following is **not** true for a system in dynamic equilibrium?

A Reactants are constantly being formed.

B The rate of the forward reaction is equal to the rate of the backward reaction.

C The temperature steadily increases over time.

D The total gas pressure of the system is constant.

Question 2

For a system in dynamic equilibrium, its concentration-time graph will show that

A all concentrations are equal.

B all concentrations are constant.

C all concentrations are both constant and equal.

D initially the concentration of reactants decreased.

Question 3

An exothermic reaction subjected to an increase in temperature will have

A an increased rate of reaction and an increase in K_c.

B an increased rate of reaction and a decrease in K_c.

C a decreased rate of reaction and an increase in K_c.

D a decreased rate of reaction and a decrease in K_c.

Question 4

The rate-time graph of an equilibrium reaction could be used to determine

I how quickly the forward and reverse reactions are occurring.

II when the system has reached equilibrium.

III whether a net forward or backward reaction has occurred.

IV whether a reaction is endothermic or exothermic.

A I, II **B** II, III **C** I, II, III **D** I, II, IV

Question 5

If an equilibrium reaction were observed to go almost to completion (almost no reactants remaining), which of the following could we conclude about the reaction?

I The forward reaction is exothermic.

II The value of K_c for the forward reaction is greater than the value of K_c for the backward reaction.

III If the temperature were increased, the reaction would reach equilibrium faster.

IV If a catalyst were later added, the reaction would continue to an even greater extent.

A II only **B** II, III **C** II, III, IV **D** III, IV

Question 6

For a given reaction vessel, if the value of Q_c is greater than the value of K_c at a constant temperature

A the system will establish equilibrium by favouring the reverse reaction.

B the system will establish equilibrium by favouring the forward reaction.

C the value of Q_c will continue to increase exponentially.

D the system is said to be in dynamic equilibrium.

Exam-style questions

Within lesson

Question 7 (1 MARK)

The value of K_c for a reaction depends on both the reaction itself and the temperature at which it is occurring. Of the following four reactions, select the one that will have substantially more reactants than products present at equilibrium.

A $2SO_{2(g)} + O_{2(g)} \rightleftharpoons 2SO_{3(g)}$ $K_c = 4.71 \times 10^{-6}$

B $2H_2O_{(g)} + 2Cl_{2(g)} \rightleftharpoons 4HCl_{(g)} + O_{2(g)}$ $K_c = 0.269$

C $2NO_{2(g)} \rightleftharpoons N_2O_{4(g)}$ $K_c = 3.84 \times 10^{9}$

D $2NO_{(g)} + 2H_{2(g)} \rightleftharpoons N_{2(g)} + 2H_2O_{(g)}$ $K_c = 78\ 675.6$

Question 8 (1 MARK)

$2NO_{2(g)} \rightleftharpoons N_2O_{4(s)}$

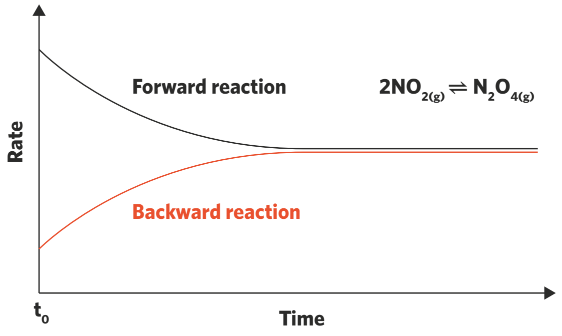
For the given equilibrium reaction, the rate-time graph shown would best represent which of the following scenarios?

A The reaction vessel initially contained only $NO_{2(g)}$.

B The reaction vessel initially contained only $N_2O_{4(g)}$.

C The reaction vessel initially contained both molecules, but there was a higher concentration of $NO_{2(g)}$.

D The reaction vessel initially contained both molecules, but there was a higher concentration of $N_2O_{4(g)}$.



Question 9 (4 MARKS)

A 7.0 L reaction vessel at 4 atm at a time $t = 0$ s contained 3.0 mol of $NO_{(g)}$, 2.0 mol of $N_{2(g)}$ and 1.0 mol of $O_{2(g)}$. These species reacted according to the given equilibrium reaction.

$2NO_{(g)} \rightleftharpoons N_{2(g)} + O_{2(g)}$

a Calculate the value of Q_c at $t = 0$. (2 MARKS)

b It was found that the K_c value for this reaction is 8.0. What would occur in the reaction vessel in order to establish equilibrium? (1 MARK)

c If the experimenter conducted the reaction $N_{2(g)} + O_{2(g)} \rightleftharpoons 2NO_{(g)}$, calculate the K_c value of this reaction. (1 MARK)

Question 10 (7 MARKS)

Carbon monoxide and chlorine gas can react together according to the following equilibrium equation to form phosgene, a highly toxic, colourless gas.

$CO_{(g)} + Cl_2 \rightleftharpoons COCl_{2(g)}$

In a sealed 7.5 L reaction vessel kept at a constant temperature, 3.0 mol of CO and 5.6 mol of Cl_2 was released. When the system had reached equilibrium after 100 seconds, it was found that the concentration of $COCl_2$ was equal to 0.32 M.

a Determine the concentration of CO and Cl_2 present at equilibrium. (3 MARKS)

b Write the expression for the equilibrium constant for this reaction. (1 MARK)

c Calculate the value of K_c for this reaction at this temperature. (1 MARK)

d Sketch a concentration-time graph for this reaction. (2 MARKS)

Question 11 (12 MARKS)

Nitrosyl chloride NOCl undergoes decomposition into NO and Cl_2 according to the following equilibrium reaction.

$2NOCl_{(g)} \rightleftharpoons 2NO_{(g)} + Cl_{2(g)}$

In a 5.00 L reaction vessel kept at constant temperature and pressure, 10.0 mol of $NOCl_{(g)}$ was injected and allowed to reach equilibrium.

a Explain why the rate of the reaction $2NO_{(g)} + Cl_{2(g)} \rightarrow 2NOCl_{(g)}$ will never be greater than the rate of the reaction $2NOCl_{(g)} \rightarrow 2NO_{(g)} + Cl_{2(g)}$

- **i** as the system reaches equilibrium. (2 MARKS)
- **ii** once equilibrium is established. (2 MARKS)

b **i** At equilibrium, it was found that the concentration of $Cl_{2(g)}$ was equal to 0.600 M. Calculate the value of the equilibrium constant for the reaction at this temperature. (3 MARKS)

- **ii** Calculate the value of the equilibrium constant for the reaction $\frac{2}{3}NO_{(g)} + \frac{1}{3}Cl_{2(g)} \rightleftharpoons \frac{2}{3}NOCl_{(g)}$. (1 MARK)

c Sketch an approximate rate-time graph for this reaction for

- **i** The system described in **a**. (2 MARKS)
- **ii** An otherwise identical system (still with 10.0 mol of $NOCl_{(g)}$), except 1.00 mol of $Cl_{2(g)}$ and 2.00 mol of $NO_{(g)}$ was also initially present in the reaction vessel. (2 MARKS)

Question 12 (14 MARKS)

$2CO_{(g)} + NH_{3(g)} \rightleftharpoons HCN_{(g)} + CO_{2(g)} + H_{2(g)}$

Carbon monoxide reacts with ammonia to form an equilibrium with the products hydrogen cyanide, HCN, as well as carbon dioxide and hydrogen. The balanced equation for this reaction is given above. At a temperature T_1 the reaction has the equilibrium constant $K_c = 0.175$. The industrial scale 7000 L reaction vessel is maintained consistently at this temperature.

a Write an expression for the equilibrium constant, K_c. (1 MARK)

b Initially, the concentrations of reactants were as follows:

$[CO] = 0.163$ M
$[NH_3] = 40.0$ M
$[HCN] = 13.4$ M
$[CO_2] = 15.3$ M
$[H_2] = 19.2$ M

  - **i** At this temperature T_1, in which direction will the reaction proceed in order to establish equilibrium? Justify your answer. (2 MARKS)
  - **ii** Calculate the amount, in grams, of NH_3 present at equilibrium if it is known that the concentration of H_2 at equilibrium was known to be 13.6 M. (2 MARKS)
  - **iii** Hydrogen cyanide, HCN, is a potent toxic gas. Since it is so dangerous, the chemist performing this experiment wanted the equilibrium concentration of HCN to be equal to 0.00100 M. To accomplish this, he decreased the temperature of the reaction vessel to a temperature T_2 until the desired concentration was reached. The initial reactant concentrations were identical. Calculate the value of the equilibrium constant for this reaction at this new temperature. (3 MARKS)
  - **iv** Is the production of HCN via this reaction endothermic or exothermic? Explain. (2 MARKS)

c The chemist tracks the concentrations of reactants and products as the temperature changes on a concentration-time graph until the system reaches equilibrium. At this point, no changes were made to the system or environment. However, a few minutes after this, he observes on the concentration-time graph that the concentration of NH_3 was decreasing and the concentration of HCN was increasing, with all other concentrations remaining constant. He hypothesises that this observation is due to a bug in his analysis software and doesn't actually reflect what is happening in the reaction vessel. Is the chemist justified in making this hypothesis? Explain. (2 MARKS)

d A second method of producing hydrogen cyanide also uses ammonia but instead of carbon monoxide involves methane and oxygen. The equilibrium reaction for this process is given below.

$2CH_{4(g)} + 2NH_{3(g)} + 3O_{2(g)} \rightleftharpoons 2HCN_{(g)} + 6H_2O_{(g)}$

At the same temperature T_1, it is observed that this second reaction results in a much higher rate of production of HCN compared with the process described by the first reaction. From this information alone, is it possible to determine anything about the relative magnitude of this second reaction's equilibrium constant compared with that of the first reaction? Explain. (2 MARKS)

Multiple lessons

Question 13 (8 MARKS)

$2SO_{2(g)} + O_{2(g)} \rightleftharpoons 2SO_{3(g)}$

The given reaction has a value of K_c equal to 12 700 M^{-1} at a constant temperature of 552 °C. A 700.0 L reaction vessel initially contains only $SO_{3(g)}$ at a concentration of 3.00 M.

a Calculate the approximate concentration of $SO_{2(g)}$ present at equilibrium. Assume that the decrease in the concentration of $SO_{3(g)}$ is negligible to its equilibrium concentration. (3 MARKS)

b For any reaction vessel that initially contains only $SO_{3(g)}$, given that this reaction is exothermic, under what conditions (high or low temperature) would this approximation be most valid? Justify your answer. (2 MARKS)

c If the reaction vessel remains at constant volume and temperature, calculate the total pressure inside the vessel when the system is at equilibrium. (3 MARKS)

Question 14 (7 MARKS)

$N_{2(g)} + 3H_{2(g)} \rightleftharpoons 2NH_{3(g)}$

At a certain temperature, the equilibrium constant for the given reaction is equal to 3000 M^{-2}. In a reaction vessel, the concentration of N_2 is 0.400 M, the concentration of H_2 is 0.0700 M and the concentration of NH_3 is 0.800 M.

a Calculate the value of Q_c for the reaction vessel. (1 MARK)

b A supervising chemical engineer calculates that the system is not at equilibrium. Explain why. (1 MARK)

c In which direction will the reaction proceed to establish equilibrium? Justify your answer. (2 MARKS)

d The chemical engineer notes that the value of K_c at this temperature is quite high, yet as she analyses the rate of formation of NH_3, she discovers that it is very low. Suggest a possible reason for this observation. (1 MARK)

e To increase the rate of reaction, the chemical engineer proposes the addition of an iron catalyst into the reaction vessel. Would this increase the amount of NH_3 present at equilibrium? Explain. (2 MARKS)

5E LE CHÂTELIER'S PRINCIPLE

In this lesson, we will learn what happens when a system in equilibrium is subjected to a change in volume, concentration, temperature or pressure.

5A Principles of a chemical reaction	5B Rates of reaction	5C Catalysts	5D Equilibrium reactions	5E Le Châtelier's principle

Study design dot point

- Le Chatelier's principle: identification of factors that favour the yield of a chemical reaction, representation of equilibrium system changes using concentration-time graphs and applications, including competing equilibria involved in the occurrence and treatment of carbon monoxide poisoning resulting from incomplete combustion of fuels.

Key knowledge units

Le Châtelier's principle	3.2.8.1
Effect of adding or removing reactants and products to equilibrium	3.2.8.2.1
Effect of changing volume and pressure on equilibrium	3.2.8.2.2
Effect of inert gases on equilibrium	3.2.8.2.3
Effect of temperature changes on equilibrium	3.2.8.2.4
Carbon monoxide poisoning	3.2.8.3

Key terms and definitions

- **Le Châtelier's principle** underlying principle that states when a system in equilibrium is subjected to a change which disturbs equilibrium, the position of equilibrium will shift to partially counteract the change
- **Competing equilibria** multiple equilibrium reactions competing with one another because they involve either the same reactants or products

Lesson links

This lesson builds on:

- 5D – Equilibrium reactions

Le Châtelier's principle applies to equilibrium reactions.

Le Châtelier's principle 3.2.8.1

OVERVIEW

Le Châtelier's principle is the governing principle of reactions in dynamic equilibrium. It states that when a system is subject to a change which disrupts equilibrium, the system will move to partially counteract this change.

THEORY DETAILS

As we learned in 5D, dynamic equilibrium is reached when the rate of the forward and back reactions are equal. This system will then remain in equilibrium until it is disturbed. After equilibrium has been disturbed, a net reaction will occur to try and restore equilibrium by favouring either the forward or reverse reaction. If a net forward reaction occurs, we can say that the equilibrium position has shifted to the right. If a net backward reaction has occurred, the equilibrium position has shifted to the left.
We will learn how to determine which way equilibrium has shifted later in this lesson.
This basic principle is called **Le Châtelier's principle**, which can be applied when one of the following changes occurs:

- Addition or removal of reactants and/or products at constant volume and temperature
- Change in volume at constant temperature
- Change in pressure at constant volume and temperature
- Change in temperature at constant volume and pressure

It is important to note that the value of the equilibrium constant K_c does not change when the first three of these changes are applied. It is only a change in temperature that will lead to a change in the value of K_c.

Tip Remember the following statement:

Le Châtelier's principle states that when a system in equilibrium is subject to a change which disrupts equilibrium, the system will adjust to **partially** counteract this change.

Effect of adding or removing reactants and products to equilibrium 3.2.8.2.1

OVERVIEW

According to Le Châtelier's principle, the addition or removal of reactants or products will disturb equilibrium, resulting in a change in the position of equilibrium.

THEORY DETAILS

Dynamic equilibrium is a state where the rate of the forward reaction is equal to the rate of the reverse reaction. However, when reactants or products are added or removed at constant volume and temperature, their concentrations change. This in turn disturbs equilibrium, resulting in a change to the system . One of the 4 events highlighted in table 1 will occur in this case.

Table 1 The effect of changes to reactants and products on equilibrium position

Change	Effect on equilibrium position
Addition of reactants	Equilibrium shifts to the right to partially counteract the increase in concentration of the reactants
Removal of reactants	Equilibrium shifts to the left to partially counteract the decrease in concentration of the reactants
Addition of products	Equilibrium shifts to the left to partially counteract the increase in concentration of products
Removal of products	Equilibrium shifts to the right to partially counteract the decrease in concentration of products

The following rate-time graph for the equilibrium reaction $H_{2(g)} + I_{2(g)} \rightleftharpoons 2HI_{(g)}$ when $H_{2(g)}$ is added at constant volume is shown in figure 1. This is not required for the purposes of the VCE study design, but can be helpful in understanding why the forward or back reaction is favoured.

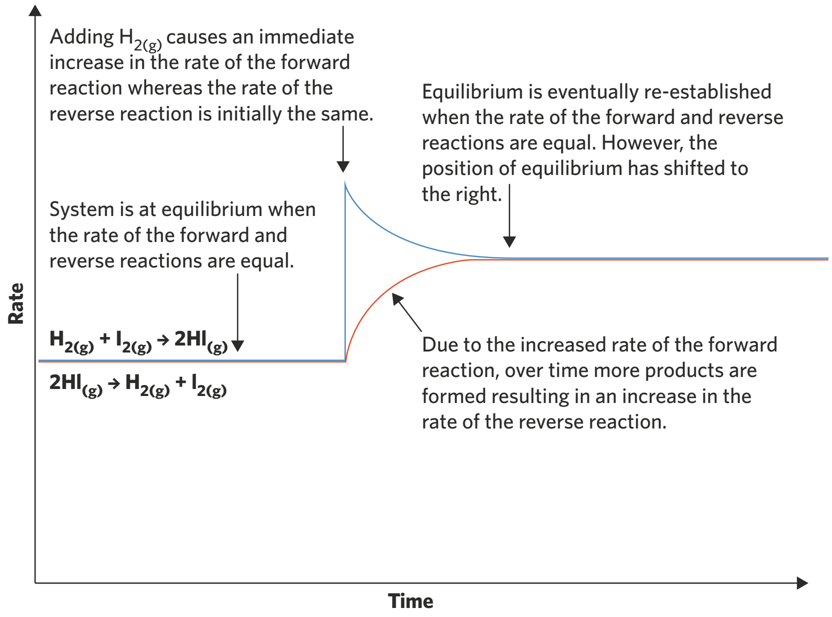


Figure 1 Rate-time graph for the addition of $H_{2(g)}$ at constant volume/temperature for the equilibrium reaction $H_{2(g)} + I_{2(g)} \rightleftharpoons 2HI_{(g)}$

It is important to remember that although the rates of the forward and reverse reactions are equal at equilibrium, the position of equilibrium is not the same. This is because Le Châtelier's principle states that the equilibrium system partially opposes any change. In this case, the increase in concentration of $H_{2(g)}$ is partially opposed as shown in the following concentration-time graph.

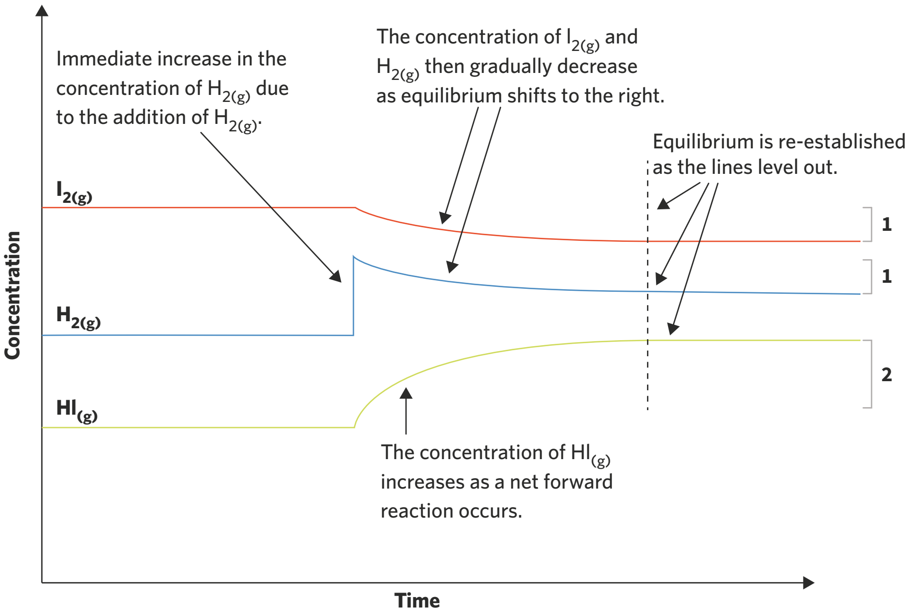


Figure 2 Concentration-time graph following the addition of $H_{2\,(g)}$ at constant volume and temperature for the equilibrium reaction $H_{2(g)} + I_{2(g)} \rightleftharpoons 2HI_{(g)}$

As can be seen, the concentration of $H_{2(g)}$ has not returned to its original level. This shows that the system has partially opposed the change. The concentration of $H_{2(g)}$ has increased relative to its initial concentration. Furthermore, another important detail is that when drawing concentration-time graphs, the stoichiometric ratio details have to be correct. In this case, since 1 mol of $H_{2(g)}$ reacts with 1 mol of $I_{2(g)}$ to produce 2 mol of $HI_{(g)}$, the concentration-time graph has to show this too through the ratio of the concentration changes. This ratio is marked on the graph.

Another way of thinking about this is to look at the expression for the equilibrium constant. In a simplified form, $K = \frac{[P]}{[R]}$ where P represents products and R represents reactants. The addition of reactants disturbs equilibrium by increasing $[R]$ and therefore the reaction quotient Q_c decreases. This means the forward reaction will be favoured in order to increase $[P]$ and decrease $[R]$ whilst regaining equilibrium. This is summarised in table 2.

Table 2 Effect of different changes to a system at equilibrium

	[*P*]	**[*R*]**	**Q_c**	**Equilibrium shifts to the...**
Addition of products	↑	No initial change	↑	Left
Addition of reactants	No initial change	↑	↓	Right

1 Worked example

The following chemical reaction is at equilibrium:

$PCl_{5(g)} \rightleftharpoons PCl_{3(g)} + Cl_{2(g)}$

Using Le Châtelier's principle, explain what happens to the equilibrium position when chlorine gas is removed from the system at a constant volume and temperature.

What information is presented in the question?

The system is at equilibrium.

$Cl_{2(g)}$ is removed at constant volume and temperature.

What is the question asking us to do?

Write a justification for what happens using Le Châtelier's principle.

What strategy(ies) do we need in order to answer the question?

1. Identify the immediate effect of the removal of $Cl_{2(g)}$ on the system.
2. Using Le Châtelier's principle, justify in which direction the position of equilibrium is going to shift.

Answer

The removal of $Cl_{2(g)}$ at constant volume immediately decreases only the concentration of $Cl_{2(g)}$. This means that equilibrium is disturbed, requiring a response to oppose the change. According to Le Châtelier's principle, the system will partially oppose this change by favouring the net forward reaction as this produces $Cl_{2(g)}$ in an attempt to increase the concentration of $Cl_{2(g)}$. Therefore, the position of equilibrium will shift to the right.

Effect of changing volume and pressure on equilibrium 3.2.8.2.2

OVERVIEW

When a change in volume at constant temperature disturbs equilibrium, Le Châtelier's principle states that the system will partially counteract this change in volume by trying to either increase or decrease the pressure.

THEORY DETAILS

A change in volume is also another factor which can disturb equilibrium. An increase in volume at constant temperature will decrease the total pressure of the vessel. Therefore, according to Le Châtelier's principle, the system will try to partially oppose this change by favouring the reaction which produces more particles, and thereby increases the pressure. A decrease in volume will have the opposite effect at a constant temperature, whereby the total pressure of the vessel increases. As a result, according to Le Châtelier's principle, the system will partially oppose the change by favouring the reaction which produces fewer particles, thereby decreasing the pressure.

The reaction that favours an increase or decrease in pressure depends on the relative number of particles on each side of the reaction. The following is an example of an equilibrium reaction.

$2NO_{2(g)} \rightleftharpoons 2NO_{(g)} + O_{2(g)}$

In this case, 2 mol of gas reacts together on the left hand side to produce 3 mol of gas on the right hand side. Therefore, if there is an increase in volume at constant temperature which decreases the pressure and concentration, in an attempt to partially counteract this decrease in pressure, there will be a net forward reaction occurring in order to increase the pressure by producing more particles as the system re-establishes equilibrium. This is shown graphically in the concentration-time graph illustrated in figure 3.

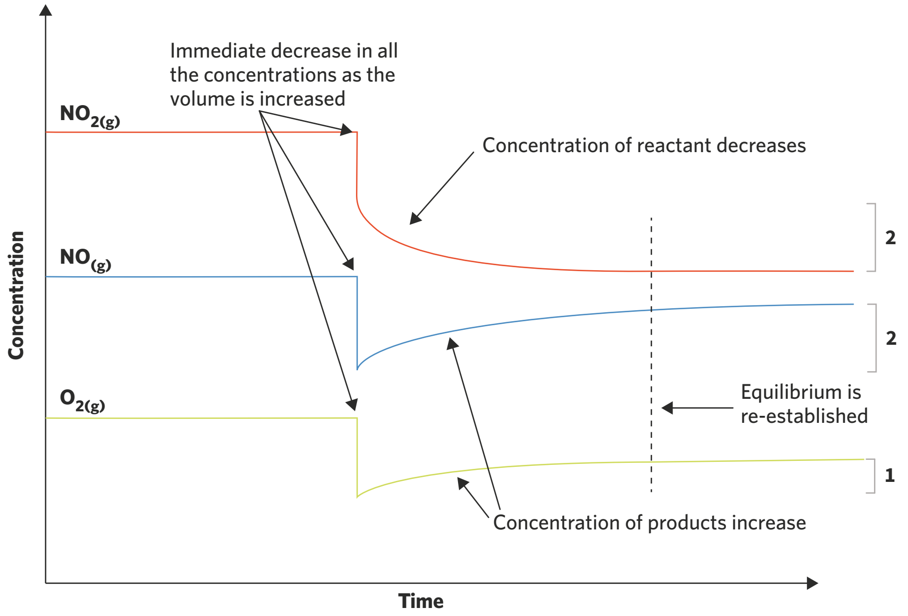


Figure 3 Concentration-time graph following the increase in volume at constant temperature for the equilibrium reaction $2NO_{2(g)} \rightleftharpoons 2NO_{(g)} + O_{2(g)}$

It is also important to note that after equilibrium has been restored, the overall concentrations of all species have decreased, even though the amount (in moles) of $O_{2(g)}$ and $NO_{(g)}$ has increased. This is due to the fact that there is a bigger volume that the particles are able to occupy. Therefore, the overall concentration is lower compared to before the change was made.

On the other hand, if there is a decrease in volume at constant temperature which increases pressure, a net back reaction will occur as 3 mol of gas reacts to produce 2 mol of gas in an attempt to decrease the pressure whilst re-establishing equilibrium.

Special case

However, to determine if any change is to occur, we need to consider the number of moles of gas on either side of the chemical reaction. If the same number of moles of gas reacts to produce the same number of moles of gas in the products and a change in volume at constant temperature has occurred, equilibrium has not been disturbed, therefore requiring no response. In this case, Le Châtelier's principle is not applicable. A simple way of thinking about this is if there are the same number of moles of reactants and products on both sides of the equation, then neither favouring the forward nor backward reaction would decrease the number of particles in the system. Therefore, any change would not have the effect of reducing pressure and so there will be no change. Although the overall concentrations and rates of reaction have changed, they do so in proportion to each other so the position of equilibrium is not disturbed, requiring no response. An example of this can be seen in the following equilibrium reaction:

$Br_{2(g)} + Cl_{2(g)} \rightleftharpoons 2BrCl_{(g)}$

A decrease in volume at constant temperature is applied to the system at equilibrium. Since 2 mol of gas reacts to produce 2 mol of gas, when this change is applied, equilibrium is not disturbed. Therefore, the concentrations of all reactants and products will increase proportional to their initial concentrations, as shown by figure 4.

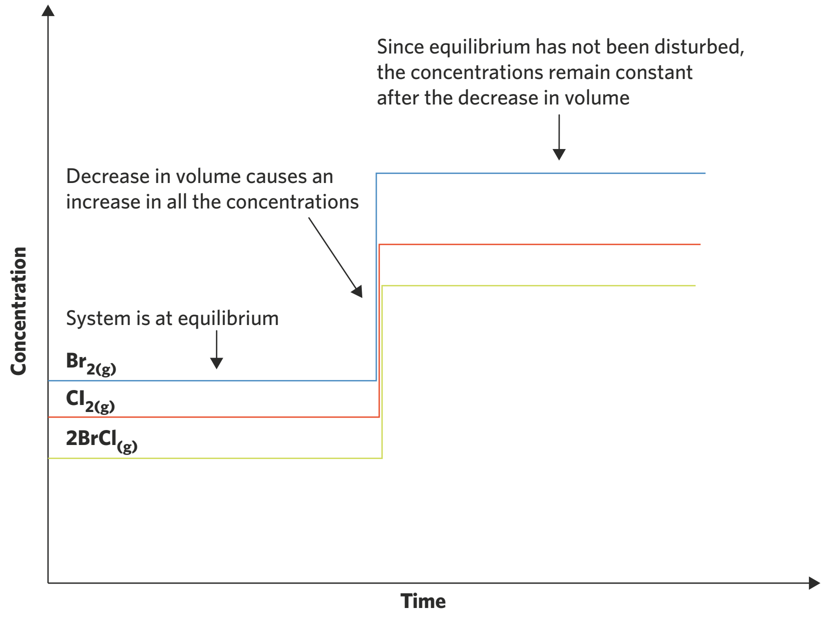


Figure 4 Concentration-time graph following the decrease in volume at constant temperature for the equilibrium reaction $Br_{2(g)} + Cl_{2(g)} \rightleftharpoons 2BrCl_{(g)}$

Dilution

As we learned in lesson 5D, equilibrium reactions can exist in an aqueous solution. Dilution is the term used to describe when the volume of an aqueous system increases by the addition of water. For example, let's look at the following reaction:

$CoCl_4{}^{2-}{}_{(aq)} \rightleftharpoons Co^{2+}{}_{(aq)} + 4Cl^-{}_{(aq)}$

The reasoning behind what happens to this system is similar to an increase in volume for a gas phase reaction. When this dilution occurs, the concentrations of all aqueous ions decrease. Since 1 mol aqueous ions ⇌ 4 mol aqueous ions, according to Le Châtelier's principle, there will be a net forward reaction occurring in order to partially counteract the decrease in concentration of ions whilst regaining equilibrium.

Effect of inert gases on equilibrium 3.2.8.2.3

OVERVIEW

In an equilibrium reaction, pressure can be changed by the addition of an inert gas at constant volume.

THEORY DETAILS

Another change that can be applied to a system in equilibrium is a pressure change at constant volume and temperature. This can be achieved by adding an inert gas such as helium, neon or argon while keeping the volume of the reaction vessel unchanged. Figure 7 illustrates this concept for the equilibrium reaction $N_2O_{4(g)} \rightleftharpoons 2NO_{2(g)}$.

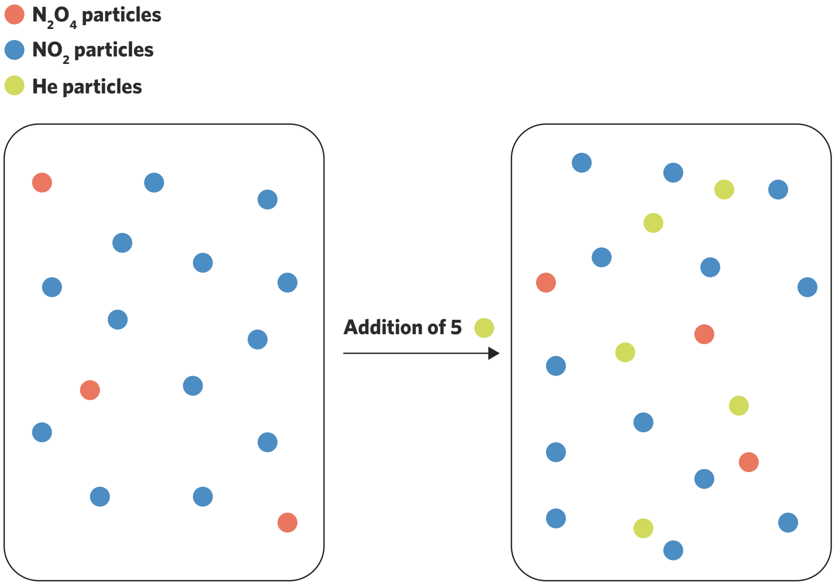


Figure 5 Addition of helium at constant volume for the reaction $N_2O_{4(g)} \rightleftharpoons 2NO_{2(g)}$ showing that concentrations of reactants and products remain unchanged.

In this case, the unreactive gas helium has been added at a constant volume. As it is an inert gas, we also know that it will not react with any of the species to change their concentrations. Since the volume is unchanged, the concentrations of the reactants and products will remain unchanged too. This means that equilibrium has not been disturbed, necessitating no response. The rate of the forward and reverse reactions also remain unchanged since we consider the effect of any interference from the inert gas to be negligible.

Effect of temperature changes on equilibrium 3.2.8.2.4

OVERVIEW

When a change in temperature at constant volume occurs, equilibrium is disturbed. According to Le Châtelier's principle, the position of equilibrium will shift depending on the endothermic or exothermic nature of the forward and reverse reactions.

THEORY DETAILS

As we learned in lesson 5D, a change in temperature affects the value of K_c as follows.

Table 3 Effect of temperature changes on equilibrium

ΔH	Temperature change	Equilibrium shifts to the	Effect on K_c
Exothermic	Increase	left	Decrease
Exothermic	Decrease	right	Increase
Endothermic	Increase	right	Increase
Endothermic	Decrease	left	Decrease

Therefore, although a temperature change doesn't instantly affect the concentrations of chemical species in equilibrium, equilibrium has been disturbed. This requires a response whilst equilibrium is reestablished at the new value of K_c.

Tip To make it easier to understand, think of energy as either a reactant or a product. However, this is not 'theoretically' true.

Let's look at an example. The following has an endothermic forward reaction which means that the backward reaction is therefore exothermic.

$CO_{(g)} + Cl_{2(g)} \rightleftharpoons COCl_{2(g)} \quad \Delta H = +ve$

If the temperature of the equilibrium system is increased, which increases the energy in the system, equilibrium is disturbed. Since the forward reaction is endothermic, it consumes heat and so can be expressed as:

$CO_{(g)} + Cl_{2(g)} + \text{energy} \rightleftharpoons COCl_{2(g)} \quad \Delta H = +ve$

Therefore, according to Le Châtelier's principle, since the energy of the system has increased, the system will partially oppose this change by favouring the net forward reaction to consume some of this energy, in an attempt to partially oppose the increase in temperature. Therefore, the position of equilibrium will shift to the right, resulting in an increase in the value of K_c.

The concentration-time graph for this scenario is shown in figure 6.

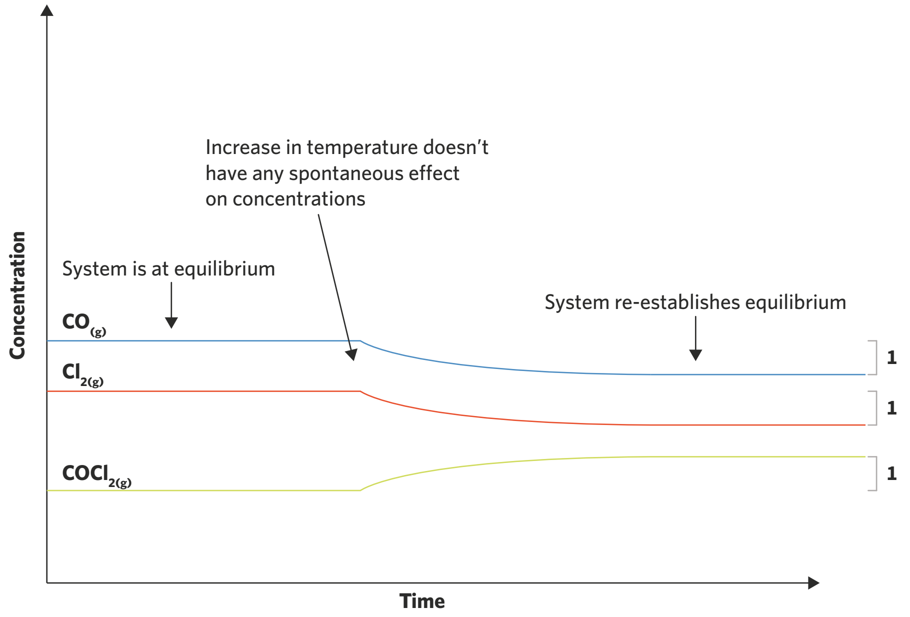


Figure 6 Concentration-time graph for the equilibrium reaction $CO_{(g)} + Cl_{2(g)} \rightleftharpoons COCl_{2(g)}$

Carbon monoxide poisoning 3.2.8.3

OVERVIEW

Carbon monoxide (CO) produced from the incomplete combustion of fuels can have devastating consequences on the human body.

THEORY DETAILS

The mechanism by which oxygen is transported throughout the body is through the protein haemoglobin (Hb) in red blood cells, which can bind with up to four O_2 molecules from the air. This reaction is described in the following equilibrium reaction with equilibrium constant K_1.

Equation 1: $Hb_{(aq)} + 4O_{2(aq)} \rightleftharpoons Hb(O_2)_{4(aq)} \qquad K_1$

This is what occurs under normal conditions. However, carbon monoxide CO, usually produced by the incomplete combustion of fuels originating from, for example, a petrol engine, can affect the position of this equilibrium reaction. This is because carbon monoxide molecules are also capable of binding to haemoglobin molecules in the same ratio. This similar process is defined in the following equilibrium reaction with equilibrium constant K_2.

Equation 2: $Hb_{(aq)} + 4CO_{(aq)} \rightleftharpoons Hb(CO)_{4(aq)} \qquad K_2$

This establishes what is known as **competing equilibria**. In this case, the binding of haemoglobin to carbon monoxide is approximately 200 times more powerful than the binding of haemoglobin to oxygen – that is, K_2 is about 200 times larger than K_1. Therefore, carbon monoxide binding to haemoglobin is especially dangerous, as it is capable of replacing the oxygen attached to haemoglobin circulating in the bloodstream, preventing tissues from accessing the oxygen they need. This results in often deadly cases of CO poisoning. A patient suffering from CO poisoning will continue to suffocate in normal air since the relatively low concentration of oxygen in air cannot replace the CO already bound to haemoglobin molecules.

However, with the right medical care, carbon monoxide poisoning is able to be reversed. This is achieved by the patient breathing in pure oxygen. This is because a large increase in the concentration of oxygen will disturb the equilibrium position of Equation 1, necessitating a response. According to Le Châtelier's principle, the system will partially oppose this change by favouring the forward reaction as this consumes some O_2 in an attempt to lower the concentration of O_2.

As a result, more haemoglobin becomes oxygenated, allowing more oxygen to be transported to tissues of the body. Since this is a situation with competing equilibria, this change will also affect the equilibrium position of Equation 2. Another change is that the concentration of free haemoglobin decreases in Equation 1, which means that Equation 2 will shift to the left according to Le Châtelier's principle in order to try to increase the haemoglobin concentration. In shifting Equation 2 to the left, then, we end up reducing the amount of haemoglobin which is bound to carbon monoxide. In turn, the CO which was previously bound to haemoglobin molecules will be expelled from the body. This 'available' haemoglobin can then be taken up by the pure oxygen and normal functioning of the body's circulatory system can be restored.

Theory summary

- Le Châtelier's principle states that if a system in equilibrium is subjected to a change which disrupts equilibrium, the system will partially oppose this change.
- A change in concentration at constant volume and temperature, a change in volume and pressure at constant temperature and a change in temperature at constant volume and pressure can all disrupt equilibrium.
- A change in temperature is the only disruption to the system that will alter K_c.
- A change in pressure from the addition of an inert gas at constant volume does not disrupt equilibrium.
- Carbon monoxide poisoning is caused by the fact that the value of K_c which governs the equilibrium reaction in which carbon monoxide binds to haemoglobin is much larger than the value of K_c which governs the equilibrium reaction where oxygen binds to haemoglobin. This scenario is known as competing equilibria.
- Carbon monoxide poisoning can be reversed by giving pure oxygen to the patient.

5E QUESTIONS

Theory review questions

Question 1

Which of the following statements is true with respect to Le Châtelier's principle?

A Le Châtelier's principle always applies when there is a change in volume.

B An increase in concentration of products at constant volume and temperature always causes equilibrium to shift to the right.

C An increase in concentration of reactants at constant volume and temperature causes equilibrium to shift to the right.

D Le Châtelier's principle applies whenever there is a change in pressure at constant volume by adding an inert gas.

Question 2

Which of the following changes will **not** disturb the position of equilibrium?

A The removal of products for any equilibrium reaction at constant volume and temperature.

B Decrease in volume for a reaction where 2 mol of gas reacts to produce 2 mol of gas.

C Increase in temperature for an equilibrium reaction whose forward reaction is exothermic.

D Increase in volume for a reaction where 3 mol of gas reacts to produce 2 mol of gas.

Question 3

Carbon monoxide poisoning results from the fact that

A oxygen binds to haemoglobin more strongly than carbon monoxide.

B carbon monoxide binds to haemoglobin more strongly than oxygen.

C carbon monoxide reacts with oxygen, removing it from the blood.

D carbon monoxide reacts irreversibly with carbon monoxide.

Exam-style questions

Within lesson

Question 4 (1 MARK)

The following is an example of an equilibrium reaction:

$Mn^{2+}_{(aq)} + 8OH^{-}_{(aq)} \rightleftharpoons MnO_4{}^{-}{}_{(aq)} + 4H_2O_{(l)} + 5e^{-}$

The position of equilibrium would shift to the right by the addition of

A $MnO_4{}^{-}{}_{(aq)}$ at constant volume and temperature.

B $H_2O_{(l)}$ at constant temperature.

C sodium hydroxide at constant temperature.

D gaseous hydrochloric acid at constant volume and temperature.

Question 5 (1 MARK)

Equilibrium reactions are very important in the human body for maintaining the necessary stable conditions that are needed for vital human functions. The following equilibrium reaction occurs in the blood to maintain a stable pH level.

$CO_{2(aq)} + H_2O_{(l)} \rightleftharpoons H^{+}_{(aq)} + HCO_3{}^{-}{}_{(aq)}$

If a patient enters the emergency department with a higher concentration of $CO_{2(aq)}$ in their bloodstream, after equilibrium has been reestablished, there would be

A a higher pH than before they arrived, because the position of equilibrium has shifted to the left.

B a lower pH than before they arrived, because the position of equilibrium has shifted to the right.

C a lower pH than before they arrived, because the position of equilibrium has shifted to the left.

D a higher pH than before they arrived, because the position of equilibrium has shifted to the right.

Question 6 (1 MARK)

The following is a list of equilibrium reactions and the respective sign of their enthalpy changes.

1 $COCl_{2(g)} \rightleftharpoons CO_{(g)} + Cl_{2(g)}$ ΔH = –ve

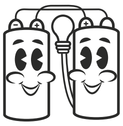
2 $N_2O_{4(g)} \rightleftharpoons 2NO_{2(g)}$ ΔH = –ve

3 $Br_{2(g)} + Cl_{2(g)} \rightleftharpoons 2BrCl_{(g)}$ ΔH = +ve

4 $2NO_{2(g)} \rightleftharpoons 2NO_{(g)} + O_{2(g)}$ ΔH = +ve

An increase in temperature and volume is then applied. In which of the following equations would the position of equilibrium shift to the right for both an increase in temperature and volume?

A Equation 1 **B** Equation 2 **C** Equation 3 **D** Equation 4



Question 7 (1 MARK)

Which of the following changes would justify the concentration-time graph shown for the following equilibrium reaction?

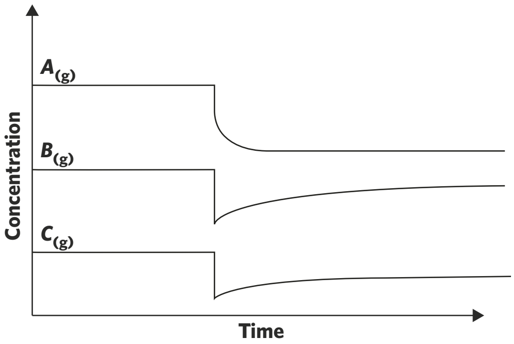
$2A_{(g)} \rightleftharpoons 2B_{(g)} + C_{(g)}$

A Increase in volume at constant temperature

B Increase in temperature at constant volume

C Addition of $A_{(g)}$ at constant volume/temperature

D Removal of $B_{(g)}$ at constant volume/temperature



Question 8 (2 MARKS)

The following reaction is in equilibrium.

$2SO_{2(g)} + O_{2(g)} \rightleftharpoons 2SO_{3(g)}$ $\Delta H = -197$ kJ mol^{-1}

Argon, an inert gas, is then added at constant volume and temperature. Explain what will happen to the concentration of oxygen gas.

Question 9 (5 MARKS)

Xavier had just been introduced to Le Châtelier's principle and he wanted a way to see by observation what reactions were occurring. To do this, he set up a gas syringe with a mixture already in equilibrium according to the following reaction:

$N_2O_{4(g)} \rightleftharpoons 2NO_{2(g)}$ $\Delta H = -ve$

He knows that $N_2O_{4(g)}$ is a colourless gas and $NO_{2(g)}$ is a brown coloured gas.

a Fill in the following table of observations (lighter, darker, no change) that Xavier would observe when each change is applied. (3 MARKS)

Change applied	**Observation of gas syringe**
Increase in temperature at constant volume	
Addition of $NO_{2(g)}$ at constant volume/temperature	
Removal of $NO_{2(g)}$ at constant volume/temperature	

b Xavier predicts that if he decreased the volume of the gas syringe by pressing in the plunger, since the position of equilibrium shifts to the left, the colour of the gas syringe would in fact be lighter than what it was before he pressed in the plunger. Is Xavier's prediction correct? Justify your answer. (2 MARKS)

Question 10 (9 MARKS)

Laura, a VCE chemistry student, loves graphs and wanted to represent an equilibrium reaction by using graphs. The reaction she chose was:

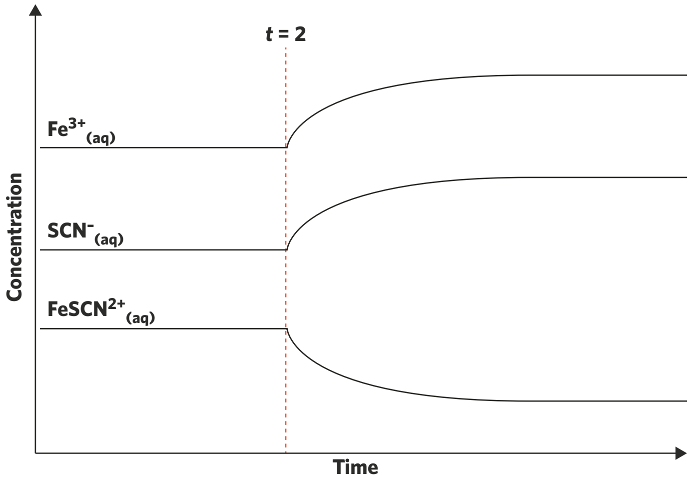
$Fe^{3+}_{(aq)} + SCN^{-}_{(aq)} \rightleftharpoons FeSCN^{2+}_{(aq)}$ $\Delta H = -ve$

a Draw the rate-time graph for the reaction when the system is diluted at constant temperature. (1 MARK)

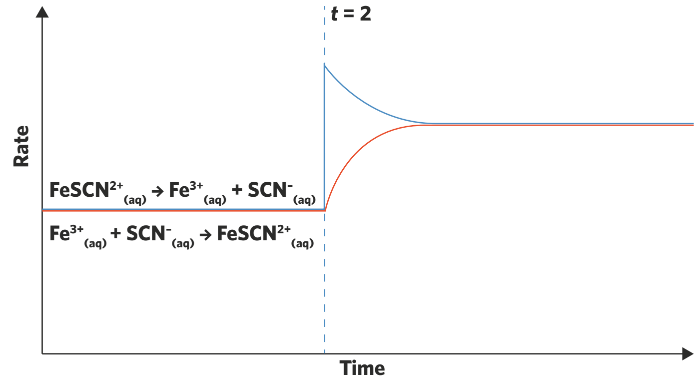
b Draw a potential concentration-time graph for the addition of $Fe^{3+}_{(aq)}$ ions. (1 MARK)

c Using Le Châtelier's principle, justify what will happen when the temperature is decreased. (2 MARKS)

d Unfortunately, a disaster struck and some of Laura's graphs had their titles removed, which means that she is no longer able to tell what change was applied to the system. She deduces that she can actually determine what change has happened just by looking at the shape of the graphs. Given the concentration-time graph shown, suggest what could have happened at time $t = 2$. Justify your answer. (3 MARKS)



e Given the rate-time graph shown, suggest a possible change that could have happened at $t = 2$. (2 MARKS)



Multiple lessons

Question 11 (6 MARKS)

A car company was recently caught trying to cut costs by removing the platinum catalytic converter from a car's fuel exhaust pipe. A catalytic converter is used to catalyse the breakdown of carbon monoxide resulting from the incomplete combustion of petrol.

a Describe the role of a catalyst in a chemical reaction. (1 MARK)

b Write the equation for the incomplete combustion of octane, one of the alkanes found in diesel. (1 MARK)

c Why is it compulsory for cars nowadays to have a catalytic converter? Justify your response by using your knowledge of carbon monoxide and competing equilibrium reactions. (2 MARKS)

d Do catalysts affect the final position of equilibrium? Explain. (2 MARKS)

Question 12 (7 MARKS)

A method by which iodine and chlorine gas can be produced through the dissociation of iodine trichloride is given.

$2ICl_{3(g)} \rightleftharpoons I_{2(g)} + 3Cl_{2(g)}$ $\Delta H = +240 \text{ kJ mol}^{-1}$

A sample of 0.70 mol iodine trichloride was initially added into a 1.0 L container and allowed to reach equilibrium, resulting in the production of 0.90 M of chlorine gas.

a Determine the K_c expression for the reaction. (1 MARK)

b Calculate the value of K_c for this reaction. (3 MARK)

c The experimenters wanted to increase the yield of iodine and chlorine gas and so increased the temperature of the vessel. Determine whether or not this would have resulted in an increase in the production of both gases. Explain. (2 MARKS)

d What effect would an increase in the temperature of the reaction have on the equilibrium constant? (1 MARK)

EXPERIMENT

EQUILIBRIUM REACTIONS

Once equilibrium has been established, changes made to the system can be counteracted (partially) by temporary adjustments from the reactions themselves. Depending on the type of reactions involved, these changes can be measured qualitatively.

$Fe^{3+}_{(aq)}$ ions can react with $SCN^{-}_{(aq)}$ to produce $FeSCN^{2+}_{(aq)}$. As this reaction proceeds, a change in colour can be observed.

$$\underset{\text{Light yellow}}{Fe^{3+}_{(aq)}} + \underset{\text{Colourless}}{SCN^{-}_{(aq)}} \rightleftharpoons \underset{\text{Red}}{FeSCN^{2+}_{(aq)}}$$

Materials

(per group)

- 3 micro test tubes
- 0.005 M solution of $FeSCN^{2+}$
- 0.05 M solution of $Fe(NO_3)_3$
- 0.05 M solution of NaF
- 0.05 M solution of KSCN
- 3 × Pasteur pipettes
- Micro test tube rack

Method

1 Place all micro test tubes into the test tube rack and label each test tube A, B and C.
2 Add 10 drops of $FeSCN^{2+}$ into each test tube.
3 Add 3 drops of $Fe(NO_3)_3$ into test tube A.
4 Record any observations.
5 Add 3 drops of NaF into test tube B.
6 Record any observations.
7 Add 3 drops of KSCN into test tube C.
8 Record any observations.

Results

	Test tube A	Test tube B	Test tube C
Observations			

QUESTIONS

Question 1 (6 MARKS)

Raya conducted the experiment described above and obtained the following results:

	Test tube A	Test tube B	Test tube C
Description	The solution turned more red in colour when $Fe(NO_3)_3$ was added.	The solution became less red as NaF was added.	The solution became more red as KSCN was added.

For each reaction, Raya assumed that equilibrium had been established prior to the addition of the additional substance. Assume that any volume changes due to the additional 3 drops of solution are negligible.

a Explain the change that occured in test tube A when $Fe(NO_3)_3$ was added. (2 MARKS)

b Upon conducting some research, Raya found that sodium ions are soluble regardless of the cation present in the solution. Using this information, explain the result obtained in test tube B once NaF was added into the test tube. (2 MARKS)

c Raya conducted a follow up test in a separate reaction vessel that initially contained only $FeSCN^{2+}_{(aq)}$. At equilibrium, it was calculated that there was 0.0200 M of $FeSCN^{2+}_{(aq)}$ and the K_c value was calculated to be 109 M^{-1}. Determine the concentration of $Fe^{3+}_{(aq)}$ present at equilibrium in the reaction vessel. (2 MARKS)

Question 2 (4 MARKS)

a Is the type of data obtained best described as qualitative or quantitative? Why? (2 MARKS)

b Based on the results obtained in the experiment, comment on the reproducibility of the results. (2 MARKS)

ANSWERS

1 **a** [Adding $Fe(NO_3)_3$ resulted in an increase in the concentration of Fe^{3+} present in the solution.[1]][To partially oppose the change and reduce $[Fe^{3+}]$, the forward reaction would be favoured, resulting in an increased concentration of $FeSCN^{2+}$.[2]][As $FeSCN^{2+}$ is red in colour, the solution would change to become more red overall.[3]]

✓ ✗ I have identified the effect of the addition of $Fe(NO_3)_3$.[1]

✓ ✗ I have explained the effect on the reaction with reference to Le Châtelier's principle.[2]

✓ ✗ I have linked my answer to the observation made in the experiment.[3]

b [Since the sodium ions are soluble, it is possible that the fluoride ions would react with the Fe^{3+} ions in the solution to form a precipitate $FeF_{3(s)}$.[1]][This would cause a decrease in the concentration of Fe^{3+} in the system. In order to partially oppose this change, the backwards reaction would be favoured to increase $[Fe^{3+}]$.[2]][This would result in the solution becoming a lighter red as $FeSCN^{2+}$ is being used to produce more Fe^{3+}.[3]]

✓ ✗ I have identified the effect of the addition of NaF.[1]

✓ ✗ I have explained the effect on the reaction.[2]

✓ ✗ I have linked my answer to the question.[3]

c $$K_c = \frac{[FeSCN^{2+}]}{[Fe^{3+}][SCN^-]} = 109 = \frac{0.0200}{x^2}$$

$$x = \sqrt{\frac{0.0200}{109}} = 0.0135\text{ M}$$

Therefore $[Fe^{3+}_{(aq)}] = 0.0135$ M

2 **a** [The data collected are qualitative data.[1]][This is because the only measurements made were whether the intensity of the red colour increased or decreased, not by how much.[2]]

✓ ✗ I have identified whether the data collected are quantitative or qualitative.[1]

✓ ✗ I have explained why the data collected are defined as qualitative.[2]

b [Although any quantitative data collected would be subjective, simply the change in colour (increase or decrease in the intensity of the red pigment) would not differ between experimenters.[1]][This would mean that the qualitative data obtained from the experiment would be reproducible.[2]]

✓ ✗ I have identified whether the data obtained are subjective.[1]

✓ ✗ I have determined whether the experiment would be repoducible.[2]

CHAPTER 5 QUESTIONS

MULTIPLE CHOICE (10 MARKS)

Question 1

According to collision theory, for a reaction to occur, the reactant particles need to

A come into direct contact with each other.

B have sufficient energy to overcome the activation energy barrier.

C collide with the correct orientation.

D All of the above

Question 2

The balanced equation for a hypothetical chemical reaction in dynamic equilibrium is given.

The letters *P*, *Q*, *R* and *S* each represent different molecules.

$4P_{(aq)} + 7Q_{(aq)} \rightleftharpoons 2R_{(aq)} + S_{(aq)}$

Which of the following represents the equilibrium constant, K_c, for this reaction?

A $\frac{[P]^4[Q]^7}{[R]^2[S]}$ **B** $\frac{[R_2][S]}{[P_4][Q_7]}$ **C** $\frac{[P_4][Q_7]}{[R_2][S]}$ **D** $\frac{[R]^2[S]}{[P]^4[Q]^7}$

Question 3

The Maxwell-Boltzmann curve labelled Graph 1 displays the distribution of the kinetic energy of particles of a gas sample in a container of fixed volume.

One change was made to the system, resulting in the kinetic energy distribution curve labelled Graph 2.

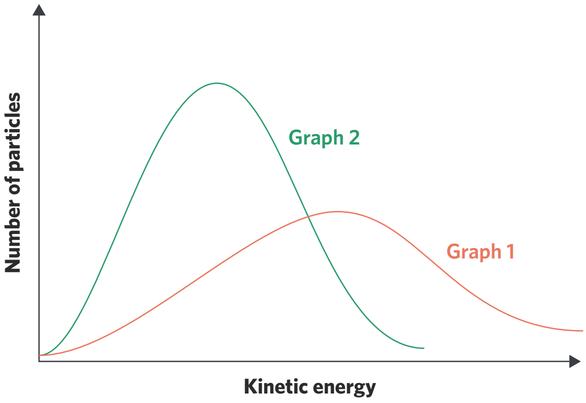
Which of the following statements explains the change to the system leading to Graph 2?

A An inert gas was added to the system at constant volume.

B The average kinetic energy of the particles decreased.

C A catalyst was added to the system to decrease the activation energy.

D The temperature of the gas was increased.



Question 4

The pH of human blood is tightly regulated between 7.35 and 7.45 by a buffering system that obeys the following set of equilibrium reactions:

$CO_{2(aq)} + H_2O_{(l)} \rightleftharpoons H_2CO_{3(aq)} \rightleftharpoons H^+_{(aq)} + HCO_3{}^-{}_{(aq)}$

If the body's carbon dioxide levels were to suddenly increase (for example, by holding one's breath), this would

A cause the blood pH to increase.

B cause the blood pH to decrease.

C lead to a decrease in the concentration of the $HCO_3{}^-{}_{(aq)}$ ion.

D increase the amount of water circulating in the bloodstream.

Question 5

A catalyst for a reaction will

A decrease the difference in enthalpy between reactants and products.

B gradually be used up in the reaction it is catalysing.

C increase the proportion of successful collisions for a given temperature.

D alter the final equilibrium by increasing the yield of the reaction.

Question 6

Given the following reactions with equilibrium constants K_1 and K_2 respectively:

$N_{2(g)} + O_{2(g)} \rightleftharpoons 2NO_{(g)}$ $\Delta H = +180\ \text{kJ mol}^{-1}$ K_1

$2NO_{2(g)} \rightleftharpoons 2NO_{(g)} + O_{2(g)}$ $\Delta H = +112\ \text{kJ mol}^{-1}$ K_2

Which of the following is equal to the value of the equilibrium constant K_3 for the reaction below?

$N_{2(g)} + 2O_{2(g)} \rightleftharpoons 2NO_{2(g)}$ $\Delta H = +68\ \text{kJ mol}^{-1}$ K_3

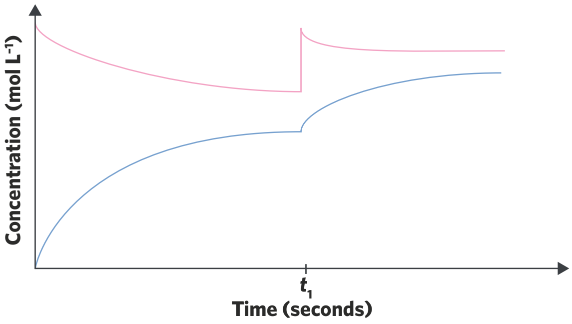
A $\frac{K_2}{K_1}$ **B** $\frac{1}{K_1K_2}$ **C** K_1K_2 **D** $\frac{K_1}{K_2}$

Use the following information to answer questions 7–9.

Nitrogen dioxide undergoes a process known as dimerisation to form dinitrogen tetroxide according to the following equilibrium reaction.

$2NO_{2(g)} \rightleftharpoons N_2O_{4(g)}$

A concentration-time graph for a particular vessel that initially contained only one of these two species is shown.



Question 7

How many times does the system appear to be at equilibrium during the given time period?

A Once

B Twice

C The system is constantly in dynamic equilibrium.

D The system never reaches dynamic equilibrium.

Question 8

The change observed at time t_1 is most likely due to

A $N_2O_{4(g)}$ being introduced to the reaction vessel at constant temperature and volume.

B $NO_{2(g)}$ being introduced to the reaction vessel at constant temperature and volume.

C an increase in the volume of the reaction vessel at constant temperature.

D a decrease in the volume of the reaction vessel at constant temperature.

Question 9

It is experimentally determined that heating the reaction vessel at constant pressure causes a decrease in the equilibrium concentration of dinitrogen tetroxide. This is strong evidence that

A the forward reaction is exothermic.

B the forward reaction is endothermic.

C the equilibrium constant, K_c, has decreased by a factor of 10.

D the reaction vessel has been contaminated.

Question 10

The protein haemoglobin (Hb) in red blood cells can bind with up to four O_2 molecules from the air, as described in the following equilibrium reaction with equilibrium constant K_1.

Equation 1: $Hb_{(aq)} + 4O_{2(aq)} \rightleftharpoons Hb(O_2)_4$ K_1

Carbon monoxide (CO) molecules are also capable of binding to haemoglobin molecules in the same ratio. This similar process is defined in the following equilibrium reaction with equilibrium constant K_2.

Equation 2: $Hb_{(aq)} + 4CO_{(aq)} \rightleftharpoons Hb(CO)_{4(aq)}$ K_2

Carbon monoxide binding to haemoglobin is especially dangerous as it is capable of replacing the oxygen attached to haemoglobin circulating in the bloodstream, preventing tissues from accessing the oxygen they need. This results in often deadly cases of CO poisoning. A patient suffering from CO poisoning will continue to suffocate in normal air and must be given pure oxygen to reverse its effects. What does this suggest about the relative magnitudes of the equilibrium constants K_1 and K_2?

A K_1 and K_2 are of approximately equal magnitude.

B K_1 is considerably greater than K_2.

C K_2 is considerably greater than K_1.

D There is not enough information to claim anything about their relative magnitudes.

SHORT ANSWER (37 MARKS)

Question 11 (15 MARKS)

The Haber process is the name given to the production of ammonia from nitrogen and hydrogen. The reaction for the Haber process is given below.

$N_{2(g)} + 3H_{2(g)} \rightleftharpoons 2NH_{3(g)}$ $\Delta H = -92.4\ \text{kJ mol}^{-1}$

At 745 K, the equilibrium constant for the reaction has a magnitude of 0.118.

a The production of ammonia via the Haber process requires careful optimisation of temperature and pressure to alter the reaction's final equilibrium.

- **i** Write the equilibrium constant for the Haber process reaction. (1 MARK)
- **ii** What are the units for this equilibrium constant? (1 MARK)
- **iii** Determine the value of the equilibrium constant for the following reaction at 745 K. (1 MARK)

$\frac{1}{2}N_{2(g)} + \frac{3}{2}H_{2\,(g)} \rightleftharpoons NH_{3(g)}$ $\Delta H = -46.2\ \text{kJ mol}^{-1}$

b To summarise the effects of changing certain experimental conditions, a student created a table that compares the values observed before and after the system re-establishes equilibrium.

Complete the following table by placing 'increase', 'decrease', or 'no change' **relative to the initial equilibrium before the change** in each of the blank fields. (4 MARKS)

	Magnitude of K	**[$N_{2(g)}$]**	**Overall rate of the forward reaction**
Temperature is decreased			
Volume is increased			
3.0 mol of neon gas is introduced to the reaction vessel at constant volume			
Ammonia gas is added (at constant volume)			

c At a different temperature, the value of the equilibrium constant for the reaction is equal to 8.0. A second reaction vessel at a constant volume of 1.0L contained 2.0 mol of $N_{2\,(g)}$, 3.0 mol of $H_{2\,(g)}$ and 4.0 mol of $NH_{3\,(g)}$.

- **i** Is this new temperature higher or lower than 745 K? (1 MARK)
- **ii** Prove that the mixture is not at equilibrium. (2 MARKS)

- **iii** For the given amounts of reactants and products, determine the volume of the container that would be required for this particular mixture of gases to be at equilibrium. (2 MARKS)
- **iv** If the volume of the reaction vessel were suddenly doubled, what effect would this have on the overall amount in mol of $N_{2(g)}$ and the overall concentration of $N_{2(g)}$ once the system re-establishes equilibrium? Justify your answer with reference to Le Châtelier's principle. Calculations are not required. (3 MARKS)

Question 12 (10 MARKS)

Diatomic hydrogen and iodine gas can react together to produce hydrogen iodide in the following equilibrium reaction. Hydrogen iodide is commonly used to convert primary alcohols into alkyl halides via a substitution reaction.

$H_{2(g)} + I_{2(g)} \rightleftharpoons 2HI_{(g)}$

a In an experiment, a chemist injected 5.00 mol of iodine and 2.00 mol of hydrogen into a 4.00 L reaction vessel, which was immediately sealed and maintained at a constant temperature. It was determined that the amount of hydrogen iodide present at equilibrium was 2.60 mol.

- **i** Determine the equilibrium concentrations of $H_{2(g)}$, $I_{2(g)}$ and $HI_{(g)}$. (3 MARKS)
- **ii** Calculate the value of the equilibrium constant for this reaction. (1 MARK)

b Explain why the rate of the reaction $2HI_{(g)} \rightleftharpoons H_{2(g)} + I_{2(g)}$ will never be greater than the rate of the reaction $H_{2(g)} + I_{2(g)} \rightleftharpoons 2HI_{(g)}$

- **i** while the system is reaching equilibrium. (2 MARKS)
- **ii** once equilibrium is established. (2 MARKS)

c Iodine gas is a vibrant purple colour, whereas both hydrogen and hydrogen iodide are colourless. The reaction $H_{2(g)} + I_{2(g)} \rightleftharpoons 2HI_{(g)}$ is an endothermic process. Compared to the results of the experiment described in part a, identify the effect of a decrease in the temperature of the reaction vessel on

- **i** the rate of the forward reaction. (1 MARK)
- **ii** the intensity of the purple colour of the final gaseous mixture. (1 MARK)

Question 13 (12 MARKS)

The formation of sulfuric acid is produced industrially by following a sequence of consecutive equilibrium reactions. The first stage in this process is the reaction of sulfur dioxide with pure diatomic oxygen as shown in the following equilibrium.

$2SO_{2(g)} + O_{2(g)} \rightleftharpoons 2SO_{3(g)}$ $\Delta H = -197$ kJ mol^{-1}

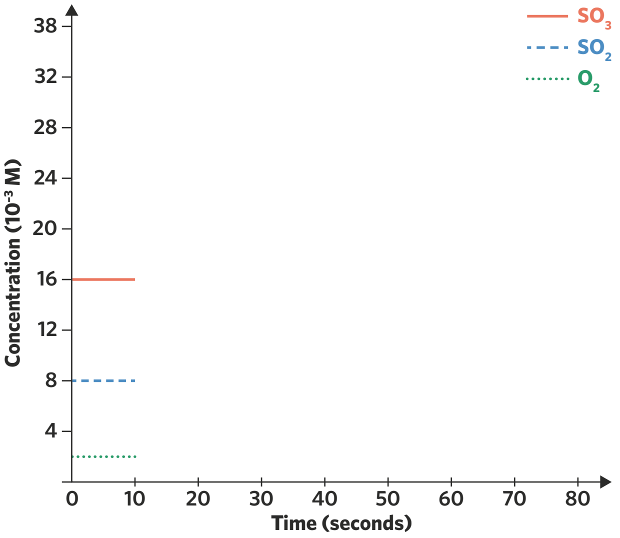
a An industrial chemist investigating this reaction uses 5.0 L vessel at equilibrium at a constant temperature of 250 °C. Upon analysis of the vessel, it is found to contain 0.040 mol of SO_2, 0.010 mol of O_2 and 0.080 mol of SO_3.

Calculate the value of the equilibrium constant for this reaction. Include units if applicable. (2 MARKS)

b In the situation described in part a, the pressure is kept constant at 120 kPa. Describe the effect of an increase in pressure on

- **i** the rate of reaction. (1 MARK)
- **ii** the equilibrium yield of SO_3. (1 MARK)

c The volume of the reaction vessel described in part a is halved at the time *t* = 10 seconds while maintaining a constant temperature. Complete the following concentration-time graph of the vessel given that the system re-establishes equilibrium at 50 seconds. (3 MARKS)



d At 250 °C, the rate of production of SO_3 is considered to be far lower than the threshold required for the industrial set-up to be financially beneficial. A visiting management executive with a basic understanding of kinetic theory suggests that the best way to increase the rate of reaction would be to increase the temperature of the reaction vessel.

- **i** Identify the primary issue with increasing the temperature of the reaction vessel if the synthesis process requires a large amount of SO_3 for its next stage. (2 MARKS) ii The industrial chemist politely suggests instead the use of an iron oxide catalyst to obtain the desired increase in rate of reaction, while keeping the temperature constant. Describe how a catalyst increases the rate of reaction and compare it with the executive's solution. (3 MARKS)

KEY SCIENCE SKILL QUESTION

Question 14 (8 MARKS)

Nitrogen dioxide and dinitrogen tetroxide exist in an equilibrium described by the following equation. The gas N_2O_4 is known to be toxic when inhaled and can be used as rocket fuel.

$2NO_{2(g)} \rightleftharpoons N_2O_{4(g)}$
Brown Colourless

Two students, Hrithik and Timothy, are investigating this particular equilibrium reaction and design an experiment where sealed syringes containing unknown amounts of NO_2 are studied under different experimental conditions. They note that one syringe has a noticeably darker colour than the other.

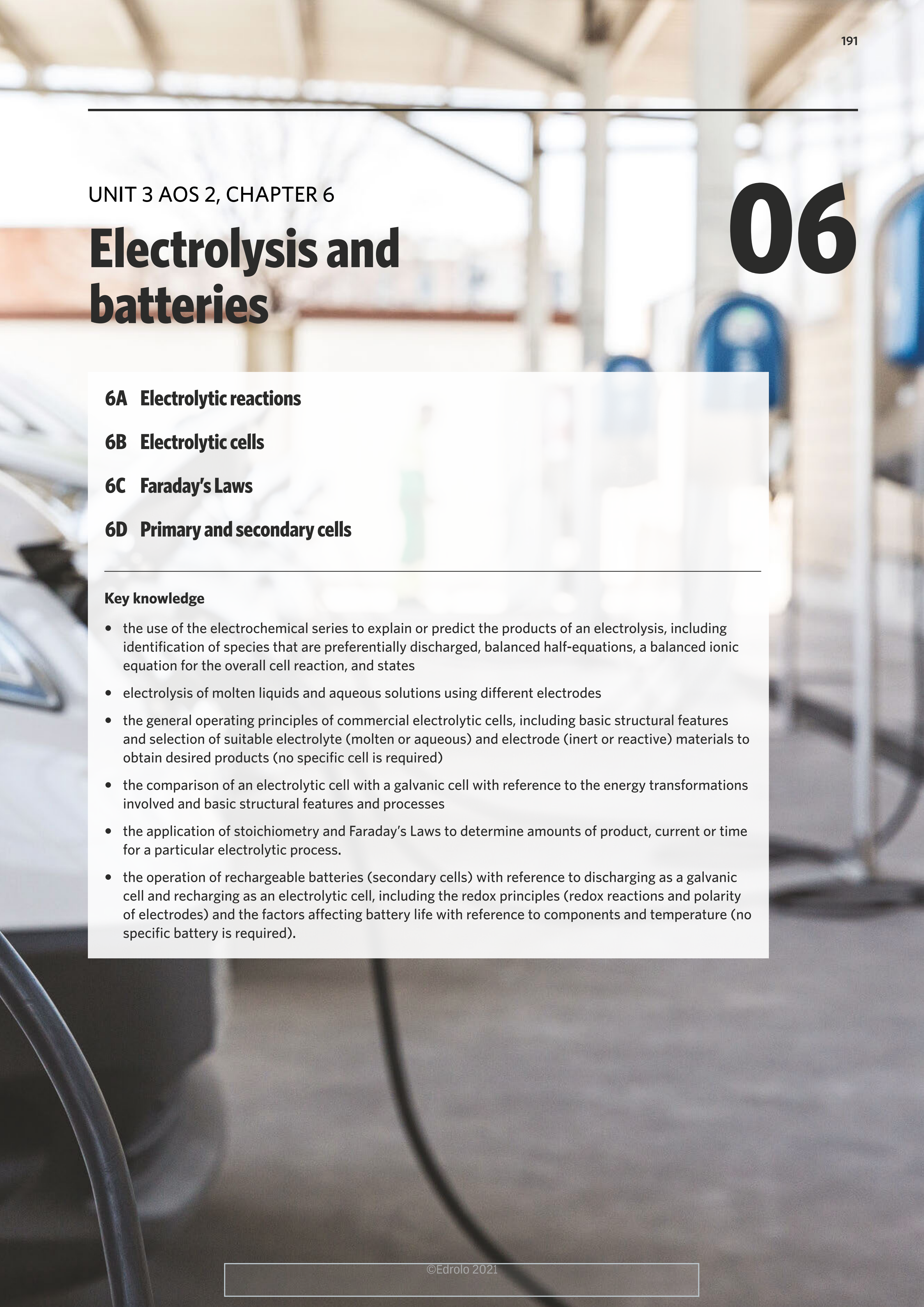
a Identify two ways in which the students could minimise the risk of experimenting with N_2O_4. (2 MARKS)

b Their first experiment involves pressing down on the syringe's plunger and observing the change in intensity of the colour. They decide that the only way to make sure they obtain unbiased data is to each perform the experiment individually and then compare their results. Since they have the two syringes available to them, the students reason that performing the same experiment twice would allow them to reduce any fluctuations in their results due to random error.

Hrithik decides to take one of the syringes and he pushes the plunger down 3.0 cm. He then returns to his desk to note down his observations on any changes in colour. While Hrithik is at his desk, Timothy pushes the plunger of the second syringe down 5.0 cm, again noting any changes in colour. The two students then compare their results.

Why might this method lead to inaccurate quantitative results? Give three reasons. (3 MARKS)

c Suggest how each of these sources of error could be corrected. (3 MARKS)



UNIT 3 AOS 2, CHAPTER 6

06

Electrolysis and batteries

Key knowledge

- the use of the electrochemical series to explain or predict the products of an electrolysis, including identification of species that are preferentially discharged, balanced half-equations, a balanced ionic equation for the overall cell reaction, and states
- electrolysis of molten liquids and aqueous solutions using different electrodes
- the general operating principles of commercial electrolytic cells, including basic structural features and selection of suitable electrolyte (molten or aqueous) and electrode (inert or reactive) materials to obtain desired products (no specific cell is required)
- the comparison of an electrolytic cell with a galvanic cell with reference to the energy transformations involved and basic structural features and processes
- the application of stoichiometry and Faraday's Laws to determine amounts of product, current or time for a particular electrolytic process.
- the operation of rechargeable batteries (secondary cells) with reference to discharging as a galvanic cell and recharging as an electrolytic cell, including the redox principles (redox reactions and polarity of electrodes) and the factors affecting battery life with reference to components and temperature (no specific battery is required).

6A ELECTROLYTIC REACTIONS

In this lesson we will be learning about electrolysis, the reaction which converts electrical energy to chemical energy.

6A Electrolytic reactions	6B Electrolytic cells	6C Faraday's Laws	6D Primary and secondary cells

Study design dot points

- the use of the electrochemical series to explain or predict the products of an electrolysis, including identification of species that are preferentially discharged, balanced half-equations, a balanced ionic equation for the overall cell reaction, and states
- electrolysis of molten liquids and aqueous solutions using different electrodes

Key knowledge units

Balancing electrolytic half-equations	3.2.11.2.1
Balancing overall electrolytic equations	3.2.11.2.2
Using the electrochemical series to predict electrolytic reactions	3.2.11.1.1 & 3.2.9.1 & 3.2.9.2

Key terms and definitions of this lesson

- **Electrolytic reaction** non-spontaneous redox reaction that requires electricity for it to occur
- **Electrolytic half-equation** one of two equations (oxidation or reduction) which describes one half of an electrolytic reaction
- **Molten electrolyte** melted ionic compound with ions that are free to move and in the liquid state
- **Aqueous electrolyte** dissolved ionic compound with ions that are free to move and in the aqueous state

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Balancing electrolytic half-equations 3.2.11.2.1

OVERVIEW

Using our knowledge of which chemical species are being reduced and oxidised, the appropriate half-equations can be constructed and balanced for an electrolytic reaction, depending on the conditions of the reaction.

THEORY DETAILS

As we learned in 4A, redox reactions are a type of chemical reaction which involves the simultaneous transfer of electrons between one chemical species and another. It is important to note that previously we only learned about spontaneous redox reactions. Sometimes two chemical species, when mixed, will not react because a spontaneous redox reaction cannot occur. However, there is a way to force redox reactions to occur, and that is what we will be learning about in this lesson.

Electrolytic reactions are a very important part of chemistry due to their ability to convert electrical energy into chemical energy. In other words, they are able to reverse spontaneous redox reactions. This is because electrolysis can be used to force non-spontaneous redox reactions to occur. Therefore, electrolytic reactions can occur by applying an external power source to force electrons to reduce a species and to forcefully remove electrons to oxidise a species by the passage of electricity.

This means that they can create substances, such as solid sodium ($Na_{(s)}$) or chlorine gas ($Cl_{2(g)}$), which are very volatile when exposed to other chemicals, such as water, and are not found in nature.

In order to correctly balance **electrolytic half-equations**, which are either the oxidation or reduction half of a redox reaction, the following pieces of information are needed.

- Does the half-equation involve oxidation or reduction?
- What is the chemical species involved in the oxidation/reduction reaction?
- What is the oxidising or reducing agent being reduced/oxidised to respectively?

The way we determine the electrolytic half-equations is the same as that for spontaneous redox half-equations. The first two pieces of information we require can be found with the use of oxidation numbers. If there is an increase in the oxidation number, we know that the chemical species has been oxidised. If there is a decrease in the oxidation number, then we know that the chemical species has been reduced. After we have determined these pieces of information, we can then balance simple equations by making sure that the charge is equal on both sides of the half-equation by adding negatively charged electrons.

1 Worked example

Write the balanced oxidation half-equation for the following electrolytic reaction:

$Cu_{(s)} + Pb^{2+}_{(aq)} \rightarrow Cu^{2+}_{(aq)} + Pb_{(s)}$

What information is presented in the question?

The complete electrolytic reaction equation.

What is the question asking us to do?

Deduce an oxidation half-equation from the complete redox equation.

What strategy(ies) do we need in order to answer the question?

1. Use oxidation numbers to determine the chemical species that is being oxidised and what it is oxidised to.
2. Balance the charge of this equation using electrons.
3. Write out the complete oxidation half-equation.

Answer

$Cu_{(s)} + Pb^{2+}_{(aq)} \rightarrow Cu^{2+}_{(aq)} + Pb_{(s)}$

The oxidation number of $Cu_{(s)}$ is 0

The oxidation number of $Pb^{2+}_{(aq)}$ is +2

The oxidation number of $Cu^{2+}_{(aq)}$ is +2

The oxidation number of $Pb_{(s)}$ is 0

Since the oxidation number of the chemical species involving copper has increased, this indicates that $Cu_{(s)}$ has been oxidised to $Cu^{2+}_{(aq)}$. The unbalanced oxidation half-equation is:

$Cu_{(s)} \rightarrow Cu^{2+}_{(aq)}$

Using electrons to balance the charge results in the following half equation:

$Cu_{(s)} \rightarrow Cu^{2+}_{(aq)} + 2e^-$

Therefore, this is the balanced oxidation half-equation.

However, this was a simple case of balancing a half reaction as only the electron charge needed to be balanced. In more complex cases, the following acronym KOHES describes all the different steps that have to be taken in order to correctly balance a half-equation:

Key elements need to be balanced

Oxygen atoms need to be balanced

Hydrogen atoms need to be balanced

Electrons need to be added to balance charge

States need to be included

This is exactly as described in lesson 4B.

Balancing overall electrolytic equations 3.2.11.2.2

OVERVIEW

The skills required for balancing electrolytic half-equations can now be applied to balancing more complex electrolytic reactions.

THEORY DETAILS

Since an electrolytic reaction consists of both a reduction half-equation and an oxidation half-equation, the overall redox reaction can be determined by adding these two half-equations together. To add together the two half-equations there must be the same number of electrons on either side of the half-equations as electrons are not present in the overall electrolytic equation. This can be achieved by multiplying one or both of the half-equations by a constant factor.

2 Worked example

Write the balanced overall electrolytic reaction using the following reduction and oxidation half-equations:

$2Cr^{3+}_{(aq)} + 7H_2O_{(l)} \rightarrow Cr_2O_7{}^{2-}_{(aq)} + 14H^+_{(aq)} + 6e^-$

$Cu^{2+}_{(aq)} + 2e^- \rightarrow Cu_{(s)}$

What information is presented in the question?

The balanced reduction and oxidation half-equations.

What is the question asking us to do?

Write out the balanced overall electrolytic equation.

What strategy(ies) do we need in order to answer the question?

1. Ensure that the oxidation half-equation has the same number of electrons as the reduction half-equation.
2. Add the half-equations together and cancel the chemical species which appear on both sides of the equation.

Answer

Multiply the reduction half-equation by a factor of 3 so that it also has 6 electrons:

$3Cu^{2+}_{(aq)} + 6e^- \rightarrow 3Cu_{(s)}$

Add the reduction and oxidation half-equations together:

$3Cu^{2+}_{(aq)} + 6e^- + 2Cr^{3+}_{(aq)} + 7H_2O_{(l)} \rightarrow 3Cu_{(s)} + Cr_2O_7{}^{2-}_{(aq)} + 14H^+_{(aq)} + 6e^-$

Cancel out the electrons to give the following balanced overall redox equation:

$3Cu^{2+}_{(aq)} + 2Cr^{3+}_{(aq)} + 7H_2O_{(l)} \rightarrow 3Cu_{(s)} + Cr_2O_7{}^{2-}_{(aq)} + 14H^+_{(aq)}$

Using the electrochemical series to predict electrolytic reactions 3.2.11.1.1 & 3.2.9.1 & 3.2.9.2

OVERVIEW

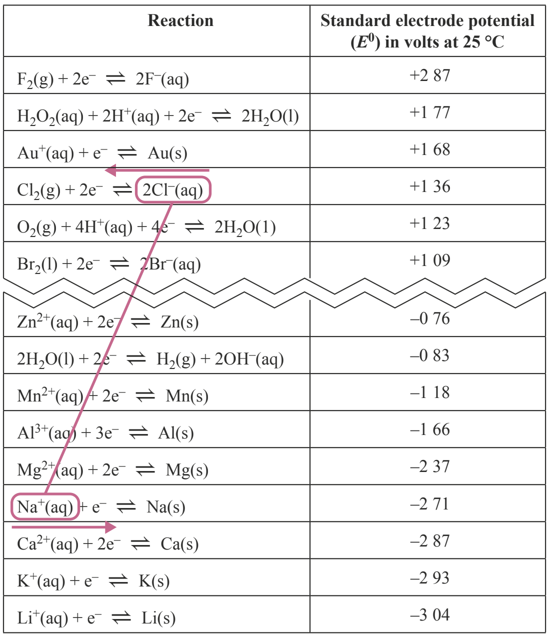
Similar to the process of predicting spontaneous redox reactions, the electrochemical series can be used to determine whether an electrolytic reaction will occur and if so, which chemical species are involved in the reaction.

THEORY DETAILS

Electrolysis is used to initiate non-spontaneous redox reactions. This can be achieved by applying an external power source which forcefully pushes electrons to reduce a species and forcefully removes electrons to oxidise a species. An important requirement to note is that the voltage of the power source must meet a particular threshold. This will be explained further in lesson 6B.

Similar to determining the reactions in a galvanic cell, it is useful to circle all the species present in the reaction on the electrochemical series. This includes the metals which make up the electrodes, the ions in the electrolyte, any gases dissolved in solution and water (if an aqueous species is present). Using this information, we will be able to deduce what reaction under standard conditions would occur, as the strongest oxidising agent will react with the strongest reducing agent. Remember, the strongest reducing agent is on the bottom right hand side of the electrochemical series, and the strongest oxidising agent is on the top left hand side of the electrochemical series. Just as in spontaneous redox reactions, the oxidising agent will undergo reduction and the reducing agent will undergo oxidation.

The most basic electrolytic reaction involves a **molten electrolyte**. Molten electrolytes are formed by the melting of an ionic compound such as $NaCl_{(s)}$ at very high temperatures, which in this case is around 800 °C. When $NaCl_{(s)}$ melts, it becomes a liquid which consists of $Na^+_{(l)}$ and $Cl^-_{(l)}$ ions. As we know from chapter 4, $Na^+_{(l)}$ is a very weak oxidising agent and $Cl^-_{(l)}$ is a very weak reducing agent. Therefore, a spontaneous redox reaction cannot occur, as shown in figure 1.



Reaction	Standard electrode potential (E^0) in volts at 25 °C
$F_2(g) + 2e^- \rightleftharpoons 2F^-(aq)$	+2 87
$H_2O_2(aq) + 2H^+(aq) + 2e^- \rightleftharpoons 2H_2O(l)$	+1 77
$Au^+(aq) + e^- \rightleftharpoons Au(s)$	+1 68
$Cl_2(g) + 2e^- \rightleftharpoons 2Cl^-(aq)$	+1 36
$O_2(g) + 4H^+(aq) + 4e^- \rightleftharpoons 2H_2O(1)$	+1 23
$Br_2(l) + 2e^- \rightleftharpoons 2Br^-(aq)$	+1 09
$Zn^{2+}(aq) + 2e^- \rightleftharpoons Zn(s)$	–0 76
$2H_2O(l) + 2e^- \rightleftharpoons H_2(g) + 2OH^-(aq)$	–0 83
$Mn^{2+}(aq) + 2e^- \rightleftharpoons Mn(s)$	–1 18
$Al^{3+}(aq) + 3e^- \rightleftharpoons Al(s)$	–1 66
$Mg^{2+}(aq) + 2e^- \rightleftharpoons Mg(s)$	–2 37
$Na^+(aq) + e^- \rightleftharpoons Na(s)$	–2 71
$Ca^{2+}(aq) + 2e^- \rightleftharpoons Ca(s)$	–2 87
$K^+(aq) + e^- \rightleftharpoons K(s)$	–2 93
$Li^+(aq) + e^- \rightleftharpoons Li(s)$	–3 04

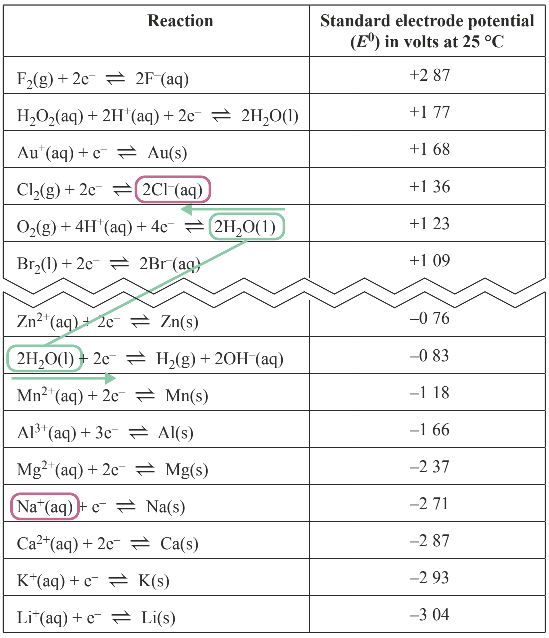
Adapted from VCAA data book

Figure 1 Electrochemical series with the present chemical species highlighted

However, as we learned earlier in this lesson, there is a way to force redox reactions to occur. This can be achieved by applying an external power source to two inert electrodes, forcefully pushing electrons to reduce $Na^+_{(l)}$ and forcefully removing electrons to oxidise $Cl^-_{(l)}$. The oxidation equation in this case is $2Cl^-_{(l)} \rightarrow Cl_{2(g)} + 2e^-$ as electrons are forcefully being pulled from the $Cl^-_{(l)}$ ions. The reduction half-equation is $Na^+_{(l)} + e^- \rightarrow Na_{(l)}$ as electrons are being forcefully pushed to reduce $Na^+_{(l)}$. It is important to note that the ionic species in this equation are going to be in a liquid state because the electrolyte is molten.

Another type of electrolyte, known as an **aqueous electrolyte**, can be formed when a chemical species is dissolved in water to form an aqueous solution. It is also important to note that water is always present in an aqueous electrolyte and therefore can participate in an electrolytic reaction. Using the same example as before, let's look at the electrolytic reaction involving a solution of 1.0 M $NaCl_{(aq)}$. In this case, the only difference is the states of the respective chemical species ($Na^+_{(aq)}$ and $Cl^-_{(aq)}$) as well as the presence of $H_2O_{(l)}$.

In this case, if we electrolyse a solution of 1.0 M $NaCl_{(aq)}$ using platinum electrodes and sufficient voltage, the strongest reducing agent and oxidising agent is $H_2O_{(l)}$, as shown in figure 2.



Reaction	Standard electrode potential (E^0) in volts at 25 °C
$F_2(g) + 2e^- \rightleftharpoons 2F^-(aq)$	+2 87
$H_2O_2(aq) + 2H^+(aq) + 2e^- \rightleftharpoons 2H_2O(l)$	+1 77
$Au^+(aq) + e^- \rightleftharpoons Au(s)$	+1 68
$Cl_2(g) + 2e^- \rightleftharpoons 2Cl^-(aq)$	+1 36
$O_2(g) + 4H^+(aq) + 4e^- \rightleftharpoons 2H_2O(1)$	+1 23
$Br_2(l) + 2e^- \rightleftharpoons 2Br^-(aq)$	+1 09
$Zn^{2+}(aq) + 2e^- \rightleftharpoons Zn(s)$	–0 76
$2H_2O(l) + 2e^- \rightleftharpoons H_2(g) + 2OH^-(aq)$	–0 83
$Mn^{2+}(aq) + 2e^- \rightleftharpoons Mn(s)$	–1 18
$Al^{3+}(aq) + 3e^- \rightleftharpoons Al(s)$	–1 66
$Mg^{2+}(aq) + 2e^- \rightleftharpoons Mg(s)$	–2 37
$Na^+(aq) + e^- \rightleftharpoons Na(s)$	–2 71
$Ca^{2+}(aq) + 2e^- \rightleftharpoons Ca(s)$	–2 87
$K^+(aq) + e^- \rightleftharpoons K(s)$	–2 93
$Li^+(aq) + e^- \rightleftharpoons Li(s)$	–3 04

Adapted from VCAA data book

Figure 2 Electrochemical series with the present chemical species highlighted

Therefore, instead of solid sodium and chlorine gas being produced, $H_2O_{(l)}$ will be reduced according to the half-equation $2H_2O_{(l)} + 2e^- \rightarrow H_{2(g)} + 2OH^-_{(aq)}$ and $H_2O_{(l)}$ will also be oxidised according to the half-equation $2H_2O_{(l)} \rightarrow O_{2(g)} + 4H^+_{(aq)} + 4e^-$. Therefore, adding these two half-equations leaves us with:

$$2H_2O_{(l)} \rightarrow 2H_{2(g)} + O_{2(g)}$$

In reality, this reaction occurs very slowly and so sometimes an electrolyte consisting of an ionic compound which doesn't interfere in the reaction can be used to increase the rate of electrolysis.

There are a couple of key complicating factors that can arise. The first is that since the values listed in the electrochemical series are measured under standard laboratory conditions and using 1.0 M concentration for all solutions, any changes from these conditions may mean that the electrolytic reactions which occur are different from the predicted electrolytic reactions. For example, if 5.0M of $NaCl_{(aq)}$ is electrolysed, chlorine gas is produced even though it is not predicted to occur.

Another complicating factor that can arise is the idea of a reactive anode (electrode where oxidation occurs). That is, if this example were changed to use copper electrodes instead of inert platinum ones, $Cu_{(s)}$ will also be present in the electrolytic cell. Since $Cu_{(s)}$ is a stronger reducing agent than $H_2O_{(l)}$, it will be oxidised preferentially and $Cu^{2+}{}_{(aq)}$ ions will enter the solution. Eventually, the concentration of $Cu^{2+}{}_{(aq)}$ will reach a point when it will start to be reduced instead of $H_2O_{(l)}$, plating the copper electrode and continuing the cycle. However, it is important to remember that only the anode can be reactive (i.e. involved in the reaction) in an electrolytic cell because since electrodes have to be conductive to allow the flow of electrons, they are (for the most part) solid metals. Since solid metals can only ever be oxidised, if the cathode is made from a metal, this metal will not be involved in the reaction. This is because electrons must flow through the electrode meaning it itself cannot be oxidised even if predicted to by the electrochemical series.

Theory summary

- Electrolytic half-equations can be balanced in the same manner as we learned in lesson 4B.
- A complete electrolytic reaction can be determined by adding the reduction and oxidation half-equations together if they both contain the same number of electrons.
- The electrochemical series is able to tell us what the strongest oxidising agent is and what the weakest reducing agent is and therefore predict possible electrolytic reactions.
- The electrochemical series is only reliable to predict redox reactions under standard laboratory conditions and 1.0 M concentrations.
- There is the possibility for an anode to react in an electrolytic reaction but not the cathode.

6A QUESTIONS

Theory review questions

Question 1

Electrolytic reactions convert

A chemical energy into electrical energy.

B electrical energy into chemical energy.

C thermal energy into electrical energy.

D kinetic energy into chemical energy.

Question 2

Can electrolytic reactions occur spontaneously?

A Yes. The strongest oxidising agent present is above the strongest reducing agent present on the electrochemical series.

B No. Heat is required.

C Yes. They are very slow and so not observable.

D No. An external power source with sufficient voltage is required.

Question 3

With respect to writing balanced electrolytic reactions, the electrochemical series can help to

I identify the strongest oxidising agent and reducing agent.

II identify the overall reaction that occurs when the voltage and concentrations are unknown.

III identify only the oxidation electrolytic half-equation.

A I & II only

B I only

C II & III only

D I & III only

Exam-style questions

Within lesson

Question 4 (1 MARK)

If the following is a spontaneous redox reaction,

$3Se_{(s)} + 4Cr(OH)_{3(aq)} + 6OH^-_{(aq)} \rightarrow 3SeO_3{}^{2-}{}_{(aq)} + 4Cr_{(s)} + 9H_2O_{(l)}$

What would the electrolytic reaction be given a sufficient voltage?

A $3SeO_3{}^{2-}{}_{(aq)} + 4Cr_{(s)} \rightarrow 3Se_{(s)} + 4Cr(OH)_{3(aq)}$

B $3SeO_3{}^{2-}{}_{(aq)} + 4Cr_{(s)} + 9H_2O_{(l)} \rightarrow 3Se_{(s)} + 4Cr(OH)_{3(aq)} + 6OH^-_{(aq)}$

C $3Se_{(s)} + 4Cr(OH)_{3(aq)} \rightarrow 3SeO_3{}^{2-}{}_{(aq)} + 4Cr_{(s)}$

D $Se_{(s)} + Cr(OH)_{3(aq)} + OH^-_{(aq)} \rightarrow SeO_3{}^{2-}{}_{(aq)} + Cr_{(s)} + H_2O_{(l)}$

Question 5 (4 MARKS)

Sarah would like an electrolytic reaction to occur between $Ni^{2+}_{(aq)}$ and $Pb_{(s)}$. She uses lead electrodes dipped into an aqueous solution of 1.0M $Ni^{2+}_{(aq)}$ and a power source. She reasons that it doesn't matter what voltage is applied and all that matters is the presence of a power source. However, when she uses a power source with a small voltage, nothing happens.

a Evaluate Sarah's statement with reference to the experimental results. (2 MARKS)

b Write the oxidation and reduction half-equations occurring when she uses a different power source with sufficient voltage. (2 MARKS)

Question 6 (3 MARKS)

The following chemical reaction represents what is occurring in a lead-acid battery during an electrolytic reaction and it is unbalanced.

$Pb^{2+}_{(aq)} + H_2O_{(l)} \rightarrow Pb_{(s)} + PbO_{2(s)} + H^+_{(aq)}$

a Write the balanced oxidation half-equation for the reaction in acidic conditions. (1 MARK)

b Write the balanced reduction half-equation for this reaction in acidic conditions. (1 MARK)

c Write the full balanced redox equation for this reaction. (1 MARK)

Question 7 (3 MARKS)

The unbalanced electrolytic equation between iron and magnesium sulphate is given below.

$Fe_{(s)} + Mg^{2+}_{(l)} \rightarrow Fe^{3+}_{(l)} + Mg_{(s)}$

a Write the balanced electrolytic reduction half-equation and the balanced electrolytic oxidation half-equation. (2 MARKS)

b Write the balanced overall electrolytic equation. (1 MARK)

Question 8 (3 MARKS)

1.00 M $Cu^{2+}_{(aq)}$ and $Co^{2+}_{(aq)}$ are dissolved and using platinum electrodes, a voltage is applied. A student predicts that $Co^{2+}_{(aq)}$ will be reduced in preference to $Cu^{2+}_{(aq)}$ under standard conditions.

a With reference to the electrochemical series, is the student's prediction correct? (2 MARKS)

b Using the fact that different voltages are required for different electrolytic reactions, how might one electrolytic reaction be favoured over another? (1 MARK)

Multiple lessons

Question 9 (4 MARKS)

Statement 1: $Cu^{2+}_{(aq)}$ and $Zn_{(s)}$ can be used in a galvanic cell to produce electricity

Statement 2: $Cu_{(s)}$ and $Zn^{2+}_{(aq)}$ cannot be used in a galvanic cell to produce electricity

With reference to the electrochemical series, explain why these two statements are correct.

Question 10 (5 MARKS)

The following reaction is an example of a spontaneous redox reaction.

$Ni_{(s)} + 2Ag^{+}_{(aq)} \rightarrow Ni^{2+}_{(aq)} + 2Ag_{(s)}$

a Write the two half-equations of this redox reaction. (2 MARKS)

b Determine the conjugate redox pair for the oxidation process and for the reduction process. (2 MARKS)

c Given sufficient voltage and using silver electrodes, what will be the overall electrolytic equation when a solution of $Ni^{2+}_{(aq)}$ is electrolysed. (1 MARK)

Question 11 (8 MARKS)

Bilbo was in a chemistry class studying redox reactions. He initially had a beaker with a 1.0 M blue solution of $Cu^{2+}_{(aq)}$ ions and accidentally put a strip of $Pb_{(s)}$ in the beaker. His teacher was angry because the class only had a short supply of lead and the following redox reaction occurred:

$Cu^{2+}_{(aq)} + Pb_{(s)} \rightarrow Cu_{(s)} + Pb^{2+}_{(aq)}$

a Is this an electrolytic reaction? Explain your answer. (2 MARKS)

b Write out the reaction that would occur if, using copper electrodes, a solution of Pb^{2+} ions is electrolysed. (1 MARK)

c Over time, during the electrolytic reaction, what would be observed with respect to the solution and electrodes? (3 MARKS)

d After this electrolytic reaction was performed, Bilbo is confused about why the teacher is angry, since the amount of $Pb_{(s)}$ present in the beaker was the same as the initial strip. Is the teacher justified in being angry? (2 MARKS)

6B ELECTROLYTIC CELLS

In this lesson, we will study the structure of an electrolytic cell, and the function of each element within its structure.

6A Electrolytic reactions	6B Electrolytic cells	6C Faraday's Laws	6D Primary and secondary cells

Study design dot points

- the general operating principles of commercial electrolytic cells, including basic structural features and selection of suitable electrolyte (molten or aqueous) and electrode (inert or reactive) materials to obtain desired products (no specific cell is required)
- the comparison of an electrolytic cell with a galvanic cell with reference to the energy transformations involved and basic structural features and processes

Key knowledge units

Design of electrolytic cells	3.2.10.1
Comparison of electrolytic cells and galvanic cells	3.2.12.1
Selecting electrolytes, electrodes and voltage	3.2.11.1.2

Key terms and definitions

- **Anode** positively charged electrode in an electrolytic cell where oxidation occurs
- **Cathode** negatively charged electrode in an electrolytic cell where reduction occurs
- **Electrolyte** chemical compound that allows the flow of electric charge within a cell
- **Overpotential** difference between the calculated potential required and actual potential required to facilitate an electrolytic reaction
- **Power supply** electrical device such as a battery or a generator that provides electrical energy to a circuit
- **Standard electrode potential** potential of the half-reaction (reduction), given in volts, relative to the standard hydrogen electrode

Design of electrolytic cells 3.2.10.1

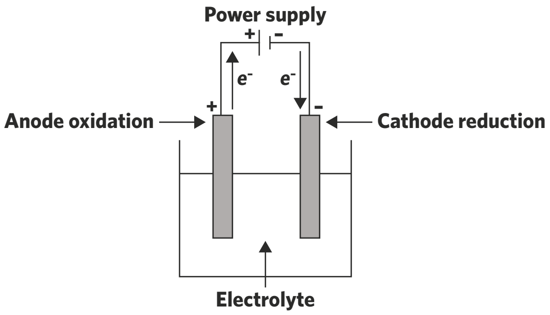
OVERVIEW

We can use our knowledge of electrolytic reactions to construct an electrolytic cell.

THEORY DETAILS

As we learned in lesson 6A, an electrolytic reaction is a type of redox reaction that is non-spontaneous. As a result, energy has to be put into the system in order for the reaction to occur. We can accomplish this by adding a power supply to the circuit, which provides the necessary electrical energy. In this process, the reducing agent undergoes oxidation and the oxidising agent undergoes reduction, consistent with the redox reactions we have studied. Electrical energy from the **power supply** provides the flow of electrons to force a non-spontaneous reaction to occur. Therefore, we can say an electrolytic cell converts electrical energy into chemical energy.

The general design of an electrolytic cell is given in figure 1.



Adapted from VCAA NHT 2018 Exam Section B Q5

Figure 1 A standard electrolytic cell

It is useful for us to become familiar with the representation of the polarity of the power supply as shown in figure 1. In this design, the electrolytic cell contains two electrodes, the anode and cathode, which act as the site of the redox reactions. By definition, the **anode** is the site of oxidation and is positive in an electrolytic cell, and the **cathode** is the site of reduction, and is negative in an electrolytic cell. As electrolytic reactions are non-spontaneous, the reactants will not directly react, and so the anode and cathode in an electrolytic cell may be in the same vessel. However, the products formed will spontaneously react, and so must be separated to avoid an undesired reaction.
The **electrolyte**, labelled in figure 1, allows the flow of charge between the reduction and oxidation reaction and in doing so, completes the circuit. Here, the power supply is represented with standard battery notation – as two horizontal lines, one longer than the other as shown in figure 2. The longer bar represents the positive terminal of the battery and the shorter bar represents the negative terminal of the battery. Take note of the direction of electron flow through each of these representations, as this indicates which electrode will act as the cathode, and which will act as the anode.

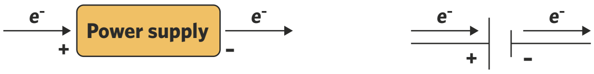


Figure 2 Representations of a power supply

We know by definition that reduction, the gain of electrons, occurs at the cathode and so we can deduce that the electrode receiving electrons from the power supply is the cathode.

In a similar manner, we know the electrode from where electrons leave must be the site of oxidation, as the reducing agent is losing electrons, and so this electrode is defined as the anode. Using this logic, we can identify the anode and cathode using the polarity of the power supply. This is useful when given a partially labelled diagram, or in recognising when a power supply has been incorrectly wired.

Comparison of electrolytic cells and galvanic cells 3.2.12.1

OVERVIEW

From the components of an electrolytic cell we have discussed, we can see a number of similarities between this type of cell and a galvanic cell, introduced in chapter 4.

THEORY DETAILS

The key difference between an electrolytic cell and a galvanic cell is that a galvanic cell uses spontaneous redox reactions to convert chemical energy to electrical energy, whereas an electrolytic cell uses non-spontaneous redox reactions to convert electrical energy to chemical energy.

The two can be thought of as complementary processes that convert one form of energy to the other, as demonstrated in figure 3.

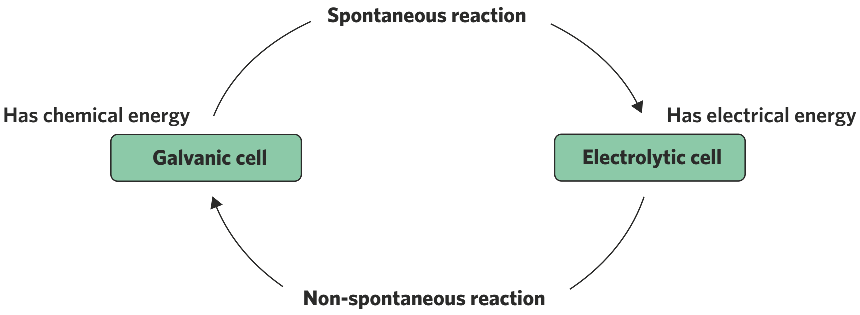


Figure 3 The relationship between energy conversions of galvanic and electrolytic cells

We can also compare the structure and function of an electrolytic cell to that of a galvanic cell, as outlined in table 1.

Table 1 Comparison of galvanic and electrolytic cells

Galvanic Cell	Electrolytic Cell
Differences	
Anode is negatively charged	Anode is positively charged
Cathode is positively charged	Cathode is negatively charged
Spontaneous reaction	Non-spontaneous reaction
Half-cells must be separate for indirect reaction	Does not require separate half-cells
Converts chemical energy to electrical energy	Converts electrical energy to chemical energy
Salt bridge required	No salt bridge required
No power supply required	Power supply required
Similarities	
Oxidation occurs at the anode	Oxidation occurs at the anode
Reduction occurs at the cathode	Reduction occurs at the cathode

Selecting electrolytes, electrodes and voltage 3.2.11.1

OVERVIEW

The electrochemical series can be used to select an appropriate electrolyte and electrode to be used in an electrolytic cell and to determine the voltage required for electrolytic reactions to take place.

THEORY DETAILS

The electrochemical series gives information about the relative strengths of various common oxidising and reducing agents at Standard Laboratory Conditions (SLC). As a result, we can use this series to predict the reactions that will occur in an electrolytic cell.

Selecting electrolytes

We discussed earlier in this lesson the importance of the electrolyte in an electrolytic cell. This is particularly so in industry, where an electrolyte for a cell must be carefully chosen in order to minimise expense and ensure the correct reaction takes place.

As we learned in lesson 6A, there are two types of electrolytes that can be used in a cell: molten or aqueous. Our choice of electrolyte will depend on the desired reaction.

An aqueous electrolyte can be used in a cell where both

- the desired oxidising agent is a stronger oxidising agent than water (i.e. oxidising agent must be higher up on the electrochemical series than water at −0.83 V).
- the desired reducing agent is a stronger reducing agent than water (i.e. reducing agent must be lower down on the electrochemical series than water at +1.23 V. Note that there is also a water present at +1.77 V but this water rarely takes part in electrolytic reactions).

However, if this is not the case, a molten electrolyte may be used. In this case, the liquid state, (l), is used to indicate molten form since a molten electrolyte will not contain water. It is preferable to use an aqueous electrolyte where possible, as molten electrolytes require high temperatures to maintain the molten form, and so are both expensive and dangerous to use.

Tip When constructing a cell, always check whether the electrolyte or the reactants need to be in liquid or molten form by referring to the electrochemical series in the data book and identifying the strongest oxidising agent and strongest reducing agent from the species present in the cell.

1 Worked example

The Downs Cell is a particular electrolytic cell that produces sodium metal and chlorine gas using inert electrodes. Use the electrochemical series to predict whether the cell will require a molten or aqueous electrolyte.

What information is presented in the question?

We have an electrolytic cell.

Sodium metal is produced.

Chlorine gas is produced.

What is the question asking us to do?

Deduce whether the electrolyte for this cell should be aqueous or molten.

What strategy(ies) do we need in order to answer the question?

1. Identify the half-equations in the electrochemical series that correspond to this reaction.
2. Circle on the electrochemical series all the species present.
3. Deduce whether the reactants required are stronger oxidising agents and/or reducing agents than water.

Answer

Reaction	Standard electrode potential (E^0) in volts at 25 °C
$F_2(g) + 2e^- \rightleftharpoons 2F^-(aq)$	+2.87
$H_2O_2(aq) + 2H^+(aq) + 2e^- \rightleftharpoons 2H_2O(l)$	+1.77
$Au^+(aq) + e^- \rightleftharpoons Au(s)$	+1.68
$Cl_2(g) + 2e^- \rightleftharpoons 2Cl^-(aq)$	+1.36
$O_2(g) + 4H^+(aq) + 4e^- \rightleftharpoons 2H_2O(1)$	+1.23
$Br_2(l) + 2e^- \rightleftharpoons 2Br^-(aq)$	+1.09
$Zn^{2+}(aq) + 2e^- \rightleftharpoons Zn(s)$	–0.76
$2H_2O(l) + 2e^- \rightleftharpoons H_2(g) + 2OH^-(aq)$	–0.83
$Mn^{2+}(aq) + 2e^- \rightleftharpoons Mn(s)$	–1.18
$Al^{3+}(aq) + 3e^- \rightleftharpoons Al(s)$	–1.66
$Mg^{2+}(aq) + 2e^- \rightleftharpoons Mg(s)$	–2.37
$Na^+(aq) + e^- \rightleftharpoons Na(s)$	–2.71
$Ca^{2+}(aq) + 2e^- \rightleftharpoons Ca(s)$	–2.87
$K^+(aq) + e^- \rightleftharpoons K(s)$	–2.93
$Li^+(aq) + e^- \rightleftharpoons Li(s)$	–3.04

Adapted from VCAA data book

1. If the reactants were in aqueous form, water would be present in the cell. As a result, we circle the water at –0.83 V and +1.23 V and +1.77 V.
2. We know that the products are chlorine gas and sodium, so we circle the reactants Na^+ and Cl^-, and draw the arrows for the direction of the reaction.
3. From the electrochemical series we can see that water is a stronger oxidising agent than Na^+ and a stronger reducing agent than Cl^-. Therefore, an aqueous electrolyte cannot be used under standard conditions, as the electrolysis of water would take preference and the desired reaction would not occur. So, a molten electrolyte is required.

Let's now have a look at the Downs Cell in more detail.

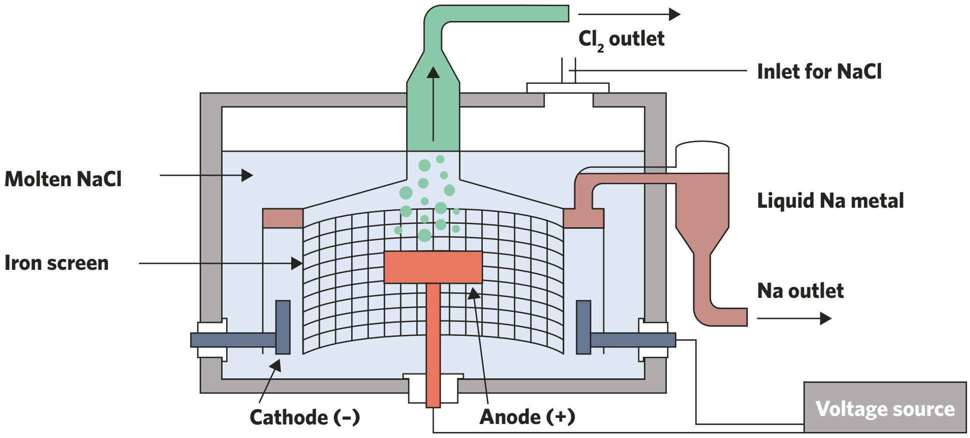


Figure 4 Downs Cell diagram

For the purposes of the VCE course, knowledge of specific electrolytic cells is not required, but it is useful to be familiar with some common design features. Since we deduced that the reaction in a Downs Cell has to take place under molten conditions, the electrolyte consists of molten sodium chloride. The anode in this case is unreactive carbon and the cathode is solid iron, which, since iron cannot be reduced, is effectively inert. The pipe which extracts chlorine gas is required to prevent sodium and chlorine gas reacting spontaneously and reversing the electrolytic reaction. Similarly, the iron mesh screen is used to prevent sodium making contact with chlorine gas. Liquid sodium is then extracted through a pipe.

Selecting electrodes

As we have learned in this lesson, selecting the electrolyte for an electrolytic cell depends on the desired products. The same process can be applied when selecting appropriate electrodes. When considering which electrodes are required for a cell, it is important to consider whether or not the electrode is intended to take part in the reaction. The selection of an anode is important, as it can play a part in the reaction, which is sometimes useful in electrolytic cells. For example, an electrode of impure metal ores is useful to obtain a pure metal sample. Otherwise, inert electrodes such as platinum or graphite rods should be used to avoid any alternative reactions occurring.

Calculating voltage

We previously learned in lesson 6A that an electrolytic reaction is non-spontaneous and therefore requires a power source to provide the energy necessary for the reaction to occur. An important application of the electrochemical series is that it can be used to predict the voltage of the power source required to enable a reaction to proceed.

The right column of the electrochemical series in the data book lists the **standard electrode potentials** (E^0) for each of the reactions given. An E^0 value gives an indication of the energy required to allow the reaction to proceed. These values are relative to the reduction reaction of hydrogen ions to form hydrogen gas in the standard hydrogen electrode (SHE), which is assigned an E^0 value of 0.00 volts. All E^0 values are given for half-cells occurring at SLC and for electrolyte solutions of concentration 1 M. To calculate the potential difference, or voltage, of a cell ($E^0{}_{\text{cell}}$), we must find the difference in E^0 values between the oxidation and reduction half-equations.

Similar to galvanic cells, the general formula for calculating the $E^0{}_{\text{cell}}$ of an electrolytic cell is:

$E^0{}_{\text{cell}} = E^0{}_{\text{reduction}} - E^0{}_{\text{oxidation}}$

Although this gives a negative value in an electrolytic cell, it shows us the potential difference and therefore highlights the minimum voltage required for this reaction to occur. When using the electrochemical series to calculate voltage, it is useful to circle all the species present and draw a line between the species reacting, as shown in figure 5. Comparing the reaction of solid lead with zinc ions with that of lead and nickel ions, we can see the difference in potentials is larger for reaction 1 than reaction 2. This indicates that reaction 1 requires a greater voltage than reaction 2.

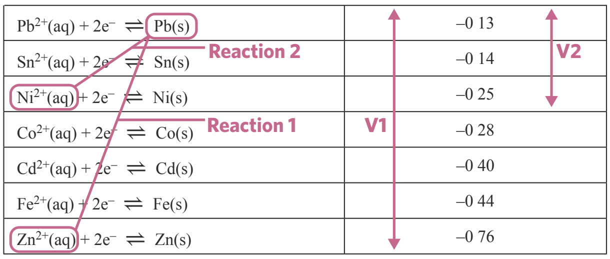


Figure 5 A comparison of voltage potentials in a cell using the electrochemical series

It is important to note that in electrolytic reactions, as with galvanic cell reactions, the strongest oxidising agent will react with the strongest reducing agent. Hence, in the above reaction $Ni^{2+}{}_{(aq)}$, the strongest oxidising agent, will react with $Pb_{(s)}$, the strongest reducing agent.

The $E^0{}_{\text{cell}}$ value corresponds to the voltage output of the cell. However, for an electrolytic cell, no electricity is being produced. The magnitude also indicates the minimum voltage required for the reaction to occur. If the power supplied is less than this value, the reaction cannot occur. However, in practice, the energy required for the reaction may be slightly higher than the theoretical voltage predicted by the electrochemical series. This concept is referred to as **overpotential**.

Therefore, $E^0{}_{\text{required}} > E^0{}_{\text{reduction}} - E^0{}_{\text{oxidation}}$

This may occur due to variations in reaction conditions including:

- Nature of electrodes
- Temperature
- Concentration of reactants

Another explanation for overpotential is that some energy may be lost in the form of heat from the power supply or wiring and hence the electrical energy introduced to the cell is less than the quantity required for the reaction to occur. A classic example of the effects of overpotential is demonstrated in the electrolytic reaction involving $NaCl_{(aq)}$. Based on the working out in Worked Example 1, we can see that water is a stronger reducing agent and oxidising agent than $Cl^-{}_{(aq)}$ and $Na^+{}_{(aq)}$ respectively. Therefore we would expect that $H_{2(g)}$, $H_2O_{(l)}$ and $O_{2(g)}$ would be produced in this cell. Let's look more closely at the possible reactions at each electrode.

Cathode		Anode	
$Na^+{}_{(aq)} + e^- \rightarrow Na_{(s)}$	$E^0 = -2.71$ V	$2Cl^-{}_{(aq)} \rightarrow Cl_{2(g)} + 2e^-$	$E^0 = -1.36$ V
$2H_2O_{(l)} + 2e^- \rightarrow H_{2(g)} + 2OH^-{}_{(aq)}$	$E^0 = -0.83$ V	$2H_2O_{(l)} \rightarrow O_{2(g)} + 4H^+{}_{(aq)} + 4e^-$	$E^0 = -1.23$ V

At the cathode, the reduction of water requires a much smaller voltage compared to sodium ions and therefore is preferred as the oxidising agent. At the anode, the electrochemical series predicts that water would also be preferred as the reducing agent as it requires less voltage. However, despite the oxidation of water requiring a lower voltage than the oxidation of chlorine ions, in reality, since this difference is small, both reactions can occur. As a result, in this reaction chloride ions can also be oxidised to produce chlorine gas instead of water and the higher the concentration of chloride ions, the more likely the chloride ions will be oxidised. This explains why some electrolytic cells are able to produce chlorine gas even though the electrolyte is aqueous.

Overpotential is not included in the study design, but may be a useful explanation of observations when undertaking experiments with electrolytic cells.

2 Worked example

An electrolytic cell with carbon electrodes contains lead (II) ions and bromide ions in the aqueous state at a concentration of 1.0 M. What is the voltage required to allow the reaction to proceed?

What information is presented in the question?

We have an electrolytic reaction.

Lead (II) ions are used in aqueous state.

Bromide ions are used in aqueous state.

What is the question asking us to do?

Calculate the voltage required for this reaction.

What strategy(ies) do we need in order to answer the question?

1. Identify the potential reactions in the electrochemical series.
2. Deduce which one will be the reaction at the cathode and anode.
3. Apply the formula $E^0{}_{cell} = E^0{}_{reduction} - E^0{}_{oxidation}$

Answer

Reaction	Standard electrode potential (E^0) in volts at 25 °C
$F_2(g) + 2e^- \rightleftharpoons 2F^-(aq)$	+2 87
$H_2O_2(aq) + 2H^+(aq) + 2e^- \rightleftharpoons 2H_2O(l)$	+1 77
$Au^+(aq) + e^- \rightleftharpoons Au(s)$	+1 68
$Cl_2(g) + 2e^- \rightleftharpoons 2Cl^-(aq)$	+1 36
$O_2(g) + 4H^+(aq) + 4e^- \rightleftharpoons 2H_2O(l)$	+1 23
$Br_2(l) + 2e^- \rightleftharpoons 2Br^-(aq)$	+1 09
$Ag^+(aq) + e^- \rightleftharpoons Ag(s)$	+0 80
$Fe^{3+}(aq) + e^- \rightleftharpoons Fe^{2+}(aq)$	+0 77
$O_2(g) + 2H^+(aq) + 2e^- \rightleftharpoons H_2O_2(aq)$	+0 68
$I_2(s) + 2e^- \rightleftharpoons 2I^-(aq)$	+0 54
$O_2(g) + 2H_2O(l) + 4e^- \rightleftharpoons 4OH^-(aq)$	+0 40
$Cu^{2+}(aq) + 2e^- \rightleftharpoons Cu(s)$	+0 34
$Sn^{4+}(aq) + 2e^- \rightleftharpoons Sn^{2+}(aq)$	+0 15
$S(s) + 2H^+(aq) + 2e^- \rightleftharpoons H_2S(g)$	+0 14
$2H^+(aq) + 2e^- \rightleftharpoons H_2(g)$	0 00
$Pb^{2+}(aq) + 2e^- \rightleftharpoons Pb(s)$	–0 13
$Sn^{2+}(aq) + 2e^- \rightleftharpoons Sn(s)$	–0 14
$Ni^{2+}(aq) + 2e^- \rightleftharpoons Ni(s)$	–0 25
$Co^{2+}(aq) + 2e^- \rightleftharpoons Co(s)$	–0 28
$Cd^{2+}(aq) + 2e^- \rightleftharpoons Cd(s)$	–0 40
$Fe^{2+}(aq) + 2e^- \rightleftharpoons Fe(s)$	–0 44
$Zn^{2+}(aq) + 2e^- \rightleftharpoons Zn(s)$	–0 76
$2H_2O(l) + 2e^- \rightleftharpoons H_2(g) + 2OH^-(aq)$	–0 83

Adapted from VCAA data book

1. We know $Br^-_{(aq)}$, $Pb^{2+}_{(aq)}$ and $H_2O_{(l)}$ are potential reactants, so we circle these on our electrochemical series.
2. As we can see, $Pb^{2+}_{(aq)}$ is the strongest oxidising agent and $Br^-_{(aq)}$ is the strongest reducing agent. Therefore, the redox reaction for this cell would involve the oxidation of $Br^-_{(aq)}$ and the reduction of $Pb^{2+}_{(aq)}$.
3. $E^0_{\text{cell}} = E^0_{\text{reduction}} - E^0_{\text{oxidation}}$
   $E^0_{\text{cell}} = -0.13 - (+1.09)$ V
   $E^0_{\text{cell}} = -1.22$ V
   Therefore a minimum of 1.22 V is required in order for the reaction to proceed (i.e. a quantity slightly greater than 1.22 V).

Theory summary

- Electrolytic cells facilitate non-spontaneous redox reactions.
- The cathode of an electrolytic cell is the site of reduction and is negative.
- The anode of an electrolytic cell is the site of oxidation and is positive.
- A power source provides the electrical energy necessary for an electrolytic reaction.
- Electrolytic cells convert electrical energy into chemical energy.
- Electrolytic reactions are considered complementary to reactions occurring in a galvanic cell, as the former converts electrical energy to chemical energy and the latter converts chemical energy into electrical energy.
- Aqueous reactants and electrolytes can change the reaction occurring if water is a stronger oxidising or reducing agent compared to the other species in the cell.
- Molten electrolytes and reactants are expensive and hazardous but can be used in place of aqueous solutions when required.
- Depending on the desired products, reactive or inert electrodes can be used.
- The E^0 of an electrolytic cell is given by $E^0_{\text{cell}} = E^0_{\text{reduction}} - E^0_{\text{oxidation}}$ and the voltage required has the same magnitude as E^0_{cell} but is positive.
- Overpotential can explain unexpected reactions in an electrolytic cell, as non-standard conditions may increase the required voltage.

6B QUESTIONS

Theory review questions

Question 1

Which of the following statements regarding electrolytic cells is correct?

A The cathode undergoes reduction or oxidation, depending on the species present.

B Electrolytic cells require the separation of half-cells.

C A redox reaction is taking place within the cell.

D Electrolytic cells convert chemical energy to electrical energy.

Question 2

Electrolytic cells all have a

A positively charged anode as the site of reduction.

B negatively charged anode as the site of oxidation.

C positively charged anode as the site of oxidation.

D negatively charged anode as the site of reduction.

Question 3

Fill in the blanks from the words listed to complete the paragraph about electrolytic cells.

- redox
- $E^0_{\text{reduction}}$
- chemical
- neutralisation
- electrical
- anode
- cathode
- mechanical
- positive
- proton
- negative

Electrolytic cells undergo __________ reactions, converting __________ energy to __________ energy. The voltage of the power source can be calculated by the equation E^0_{cell} = __________ – $E^0_{\text{oxidation}}$. Electrons flow from the power source to the __________ and from the __________ back to the power source.

Exam-style questions

Within lesson

Question 4 (1 MARK)

An electrolytic cell is set up with two platinum electrodes in a solution of tin (II) chloride using a sufficient voltage. The reaction occurring at the positive electrode under standard conditions would be

A $Pb^{2+}_{(aq)} + 2e^- \rightarrow Pb_{(s)}$

B $Sn^{2+}_{(aq)} \rightarrow Sn^{4+}_{(aq)} + 2e^-$

C $2H_2O_{(l)} \rightarrow O_{2\,(g)} + 4H^+_{(aq)} + 4e^-$

D $2Cl^-_{(aq)} \rightarrow Cl_{2\,(g)} + 2e^-$

Question 5 (1 MARK)

Electrolytic cells may make use of reactants in molten or aqueous form. When comparing a cell undergoing electrolysis of molten $KI_{(l)}$ and aqueous $KI_{(aq)}$ using a sufficient voltage, we would expect that

A the products at the anode will be the same but the products at the cathode will be different.

B the products at the anode will be the same and the products at the cathode will be the same.

C the products at the anode will be different but the products at the cathode will be the same.

D the products at the anode will be different and the products at the cathode will be different.

Adapted from VCAA 2008 Q20

Question 6 (3 MARKS)

Sally and Sam are exploring the differences between a galvanic cell and an electrolytic cell. The two compile their findings into a series of statements. Evaluate each of these statements, providing justification for your answer.

a Both galvanic and electrolytic cells require a power supply. (1 MARK)

b A galvanic cell converts electrical energy to chemical energy, and an electrolytic cell converts chemical energy to electrical energy. (1 MARK)

c The anode and cathode of a galvanic cell have the same polarity as the anode and cathode of an electrolytic cell. (1 MARK)

Question 7 (9 MARKS)

A cell is to be constructed to convert lithium ions to solid lithium from lithium chloride, LiCl, using a carbon anode and cathode.

a What type of electrolyte, molten or aqueous, would be more suitable for this cell? Justify your response using evidence from the electrochemical series. (2 MARKS)

b Two cells are constructed and tested with different anodes: one with an iron anode and carbon cathode (cell 1) and the other with a carbon anode and iron cathode (cell 2). It is found that the cells create different products, even with all other factors controlled. Assume the use of the electrolyte determined to be more suitable in part a.

- **i** Explain this result, providing the reactions happening at the anode in each case. (3 MARKS)
- **ii** Which of either cell 1 or cell 2 would result in the desired reaction and both electrodes remaining intact? (2 MARKS)

c Another cell is now constructed using a platinum electrode for the anode, the electrolyte identified in your answer to part a and graphite as the cathode. This cell is supplied with 1.05 V and it is observed that no products are created. Explain this result, using calculations in your answer. (2 MARKS)

Question 8 (6 MARKS)

A student prepares a beaker with a solution of tin (II) ions and manganese (II) ions and adds 2 carbon electrodes connected to a power source. The student predicts that a gas will be produced. However, no bubbling was observed during the reaction.

a Why did the student's prediction not match the observation? Justify your response with reference to the electrochemical series. (2 MARKS)

b Write the two half-equations for the reactions happening at the anode and cathode, and circle the species accounting for the observation contradicting the prediction. (3 MARKS)

c What effect would using a molten electrolyte have on the overall reaction of the cell? (1 MARK)

Multiple lessons

Question 9 (13 MARKS)

A new industrial company is looking for a way to produce solid sodium using electrolysis. The first proposal is presented by the company's chemical engineer who suggests the use of platinum cathode with solid copper anode and aqueous sodium ions as the electrolyte. The requirements of the project are that the cost must be minimised, and the safety of all factory employees be taken into account.

a Identify the reducing and oxidising agent in the reaction. (2 MARKS)

b Write the half-equation for the reaction occurring at the cathode. (1 MARK)

c Write an overall equation for the redox reaction occurring. (1 MARK)

d Identify whether the electrolyte required should be in aqueous or molten form, and justify this decision in regards to the requirement of minimal cost of the project. (2 MARKS)

e The company now requests a model for the proposed setup. Draw a diagram of an electrolytic cell that could be used, assuming any change implemented in part d and that the vessels are not required to be separated. Include labelling of the polarity of the electrodes, the flow of electrons, the power source, the reactions occurring at each electrode and the nature of the electrolyte. (4 MARKS)

f Now, the company's electrical engineer is tasked with calculating the voltage required for the correct functioning of the cell from part e. Using the electrochemical series, calculate this voltage. (1 MARK)

g The final step in the planning process is to consider the second requirement of the project, which is the safety of the employees. The OHS manager of the project finds the Material Safety Data Sheet for sodium metal and is required to report back to the company. Using the Material Safety Data Sheet given, identify one measure that should be taken when storing the liquid sodium produced. (2 MARKS)

Material Safety Data Sheet
Product name: SODIUM
Formula: $Na_{(s)}$

Hazard Statements
In contact with water releases flammable gases which may ignite spontaneously
Causes severe skin burns and eye damage

6C FARADAY'S LAWS

In this lesson we will learn how to apply Faraday's Laws to obtain quantitative information about electrolytic reactions, including how to determine the amount of product that can be produced as a result of electrolysis.

6A Electrolytic reactions	6B Electrolytic cells	6C Faraday's Laws	6D Primary and secondary cells

Study design dot point

- the application of stoichiometry and Faraday's Laws to determine amounts of product, current or time for a particular electrolytic process.

Key knowledge units

Faraday's first law	3.2.13.1.1
Faraday's second law	3.2.13.1.2
Electroplating	3.2.13.2.1
Application of Faraday's Laws	3.2.13.2.2

Key terms and definitions

- **Coulomb (C)** unit used to measure the amount of electrical charge
- **Current (I)** rate of flow of electric charge
- **Electric charge (Q)** amount of charge (usually measured in coulombs)
- **Electroplating** application of electrolysis used to coat a substance with a metallic layer
- **Faraday's constant (F)** total electric charge of 1 mol of electrons
- **Amperes (A)** unit used to measure the amount of current

Faraday's first law 3.2.13.1.1

OVERVIEW

Faraday's Laws of electrolysis provide a way for us to quantify the amount of material that can be produced (or consumed) during an electrolytic reaction. This is achieved by taking into consideration the current, total charge and time over which the current is applied.

THEORY DETAILS

Faraday's first law highlights the relationship between the electrical charge passing through an electrolytic cell and the amount of substance produced or consumed during electrolysis. It states that the mass of the substance deposited, evolved or dissolved at any electrode during electrolysis is directly proportional to the quantity of charge (i.e. electricity) passed through the cell. This relationship can be represented as $m \propto Q$ where m is the mass of substance produced at the cathode, Q is the electric charge and $\propto$ is the symbol used to represent the term 'proportional'. When two terms are proportional it means that they vary directly with each other.

As we can see in figure 1, the mass of a product increases as the total charge increases. The law is a mathematical representation of our understanding of the relationship between **current**, **electric charge** and time.

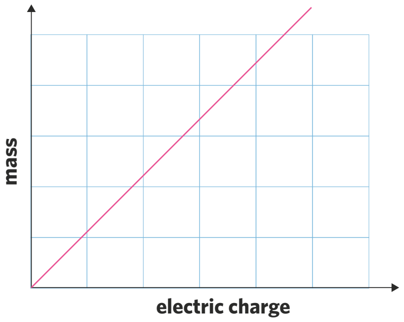


Figure 1 A graph representing the relationship between the mass of a product formed during electrolysis and the charge applied

We learned in lesson 4A that redox reactions involve the transfer of electrons. As a result, we can say that electric charge is transferred during redox reactions. For this lesson, we are referring specifically to electrolytic reactions.

During electrolysis, the amount of product that forms depends on the total electric charge flowing through the cell. The electric charge we are referring to is that supplied by the power supply which is connected to the electrolytic cell. As we can directly measure the mass of the products formed, we can use this to indirectly determine the total electric charge flowing through the cell.

To determine the total charge required for the reaction to occur, we need to know the current that is applied to the cell and how long it is applied for. The greater the current and the longer that it is applied, the greater the electric charge. This relationship is expressed as $Q = I \times t$ where Q = electric charge in **coulomb** (C), I = current in **Amperes** (A) and t = time in seconds.

Tip This formula can be found in the data book.

1 **Worked example**

A current of 1.5 A was applied to an electrolytic cell for 12 minutes. What is the total electric charge that passed through the cell?

What information is presented in the question?	Answer
$I = 1.5$ A $t = 12$ minutes	$Q = 1.5 \times (12 \times 60)$ $= 1080$ $= 1.1 \times 10^3$ C

What is the question asking us to do?

Find the total electric charge (Q) that passes through the cell.

What strategy(ies) do we need in order to answer the question?

1. Convert 12 minutes into seconds.
2. Use $Q = It$ to determine the charge.

Faraday's second law 3.2.13.1.2

OVERVIEW

Faraday's second law states that the production of 1 mole of a substance requires a whole number quantity of electrons (in mol).

THEORY DETAILS

The mass of product that is formed during electrolysis not only depends on the electric charge flowing through the cell but also on the ratio between the desired product and the amount of electrons, in mol. Consider the reduction half-equations below:

$Ag^+_{(aq)} + e^- \rightarrow Ag_{(s)}$

$Sn^{2+}_{(aq)} + 2e^- \rightarrow Sn_{(s)}$

$Cr^{3+}_{(aq)} + 3e^- \rightarrow Cr_{(s)}$

Using a half-equation, we can deduce the molar ratio between the metal ion and the number of electrons required to produce the solid metal. From the equations given, we can see that the production of 1 mol of solid silver requires 1 mol of electrons, the production of 1 mol of solid tin requires 2 mol of electrons and the production of 1 mol of solid chromium requires 3 mol of electrons. A single electron is known to have an electric charge of -1.60×10^{-19} C. The magnitude of the charge on one electron is termed the elementary charge, and we can find this information in the data book. Using this information, we can see that the charge of 1 mol of electrons would be equivalent to:

$$\text{total charge of 1 mol of electrons} = \text{number of particles in 1 mol} \times \text{charge per } e^-$$

$$= (6.02 \times 10^{23}) \times (1.60 \times 10^{-19})\, coulomb$$

$$= 96\ 500\ \text{C}$$

The total charge of 1 mol of electrons is also referred to as a faraday, which is represented by F. Therefore, from the above calculation we can say that 1 faraday is equal to 96 500 C. The charge on a given number of moles of electrons can be calculated by the following equation:

$$Q = n(e^-) \times F$$

Here Q is the electric charge in coulombs, $n(e^-)$ is the number of moles of electrons and F is **Faraday's constant** (96 500 C mol^{-1}).

Tip The formulas relating to Faraday's law and Faraday's constant can be found in the data book.

This equation is known as Faraday's second law and demonstrates that in order to produce one mole of a metal, a whole number quantity of electrons must be consumed.

We can use this equation to calculate that the production of 1 mol of solid silver requires a total charge of 96 500 C, the production of 1 mol of solid tin requires a total charge of 193 000 C and the production of 1 mol of solid chromium requires 289 500 C. A visual representation of this relationship can be seen in figure 2.

In figure 2 we can see that given the same amount of electric charge, the mass of chromium produced during electrolysis is much less than the mass of silver produced. This is due to the fact that chromium requires 3 times as much charge (i.e. 3 times the quantity of electrons flowing through the cell) as silver in order to produce the same amount of product (in mol). It is important to note that the mass produced depends on the molar mass of each of the metals. Hence, even if the same quantity (in mol) of two metals is produced via electrolysis, the mass of the metals would differ due to their unique molar masses.

If we know the total charge applied to an electrolytic cell, we can use Faraday's second law to determine how much of a desired species can be produced as a result of electrolysis.

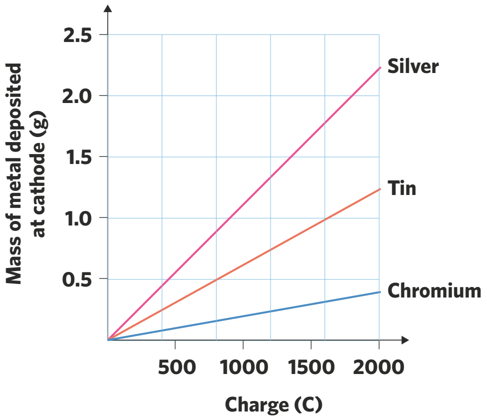


Figure 2 The mass of metal deposited over time at the cathode during an electrolytic reaction at different charges

2 **Worked example**

An electrolytic reaction resulted in the production of 0.113 mol of solid sodium. How much electric charge was required in order for this to happen?

What information is presented in the question?

$n(\text{Na}) = 0.113$ mol

What is the question asking us to do?

Find the electric charge (Q) required.

What strategy(ies) do we need in order to answer the question?

1. Identify the appropriate half-equation
2. Identify the molar ratio required
3. Calculate $n(e^-)$
4. Apply the formula $Q = n(e^-) \times F$

Answer

We first write the half-equation for the reduction reaction, from the electrochemical series in our data book.

$\text{Na}^+_{(l)} + e^- \rightarrow \text{Na}_{(s)}$

Determine the molar ratio of sodium to electrons.

$n(\text{Na}):n(e^-)$

1:1

We can therefore say that the number of moles of sodium is equal to the number of moles of electrons.

$0.113 \text{ mol} = n(e^-)$

Now we are able to calculate the charge.

$Q = n(e^-) \times F$

$Q = 0.113 \times 96500$

$= 10904.5\ C$

$1.09 \times 10^4\ C$ correct to 3 sig figs

Electroplating 3.2.13.2.1

OVERVIEW

Industrial chemists utilise the process of electrolysis and apply Faraday's Laws to undertake a process known as electroplating.

THEORY DETAILS

Electroplating is the process by which a layer of metal is deposited onto the surface of another metal by electrolysis. It is an important process that can enhance the properties of objects such as improving electrical conductivity and strength, altering appearance and protecting metals from corrosion.

This process is often used for products such as jewellery, cutlery, car parts and tin cans. In the example of tin cans, steel is coated with a thin layer of tin. The can will not rust following this process since the outer tin coating prevents the steel underneath from having contact with oxygen and moisture.

The process of electroplating, as shown in figure 3, is performed in an electrolytic cell, whereby the object that is being electroplated is connected by a wire to the negative terminal of a power supply (negative electrode). The object is then immersed in an electrolyte solution which contains the ions of the metal plating the object. When the cell is in operation, the power supply acts as an electron pump, pushing electrons onto the negative electrode (cathode), removing electrons from the positive electrode (anode). Identical to galvanic cells, reduction occurs at the cathode whilst an oxidation reaction occurs at the anode.

Other metals that are commonly used in electroplating include copper, gold and silver. As seen in figure 3, the object to be electroplated (the spoon) is connected at the cathode. In this particular electrolytic reaction, the half-reactions occurring at each electrode are:

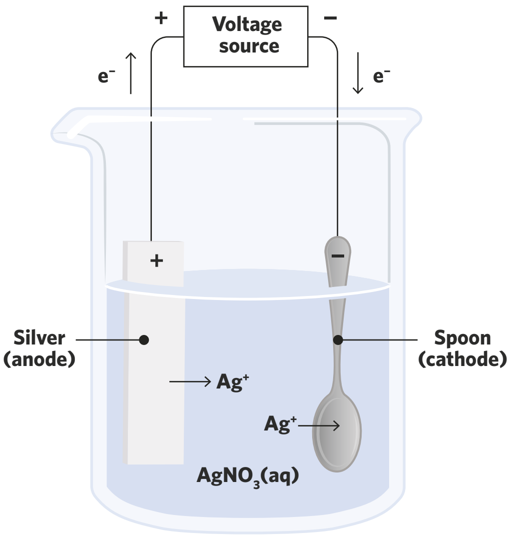


Figure 3 The process involved in electroplating a spoon with silver metal

Anode: $Ag_{(s)} \rightarrow Ag^{+}{}_{(aq)} + e^{-}$

Cathode: $Ag^{+}{}_{(aq)} + e^{-} \rightarrow Ag_{(s)}$

The overall reaction for the electroplating process is:

Overall: $Ag_{(s)(rod)} \rightarrow Ag_{(s)(spoon)}$

The silver atoms from the anode are oxidised to form silver ions and these silver ions are reduced at the cathode, producing silver atoms which coat the spoon. Hence, the electroplating process simply involves the metal of the anode being transferred to the object being plated.

As a result of these reactions, the mass of the silver anode decreases and the spoon's mass increases as it is coated in silver metal.

It is important to note that in the electroplating process, the concentration of the metal ion electrolyte remains fairly constant. As each silver atom is oxidised at the anode, another silver ion enters the electrolyte solution and then that silver ion is reduced at the cathode spoon. This process will continue until the silver anode is so corroded that it can no longer be oxidised.

An important aspect of the electroplating process is the ability for industrial chemists to construct a setup that allows the electroplating of the desired metal and to predict the amount of metal that will be electroplated onto the object. In order to do so, Faraday's Laws can be applied.

Application of Faraday's Laws 3.2.13.2.2

OVERVIEW

Faraday's Laws can be combined to quantitatively determine the amount of product produced during electrolysis.

THEORY DETAILS

As well as determining the amount of substance produced in electrolysis, Faraday's Laws can also be used to determine the current and time required for reactions like electrolysis to occur, which is particularly useful for industrial processes like electroplating.

Looking at both of Faraday's Laws together, we can see that a relationship exists between the two:

$Q = It$

$Q = n(e^{-}) \times F$

We can combine these two equations, as they each provide information about the electric charge. We obtain the relationship: $It = n(e^{-}) \times F$, which will be useful in our calculations.

In these equations we have demonstrated that current, charge and the time over which the current is applied to an electrolytic cell all affect the amount of product that can be produced.

We also know that the ratio between the amount of electrons and the desired product can affect the total mass of the metal produced. Therefore, it is important to identify the half-equation of the reaction occurring to obtain the molar ratio between the electrons and the metal ion.

3 Worked example

A bracelet was attached to a power source as the cathode of an electrolytic cell and a gold rod was the anode. The bracelet was plated according to the following equation:

$Au^{2+}_{(aq)} + 2e^- \rightarrow Au_{(s)}$

Given that the cell was operating for 2.5 minutes with a current of 3.0A, what mass of gold was plated on the bracelet?

What information is presented in the question?

$I = 3.0$ A

$t = 2.5$ minutes

What is the question asking us to do?

Find the mass of gold plated at the end of the reaction.

What strategy(ies) do we need in order to answer the question?

1. Determine the charge passing through the cell.
2. Find $n(e^-)$.
3. Identify the molar ratio required.
4. Determine m(Au) produced.

Formulas required:

$Q = It$

$Q = n(e^-) \times F$

$m = n \times M$

Answer

First, determine the charge.

$$Q = It$$
$$= 3.0 \times (2.5 \times 60)$$
$$= 450\ C$$

Using Q, we can find $n(e^-)$.

$$Q = n(e^-) \times F$$
$$450 = n(e^-) \times 96500$$
$$n(e^-) = \frac{450}{96500}$$
$$= 0.004663 \text{ mol}$$

As there is a 2:1 e^-: Au ratio,

$$n(\text{Au}) = 0.004663 \div 2$$
$$= 0.0023315$$

Now we find the mass.

$$m = n \times M$$
$$= 0.0023315 \times 197.0$$
$$= 0.4593$$
$$= 0.46 \text{ g (2 sig. figs.)}$$

Industrial chemists make use of all of these pieces of information and equations, to predict and optimise the yield of their electrolytic reactions.

From the worked example above, we can see that the electric charge that we calculate using Faraday's first law can then be used to find unknown variables using Faraday's second law (and vice versa). This will be an important concept to understand as it will help us with all calculations in this topic.

The formula $It = n(e^-) \times F$ can be used as a shortcut when we do not need to calculate the charge.

Another industrial application of electrolysis and Faraday's Laws, other than electroplating, is the process of electrorefining. In electrorefining, metals are purified from their impure forms. An example of this is the electrorefining of copper as shown in figure 4. Copper is oxidised from the impure copper sample (anode) and the copper ions form part of the copper (II) sulfate ($CuSO_4$) electrolyte. Pure copper is then electrochemically deposited from the electrolyte solution onto a stainless steel or copper cathode.

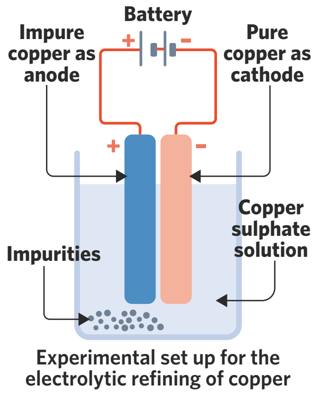


Figure 4 Setup for the electrolytic refining of copper

Theory summary

- Faraday's first law relates the mass of product produced at the cathode of an electrolytic cell in relation to the electric charge passing through the cell: $Q = It$
- Faraday's second law relates the ratio of the number of mols of electrons to the number of moles of metal product, $n(e^-)$: $n(product)$ as outlined in the balanced half-equations found in the electrochemical series.
- Faraday's constant refers to the total charge of 1 mol of electrons: $1 \text{ Faraday } = 96\ 500 \text{ C mol}^{-1}$
- The relationship between electric charge, mol of electrons and Faraday's constant can be calculated using $Q = n(e^-) \times F$
- The combination of both of Faraday's Laws allows us to quantitatively determine how much of a product we produce. This is particularly useful for electroplating.
- Electrorefining is the process of purifying an impure metal by the use of electrolysis.

6C QUESTIONS

Theory review questions

Question 1

Complete the sentence below.

As a general rule of thumb, the more ___________ that an electrolytic cell receives in a given amount of time, the ___________.

A time; more power it can generate
B charge; less work that is required for a reaction to occur
C current; more product that can be produced at the cathode
D charge; the less reducing agent that needs to be used during the reaction

Question 2

Faraday's Laws can be used to determine

A the current required for electrolysis to occur.
B the time taken for electrolysis to occur.
C the amount of substance produced by electrolysis.
D All of the above

Exam-style questions

Within lesson

Question 3 (1 MARK)

Jason wanted to electroplate his key to prevent it from rusting. He had a choice between 2 different metals.

$A^{2+} + 2e^- \rightarrow A$

$B^+ + e^- \rightarrow B$

Assuming that the difference in molecular masses of both *A* and *B* are negligible and that the current flowing through both cells is identical, which of the following statements would be true?

A There would be half as much of metal *A* produced compared to metal *B*.
B There would be twice as much metal *A* produced compared to metal *B*.
C The mass of metal *A* and metal *B* produced would be the same.
D There would be three times as much metal *B* produced compared to metal *A*.

Question 4 (1 MARK)

Gabriella wanted to coat a ring in 0.300 g of gold. If a current of 2.00 A is flowing through the cell, the minimum time, in seconds, required to complete this process is

A 73

B 153

C 55

D 92

Question 5 (3 MARKS)

An electroplating process uses silver cyanide to deposit a thin layer of silver on the surface of a spoon. In this process, silver ions are reduced according to the equation:

$Ag^+_{(aq)} + e^- \rightarrow Ag_{(s)}$

a A current of 3.1 A is maintained. How long does it take, in seconds, to deposit 0.412 mol of silver on the surface? (1 MARK)

b If the same conditions were used in an experiment involving the electroplating of cobalt metal, would this lead to the same amount, in mol, of cobalt being produced? Explain. (2 MARKS)

Question 6 (2 MARKS)

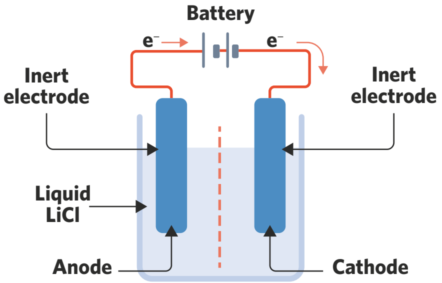
A cell conducting the electrolysis of lithium chloride is shown.

During electrolysis, lithium ions are reduced according to the equation:

$Li^+_{(l)} + e^- \rightarrow Li_{(s)}$

a If lithium chloride was electrolysed by a current of 3.50 A for 21.0 minutes, how much charge was flowing through the cell? (1 MARK)

b How much current would need to flow through the cell if 4.22×10^{-2} mol of lithium ions were reduced over 9.0 minutes. (1 MARK)



Question 7 (3 MARKS)

Khan wanted to test the effects of using electric charge on the production of 3 different metals: chromium, copper and sodium. In his experiment, he used 1.0 M solutions of $Cr(NO_3)_3$, $Cu(NO_3)_2$ and $NaNO_3$. He decided to use 0.045 faraday of electric charge for all experiments.

a Determine the amount, in mol, of metal deposited on the cathode of the electrolytic reaction involving chromium (III) nitrate. (1 MARK)

b Compare the 3 metals in terms of the number of moles of metal deposited during electrolysis involving their corresponding electrolyte. (2 MARKS)

Question 8 (3 MARKS)

Solid chromium can be produced through electrolysis using ions found in both aqueous and molten electrolytes.

a Determine the number of moles of chromium produced if 1.02 g of chromium was formed as a result of an electrolytic reaction. (1 MARK)

b If a total of 0.0392 faradays of charge passed through the cell, use your answer from part a. to determine the oxidation number of chromium in the compound. (2 MARKS)

Multiple lessons

Question 9 (5 MARKS)

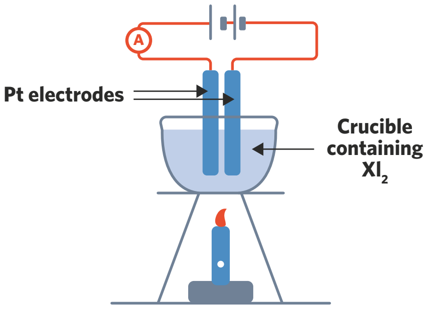
A metal sulfate solution was electrolysed in a cell containing unreactive electrodes. After a total of 1.20 A was applied for 2.0 minutes, it was found that 7.46×10^{-4} mol of the metal was produced.

a Identify the charge, x, of the metallic ion (A^{x+}). (2 MARKS)

b Given that water was the strongest reducing agent, the metal ion was the strongest oxidising agent, and a total of 1.67 V was required to drive the reaction, identify the half-equation occurring at the cathode. Assume the experiment was performed under ideal conditions. (3 MARKS)

Question 10 (5 MARKS)

Nicci set up an electrolytic cell involving an unknown molten salt electrolyte. The experiment is illustrated in the diagram given. A total of 2.98 A was applied to the cell for 12.0 minutes. A total of 0.97 g of solid metal *X* was produced.



a Write a balanced half-equation for the reaction occuring at the cathode. (1 MARK)

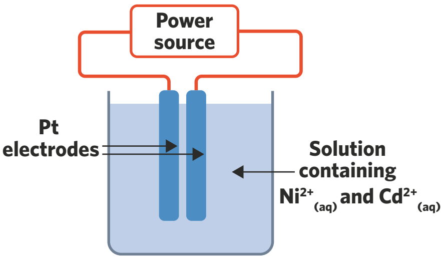
b What amount, in mol, of metal *X* was produced? (2 MARKS)

c Identify the name of metal *X*. (1 MARK)

Adapted from VCAA 2012, Short Answer Q9

Question 11 (7 MARKS)

A mineral ore containing nickel and cadmium was extracted and treated with an acid. The solution obtained from the treatment after the acid had been neutralised was placed in an electrolytic cell as shown in the diagram.



a Write balanced half-equations for the reaction occurring at

- **i** the anode (1 MARK)
- **ii** the cathode (1 MARK)

b Given that 0.351 A was applied to the cell over 10.0 minutes, what mass of metal accumulated on the cathode? (2 MARKS)

c If the platinum cathode were replaced with lead, what effect would this have on the cell's function? (3 MARKS)

Adapted from VCAA 2005, Short Answer Q7.

Question 12 (7 MARKS)

Industrial processes of electroplating items with copper can sometimes involve an electrolytic reaction with an electrolyte that contains CuCN (copper cyanide), KCN (potassium cyanide) or KOH (potassium hydroxide).

a Give the half-equation for the reaction where copper ions are reduced. (1 MARK)

b To achieve a consistent coating of copper, it is important to keep the concentration of copper ions low in the reaction.

$Cu^{+}_{(aq)} + 4CN^{-}_{(aq)} \rightarrow Cu(CN)_4{}^{3-}{}_{(s)}$ $\qquad K_c = 1.0 \times 10^{18}\ M^{-2}$

- **i** Based on the equation, describe the function of potassium cyanide in the electrolyte. (2 MARKS)
- **ii** What effect would adding a catalyst into the reaction have on K_c? Explain. (2 MARKS)

c Given that 0.331 A of current was allowed to flow through the electrolytic cell for 1.50 minutes, determine the mass of solid copper produced. (2 MARKS)

6D PRIMARY AND SECONDARY CELLS

In this lesson we will use our knowledge of galvanic cells to understand primary and secondary cells and their applications, as well as the factors that affect the battery life of a cell.

6A Electrolytic reactions	6B Electrolytic cells	6C Faraday's Laws	6D Primary and secondary cells

Study design dot point

- the operation of rechargeable batteries (secondary cells) with reference to discharging as a galvanic cell and recharging as an electrolytic cell, including the redox principles (redox reactions and polarity of electrodes) and the factors affecting battery life with reference to components and temperature (no specific battery is required)

Key knowledge units

Primary cells	3.2.14.1
Secondary cells	3.2.14.2
Factors affecting battery life	3.2.14.3

Key terms and definitions of this lesson

- **Primary cells** non-rechargeable electrochemical cells in which a chemical reaction generates electrical energy
- **Secondary cells** rechargeable electrochemical cells in which a chemical reaction generates electrical energy
- **Recharge** conversion of electrical energy into chemical energy through redox reactions with the aid of an external power source
- **Discharge** conversion of chemical energy to electrical energy as a result of spontaneous redox reactions
- **Batteries** devices consisting of cells that convert chemical energy to electrical energy

Lesson links

This lesson builds on:

▶ 4C – Galvanic Cells

Primary and secondary cells are types of galvanic cells.

▶ 6B – Electrolytic cells

Rechargeable batteries are a type of electrolytic cell.

Primary cells 3.2.14.1

OVERVIEW

Primary cells are non-rechargeable galvanic cells that produce electricity using redox reactions for the use of everyday appliances.

THEORY DETAILS

As we learned in lesson 4C, galvanic cells are cells in which spontaneous redox reactions are used to convert chemical energy into electrical energy. These cells can be used as fixed energy storage systems known as **batteries**. There are two different types of cells that we use to produce electricity everyday, both of which are galvanic cells. We will be discussing the first one, **primary cells**, in this section and the second, **secondary cells**, we will look at later on in this lesson.

Primary cells are disposable galvanic cells that are non-rechargeable. Most batteries that are used everyday, like in TV remotes, torches and calculators, are non-rechargeable, as they go flat and need to be replaced. This is due to all the reactants running out, meaning no more electrical energy is being produced to power the device. These cells cannot be recharged as the products of the reaction either move away from the electrodes during the reaction or they are consumed in side reactions, preventing the cell from being able to be recharged. The non-rechargeable nature of primary cells is particularly problematic if primary cells are disposed of unsafely. There is a risk that materials within the cell such as heavy metals or alkaline electrolytes could leak out and negatively impact the environment.

Alkaline cells are common primary cells, where the two redox half-reactions occur in separate compartments in the cell, as shown in figure 1. They are termed ‘alkaline’ cells as they use an alkaline electrolyte to separate the two half-reactions. As the electrolyte is contained within a separator, an absorbent material, it is also termed a dry cell.

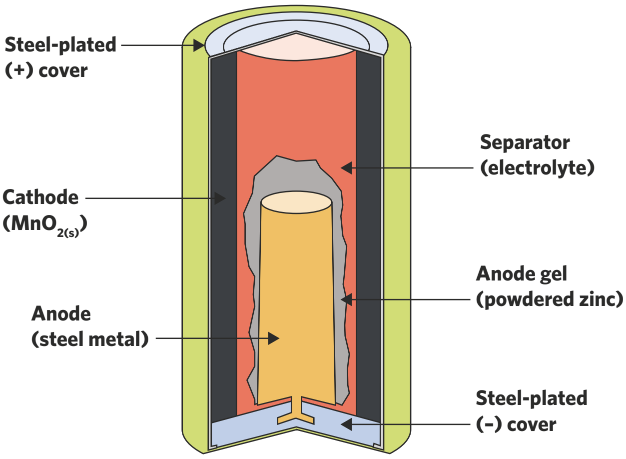


Figure 1 The constituents of an alkaline cell battery

For the purpose of this study design, you are not required to know specific battery types, just the overall function.

In the alkaline cell from the diagram, the following reaction occurs at the anode:

$$Zn_{(s)} + 2OH^-_{(aq)} \rightarrow ZnO_{(s)} + H_2O_{(l)} + 2e^- \qquad E^0 = -1.28V$$

This reaction shows that the zinc powder around the steel/brass metal rod reacts with hydroxide ions, oxidising, to form zinc hydroxide.

At the cathode the following reaction occurs:

$$2MnO_{2(s)} + H_2O_{(l)} + 2e^- \rightarrow Mn_2O_{3(s)} + 2OH^-_{(aq)} \qquad E^0 = +0.15V$$

This reaction shows that manganese dioxide is reduced.

The overall reaction for this particular cell is:

$$Zn_{(s)} + 2MnO_{2(s)} + H_2O_{(l)} \rightarrow ZnO_{(s)} + Mn_2O_{3(s)} \qquad E^0 = +1.43V$$

Secondary cells 3.2.14.2

OVERVIEW

Secondary cells are rechargeable galvanic cells that can be reused many times.

THEORY DETAILS

Rechargeable batteries are increasingly popular galvanic cells that are used in laptops, cameras and mobile phones, and they are known as **secondary cells**.

When these batteries are connected to an external power source, electrical energy is provided to drive a chemical reaction resulting in the conversion of the products of the discharge reaction into its original reactants. That is, electrical energy is converted back into chemical energy (stored within the products of the recharge reaction). Such a reaction as we recall from 6B is called an electrolytic reaction. As we explored in 6B, this electrolytic reaction requires a power source with a voltage (potential difference) greater than that of the cell. To do this, the positive and negative electrodes of the power source are connected to the positive and negative electrodes, respectively, of the cell.

For the products to be converted back into the reactants, the products formed in the cell during **discharge** must remain in contact with the electrodes, which is why primary cells cannot be recharged, because they lack this important factor.

During the discharge process, oxidation occurs at the negative terminal and reduction occurs at the positive terminal, as we learned in lesson 4C. This is a spontaneous reaction, where the negative terminal is the anode and the positive terminal is the cathode, as shown in figure 2.

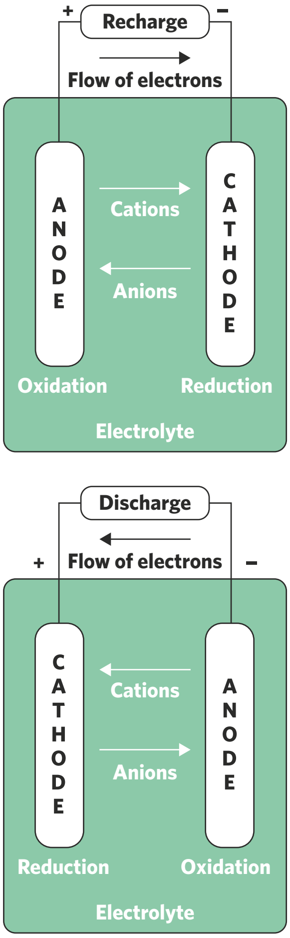


Figure 2 Electrolytic cell during recharge and discharge

However, to **recharge**, the cell reaction is reversed, therefore, oxidation occurs at the positive terminal (the anode) and reduction occurs at the negative terminal (the cathode). This is a non-spontaneous reaction.

As shown in figure 3, when the cell is discharging, chemical energy is transformed into electrical energy. Whereas, during the recharging process, electrical energy is transformed into chemical energy.

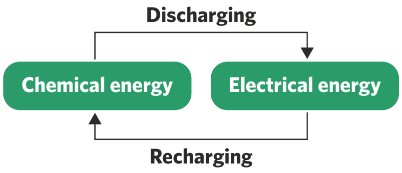


Figure 3 Energy transformation during the discharge and recharge process of a secondary cell.

Uses of secondary cells

A very common use of secondary cells is lead-acid batteries due to their long life-time. As shown in figure 4, lead acid batteries usually consist of 6 separate cells connected in series. The positive electrodes consist of lead dioxide, whilst the negative electrodes consist of powdered lead. A sulfuric acid solution sits around the electrodes as the electrolyte.

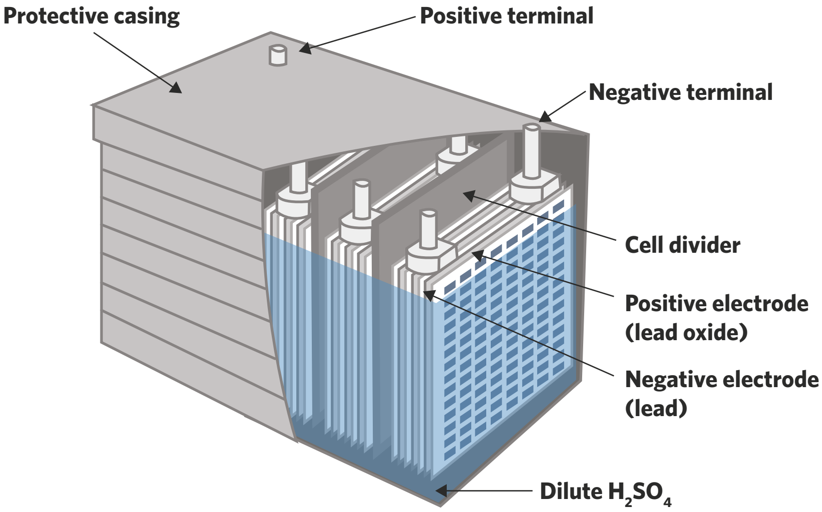


Figure 4 Composition of a lead acid battery

During discharge of a lead acid cell, the following reaction occurs at the anode:

$Pb_{(s)} + SO_4{}^{2-}{}_{(aq)} \rightarrow PbSO_{4\,(s)} + 2e^-$

This reaction shows that lead is oxidised.

At the cathode the following reaction occurs:

$PbO_{2\,(s)} + SO_4{}^{2-}{}_{(aq)} + 4H^+{}_{(aq)} + 2e^- \rightarrow PbSO_{4\,(s)} + 2H_2O_{(l)}$

This reaction shows that lead dioxide is reduced.

The overall reaction can be written as:

$Pb_{(s)} + PbO_{2\,(s)} + 2SO_4{}^{2-}{}_{(aq)} + 4H^+{}_{(aq)} \rightarrow 2PbSO_{4\,(s)} + 2H_2O_{(l)}$

Lead sulfate is formed at both electrodes as a solid, enabling the battery to be recharged. Lead acid batteries are used to power cars, electrical accessories, golf carts and other battery-operated vehicles.

Factors affecting battery life 3.2.14.3

OVERVIEW

There are several factors that affect the battery life of a cell.

THEORY DETAILS

Battery life refers to the performance of a cell, indicating the extent to which the battery can power something. It can also be thought of as the number of recharge-discharge cycles before the battery "runs out". There are many factors that influence the rate at which a battery's life decreases and the general deterioration of the battery.

A key factor influencing battery life and capacity is temperature. As shown in figure 5, the higher the temperature of the battery, the faster it will deteriorate. As the temperature of the battery increases, the rate of reaction of side reactions compromising the battery's functionality increases and so the battery life decreases. Conversely, as the temperature decreases, so too does the capacity of the battery because the cell reaction rate decreases. This means that the discharge rate decreases and so less electricity can be generated.

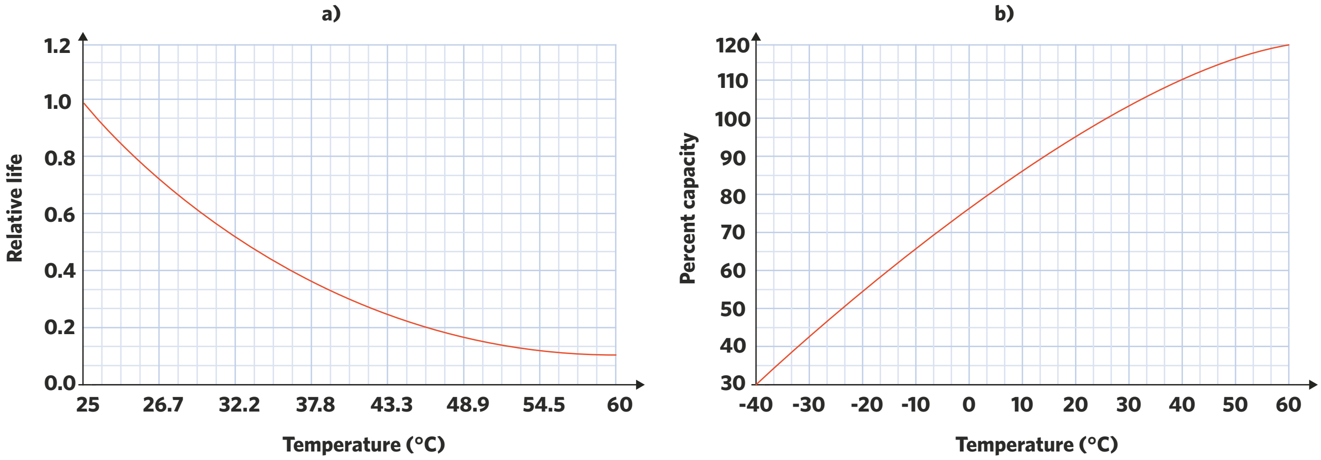


Figure 5 Graph of the temperature of a battery against a) the life and b) the capacity of a battery

Other factors affecting battery life include the following:

- Reactants and products of a cell reaction may become detached from their electrodes.
- Reactants and products may be converted into inactive forms via side reactions.
- Other chemicals interfering with the internal mechanisms of the battery could be formed in side reactions, affecting the functionality of the cell.
- Impurities in the cell could react with the products or reactants affecting the functionality of the cell.
- Corrosion of internal components could inhibit the cell reactions.
- Leakage of the electrolyte solution could decrease contact between electrodes and the electrolyte.

Self-discharge is the loss of the electrical capacity of a battery due to the deterioration of battery components. Self discharge is also caused by side reactions that occur even when the battery is not in use. To slow the process of self-discharge, batteries should be stored at a low temperature to slow the rate of side reactions.

Theory summary

- Primary cells are non-rechargeable galvanic cells that are used as single-use batteries.
- Secondary cells are rechargeable galvanic cells that are used in applications where the battery can be recharged, like phones and computers.
- The recharge process in a secondary cell is an example of an electrolytic reaction.
- When a cell discharges, chemical energy is converted to electrical energy. When a secondary cell recharges electrical energy is converted to chemical energy.
- Factors affecting battery life include temperature, the rate of side reactions, corrosion and leakage of cell components.

6D QUESTIONS

Theory review questions

Question 1

What is the key difference between primary and secondary cells?

A Primary cells are rechargeable, secondary cells are non-rechargeable.

B Secondary cells are rechargeable, primary cells are non-rechargeable.

C Secondary cells are galvanic cells, primary cells are not.

D Primary cells are galvanic cells, secondary cells are not.

Question 2

When a cell recharges

A oxidation occurs at the anode, which is the negative terminal.

B oxidation occurs at the anode, which is the positive terminal.

C oxidation occurs at the cathode, which is the positive terminal.

D oxidation occurs at the cathode, which is the negative terminal.

Question 3

A battery

A can always be recharged.

B has a positive terminal known as the anode during discharge.

C converts chemical energy to electrical energy during discharge.

D has a positive terminal known as the cathode during recharge.

Question 4

Battery life is affected the least by

A high temperatures.

B leakages.

C cold, but not freezing, temperatures.

D products of the discharge reaction falling off their electrodes.

Exam-style questions

Within lesson

Question 5 (1 MARK)

Most mobile phones have a lithium-ion battery that allows the phone to be recharged numerous times. Which statement(s) are correct about the process of a phone battery being recharged?

I Non-spontaneous reaction

II Spontaneous reaction

III Acts as a galvanic cell

IV Acts as an electrolytic cell

A I only

B I and III

C II and III

D I and IV

Question 6 (2 MARKS)

Crystal is at the beach with her friends and has her phone sitting out in the sun while she goes in the water for a swim. When she gets back to her phone after 10 minutes she notices that the battery life of her phone has dropped significantly. Explain why this is the case?

Question 7 (5 MARKS)

The silver oxide-zinc battery is rechargeable and utilises sodium hydroxide, NaOH, solution as the electrolyte. The battery is used as a backup in spacecraft, if the primary energy supply fails. The overall reaction during discharge is

$Zn_{(s)} + Ag_2O_{(s)} \rightarrow ZnO_{(s)} + 2Ag_{(s)}$

Adapted from VCAA 2018 Exam Section A Q16

a Write a balanced equation to represent the recharging of this battery. (1 MARK)

b Write the reaction at the anode when the silver oxide-zinc battery is being recharged. (1 MARK)

c What is necessary for secondary cells to be recharged? (3 MARKS)

Question 8 (3 MARKS)

Lead acid batteries are made up of a series of secondary cells. The following are reactions that take place during discharge:

$Pb_{(s)} + SO_4{}^{2-}{}_{(aq)} \rightarrow PbSO_{4(s)} + 2e^-$

$PbO_{2\,(s)} + 4H^+{}_{(aq)} + SO_4{}^{2-}{}_{(aq)} + 2e^- \rightarrow PbSO_{4\,(s)} + 2H_2O_{(l)}$

a When the battery is recharging, what energy transformation occurs? (1 MARK)

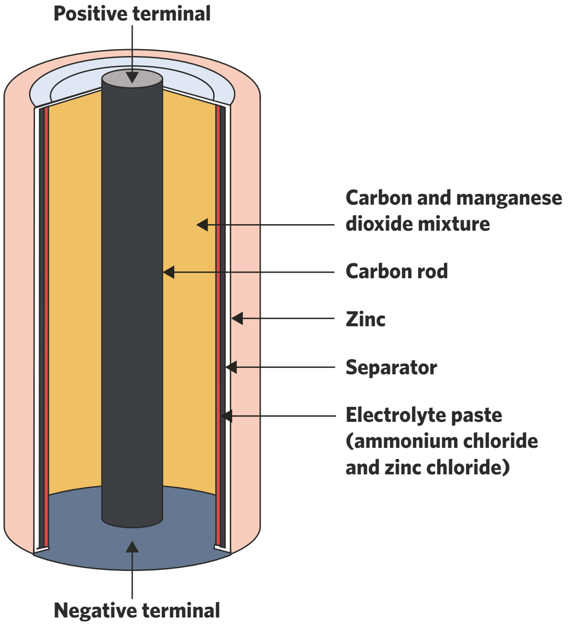
b Write the reaction that occurs at the anode when the battery is recharging. (1 MARK)

c When recharging the battery, the positive terminal of the battery should be connected to which terminal of the power supply? (1 MARK)

Multiple lessons

Question 9 (4 MARKS)

A common dry cell is a zinc-carbon dry cell which consists of zinc (anode), a carbon rod (cathode), and manganese (IV) oxide paste (MnO_2) as shown in the given diagram. The products of the discharge reaction, $ZnO_{(s)}$ and $Mn_2O_{3(s)}$ do not adhere to the electrodes.



The overall reaction for the given dry cell is as follows.

$2MnO_{2(s)} + Zn_{(s)} + H_2O_{(l)} \rightarrow Mn_2O_{3(s)} + Zn^{2+}{}_{(aq)} + 2OH^-{}_{(aq)}$

a Is this an example of a primary or a secondary cell? Explain. (2 MARKS)

b Write the half-reaction that occurs at the anode and the half-reaction that occurs at the cathode. (2 MARKS)

Question 10 (7 MARKS)

The lithium button cell, used to power portable electronic devices, is a primary cell containing lithium metal. The lithium ion cell is a secondary cell that is used to power mobile phones and laptops.

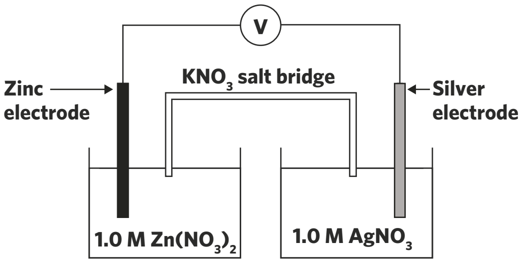
a What is the difference between primary and secondary cells? (2 MARKS)

b Referring to the information in the data book, give one reason for why lithium is used as a reactant in these galvanic cells. (2 MARKS)

c Early lithium metal batteries exploded when they were exposed to water. To explain why an explosion may occur, write a balanced equation for the reaction between lithium metal and water. (3 MARKS)

Question 11 (8 MARKS)

Given is an example of a galvanic cell.



Adapted from VCAA 2014 Exam Section A Q1

a Identify the electrode that is acting as the anode and the electrode acting as the cathode, stating whether oxidation or reduction is occurring. (4 MARKS)

b Write the half-reactions occurring at the anode and the cathode, respectively. (2 MARKS)

c In what direction are the electrons flowing? (1 MARK)

d As the cell discharges, what change would occur to the concentration of Zn^{2+} ions? (1 MARK)

EXPERIMENT

ELECTROLYSIS OF WATER

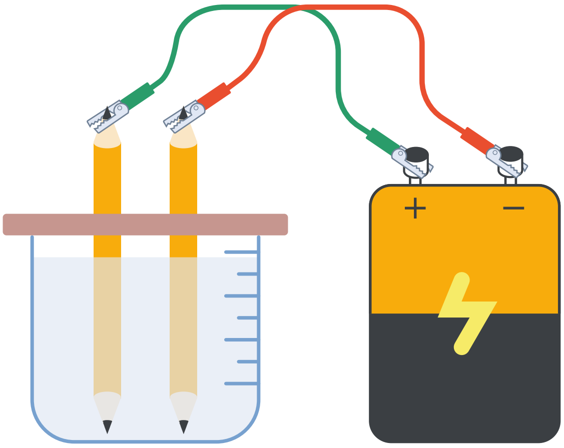
Water is an incredibly valuable resource that is required for a multitude of different processes that help us to survive. Water is produced through a chemical reaction as shown.

$2H_{2(g)} + O_{2(g)} \rightleftharpoons 2H_2O_{(l)}$

Water can be broken down into its individual components through electrolysis using a simple experimental set-up.

Materials

- 6V/9V battery
- 2 × alligator clips
- Piece of cardboard
- 2 × graphite pencils
- 500 mL beaker
- 250 mL deionised water



Method

1 Sharpen both ends of the pencil so that the graphite is exposed on both ends.
2 Punch two holes into the piece of cardboard so that each pencil can be placed inside. Leave a 5 cm gap between the two holes so that the pencils will not come into contact with each other.
3 Add 250 mL of deionised water into a 500 mL beaker.
4 Place the pencils into the cardboard, and place this on top of the beaker so that the pencils are submerged into the water as shown.
5 Using the alligator clips, connect each pencil to a terminal of the battery.
6 Record any observations.

Results

	Contents in the beaker prior to completing the circuit	Contents in the beaker after connecting the circuit.
Observations		

QUESTIONS

Question 1 (3 MARKS)

a Calculate the minimum voltage that would have been required to power this reaction. (1 MARK).

b Write the redox half-equations occurring at the anode and cathode assuming that the voltage calculated in part a is used. (2 MARKS)

Question 2 (3 MARKS)

a Suppose the experimenter accidentally used a solution of $KNO_{3(aq)}$ in the experiment instead of deionised water. What effect would this have on the products produced by the electrolysis? (1 MARK)

b To better visualise the reaction, the experimenter added the indicator phenol red into the solution. Describe the change, if any, that would occur during the reaction. (2 MARKS)

ANSWERS

1 a 1.23 - (–0.83) = 2.06 V

b Anode: $2H_2O_{(l)} \rightarrow 4e^- + 4H^+_{(aq)} + O_{2(g)}$

Cathode: $2H_2O_{(l)} + 2e^- \rightarrow H_{2(g)} + 2OH^-_{(aq)}$

2 a [As $H_2O_{(l)}$ is a stronger oxidising agent than $K^+_{(aq)}$,[1]][the use of $KNO_{3(aq)}$ would result in the same products being produced as the electrolysis of deionised water.[2]]

✓ ✗ I have compared the relative oxidising agent strength of $H_2O_{(l)}$ and $K^+_{(aq)}$.[1]

✓ ✗ I have described the effects of the use of $KNO_{3(aq)}$.[2]

b [The $H^+_{(aq)}$ and $OH^-_{(aq)}$ produced as part of the oxidation and reduction reactions respectively would result in the production of water. As a result, the pH of the solution would stay relatively neutral.[1]][As given by the data book, phenol red exists as a yellow colour in solutions of pH 6.8 and changes to red only when the pH of the solution has reached a value of 8.4 or above.[2]][Therefore, the colour of the solution would remain a yellow colour during the reaction.[3]]

✓ ✗ I have explained why the pH of the solution would be relatively neutral.[1]

✓ ✗ I have identified the colour change range for phenol red.[2]

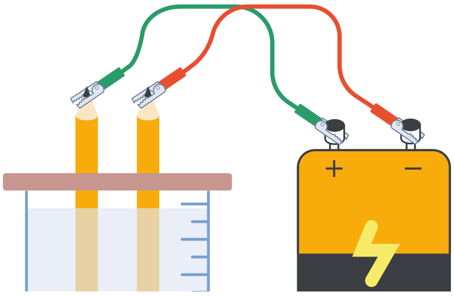
✓ ✗ I have linked the answer to the question.[3]

CHAPTER 6 QUESTIONS

MULTIPLE CHOICE (10 MARKS)

Question 1

An electrolytic cell is created as shown in the following diagram using platinum electrodes. If a voltage of 1.5 V is run through the cell, what reaction would be occurring at the anode?



A $O_{2(g)} + 2H_2O_{(l)} + 4e^- \rightarrow 4OH^-_{(aq)}$

B $K_{(s)} \rightarrow K^+_{(aq)} + e^-$

C $2H_2O_{(l)} + 2e^- \rightarrow H_{2(g)} + 2OH^-_{(aq)}$

D $2I^-_{(aq)} \rightarrow I_{2(s)} + 2e^-$

Question 2

In electrolysis, what is the purpose of the electrolyte?

A To maintain charge neutrality

B To complete the circuit

C To increase the rate of electrolysis

D All of the above

Question 3

Nickel-cadmium batteries are a type of rechargeable battery that are very common nowadays. Which of the following temperature environments will ensure optimum battery performance and number of recharge cycles?

	Minimum temperature (°C)	Maximum temperature (°C)
A	−23	−15
B	35	52
C	8	24
D	-7	3

Question 4

The following chemical reaction represents what is occurring in a lead-acid battery while it is discharging.

$Pb_{(s)} + PbO_{2(s)} + 2H_2SO_{4(aq)} \rightarrow 2PbSO_{4(aq)} + 2H_2O_{(l)}$

Which of the following statements is correct?

A $Pb_{(s)}$ is the oxidising agent and $PbO_{2(s)}$ is the reducing agent.

B $Pb_{(s)}$ is the reducing agent and $PbO_{2(s)}$ is the oxidising agent.

C The oxidation number of Pb in $PbO_{2(s)}$ is +3.

D The oxidation number of Pb in $Pb_{(s)}$ is +1.

Question 5

An electrolytic cell containing two platinum electrodes and an electroplating solution was run for 10 minutes at a current of 0.40 A. At the end, the cathode was dried and weighed and it increased in mass by 0.27 g. Which of the following could have made up the electroplating solution?

A $AgNO_{3(aq)}$

B $Pb(NO_3)_{2(aq)}$

C $Al(NO_3)_{3(aq)}$

D $Cu(NO_3)_{2(aq)}$

Question 6

When 1.0 M $NaCl_{(aq)}$ solution is electrolysed using platinum electrodes, which one of the following chemical species is produced at the cathode?

A $Na_{(s)}$

B $Cl_{2(g)}$

C $H_{2(g)}$

D $HCl_{(aq)}$

Question 7

The energy storage battery in a new type of electric car consists of a series of NiMH cells where M represents an unknown metal. The equation that occurs when the battery is recharging at the anode is:

$Ni(OH)_{2(s)} + OH^-_{(aq)} \rightarrow NiOOH_{(s)} + H_2O_{(l)} + e^-$

The equation that occurs when the battery is recharging at the cathode is:

$M_{(s)} + H_2O_{(l)} + e^- \rightarrow MH_{(s)} + OH^-_{(aq)}$

What is the overall discharge equation?

A $NiOOH_{(s)} + MH_{(s)} \rightarrow Ni(OH)_{2(s)} + M_{(s)}$

B $Ni(OH)_{2(s)} + M_{(s)} \rightarrow NiOOH_{(s)} + MH_{(s)}$

C $MH_{(s)} + OH^-_{(aq)} \rightarrow M_{(s)} + H_2O_{(l)} + e^-$

D $NiOOH_{(s)} + H_2O_{(l)} + e^- \rightarrow Ni(OH)_{2(s)} + OH^-_{(aq)}$

Question 8

Why is it not possible to produce $Na_{(s)}$ by electrolysing $NaCl_{(aq)}$ with platinum electrodes?

A $Cl^-_{(aq)}$ is a stronger oxidising agent than $H_2O_{(l)}$.

B $Na^+_{(aq)}$ is a stronger oxidising agent than $H_2O_{(l)}$.

C $Na^+_{(aq)}$ is a weaker oxidising agent than $H_2O_{(l)}$.

D $Na^+_{(aq)}$ is a stronger reducing agent than $H_2O_{(l)}$.

Question 9

Calculate the volume, in L, of $F_{2(g)}$ produced at SLC from the electrolysis of molten potassium fluoride using platinum electrodes at a current of 0.60 A for 3400 seconds.

A 0.0026 L

B 0.26 L

C 1.7 L

D 0.52 L

Question 10

Which of the following cells is/are rechargeable?

A Primary cell

B Secondary cell

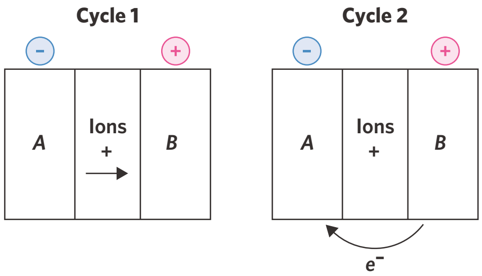
C Fuel cell

D All of the above

SHORT ANSWER (32 MARKS)

Question 11 (7 MARKS)

The following diagrams both show what occurs in a secondary cell during discharge and recharge, in no particular order.



a Identify what is happening in cycle 1 and what is happening in cycle 2 with respect to the cell's recharge and discharge cycles. (1 MARK)

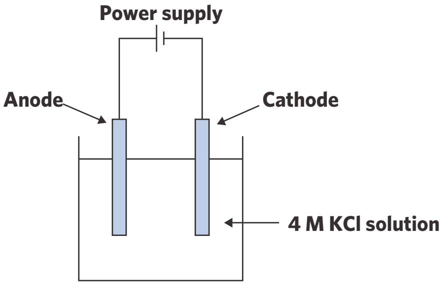
b Draw the arrows indicating electron flow and positive ion flow on the diagram. (2 MARKS)

c What are two purposes of the electrolyte in a primary cell? (2 MARKS)

d Are all batteries rechargeable? Using your knowledge of primary and secondary cells, explain why or why not. (2 MARKS)

Question 12 (5 MARKS)

The following diagram represents the setup of an electrolytic cell that Chris used to produce KOH.



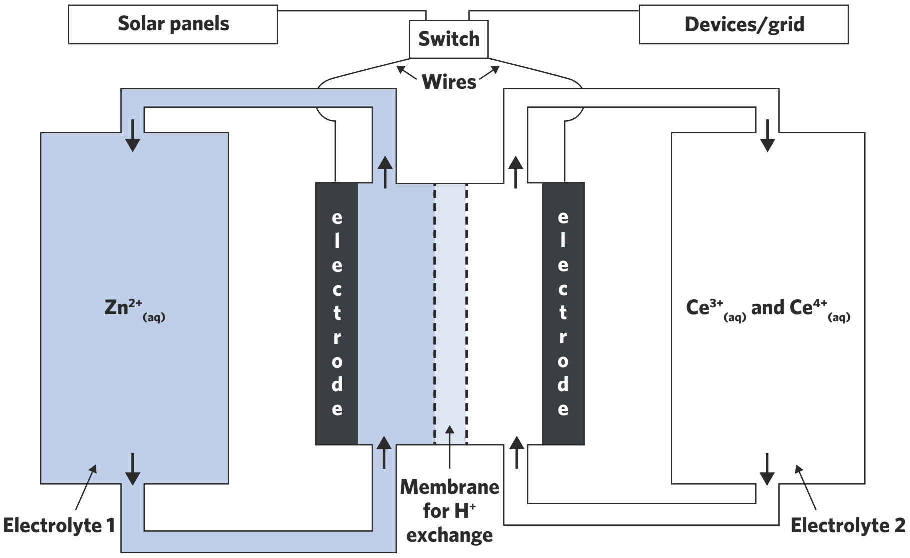
a Would iron be an appropriate choice for the composition of the anode? Explain why or why not. (2 MARKS)

b Chris decides to use inert graphite electrodes to conduct the electrolysis. During the electrolysis, Chris notices that his laboratory is beginning to smell like a chlorinated swimming pool. Is this predicted by the electrochemical series? If not, suggest a possible reason for this to occur. (2 MARKS)

c Chlorine gas is considered a toxic substance. Suggest a safety technique that could minimise the risk of Chris harming himself. (1 MARK)

Question 13 (7 MARKS)

The zinc-cerium battery is currently in the research and development stage.



The following equations are taken from an electrochemical series with the E^0 values calculated under a certain set of conditions.

$Zn^{2+}_{(aq)} + 2e^- \rightleftharpoons Zn_{(s)}$ $E^0 = -0.76$ V

$Ce^{4+}_{(aq)} + e^- \rightleftharpoons Ce^{3+}_{(aq)}$ $E^0 = +1.20$ V

a During discharge, which electrode, the one on the left or the one on the right, will be the cathode? Explain your answer. (2 MARKS)

b Write out the full recharge equation. (1 MARK)

c What is the purpose of the proton exchange membrane which is only permeable to protons, but no other aqueous ions? (2 MARKS)

d Is this a renewable source of energy? Justify your answer. (2 MARKS)

Question 14 (4 MARKS)

The nickel-metal battery is currently used as a rechargeable battery. During discharge, the chemical species MH is oxidised to M (where M is an abbreviation of a more complex chemical compound) and nickel oxyhydroxide, NiOOH, is reduced to nickel (II) hydroxide, $Ni(OH)_2$.

a If a basic electrolyte is used, write the half-equations for the discharge reaction without states. (2 MARKS)

b This battery is used in phones. A scientific researcher working in Antarctica whose phone uses this battery soon discovers that his phone is not turning on. Suggest a reason for this. (2 MARKS)

Question 15 (5 MARKS)

An unscrupulous jeweller would like to trick clients into paying for a solid gold ring when in fact it is only a silver ring plated with gold. He uses a gold electroplating solution and sets up an appropriate electrolytic cell.

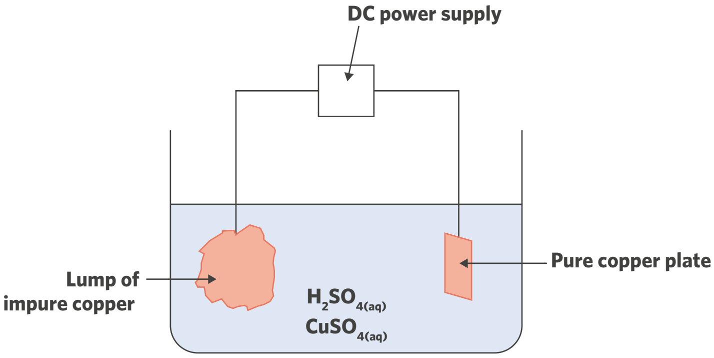
a Should the silver ring be attached to the positive or negative end of the power supply once it is dipped in the solution? Explain your answer. (2 MARKS)

b 0.240 cm^3 of gold is required. Using the fact that the density of gold is 19.3 g/cm^3, what is the mass of gold required? (1 MARK)

c Calculate the time required for the electrolytic cell to operate to electroplate this quantity of gold if the power source runs at a current of 5.00 amps. (2 MARKS)

Question 16 (4 MARKS)

Electrorefining is a process used to extract a pure metal from its ore. A mining company wanted to extract pure copper from a lump of impure copper (II) oxide ore, with various other metals and impurities in it, and set up the following electrolytic cell.



During the process, the positive electrode begins to shrink in size and the negative electrode grows in size.

a Which electrode should the lump of impure copper be attached to? (1 MARK)

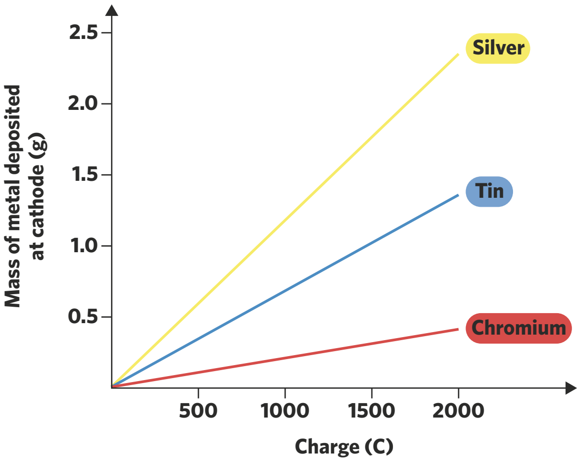
b What is the reaction occurring at the negative electrode? (1 MARK)

c When this electrorefining process is carried out, the mining engineer notices a thick sludge directly below the lump of impure copper. Why has this occurred? (2 MARKS)

KEY SCIENCE SKILL QUESTION

Question 17 (5 MARKS)

A student designed an experiment and produced the following results:

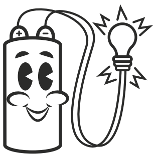


a Which of Faraday's laws is the student examining? (1 MARK)

b What is the independent variable in this experiment? (1 MARK)

c What is the dependent variable in this experiment? (1 MARK)

d Name two variables that should be controlled in this experiment. (2 MARKS).



BONUS – CARTOON QUESTIONS

Using the flip cartoon of the batteries in the corners of the pages of this book, answer the following questions.

Boop likes light bulbs and decides to help his friend Lumos, the bulb. However, Lumos wants too much power, so Boop runs out of charge. Luckily, Beep comes along and helps Boop.

Multiple choice questions

Question 1 (1 MARK)

To power Lumos, Boop

A. **converts electrical energy into chemical energy.**

B. **converts chemical energy into electrical energy.**

C. **is a fuel cell.**

D. **relies on non-spontaneous redox reactions.**

Question 2 (1 MARK)

What temperature would affect Boop's battery life the most?

A. **70 °C**

B. **50 °C**

C. **-10 °C**

D. **23 °C**

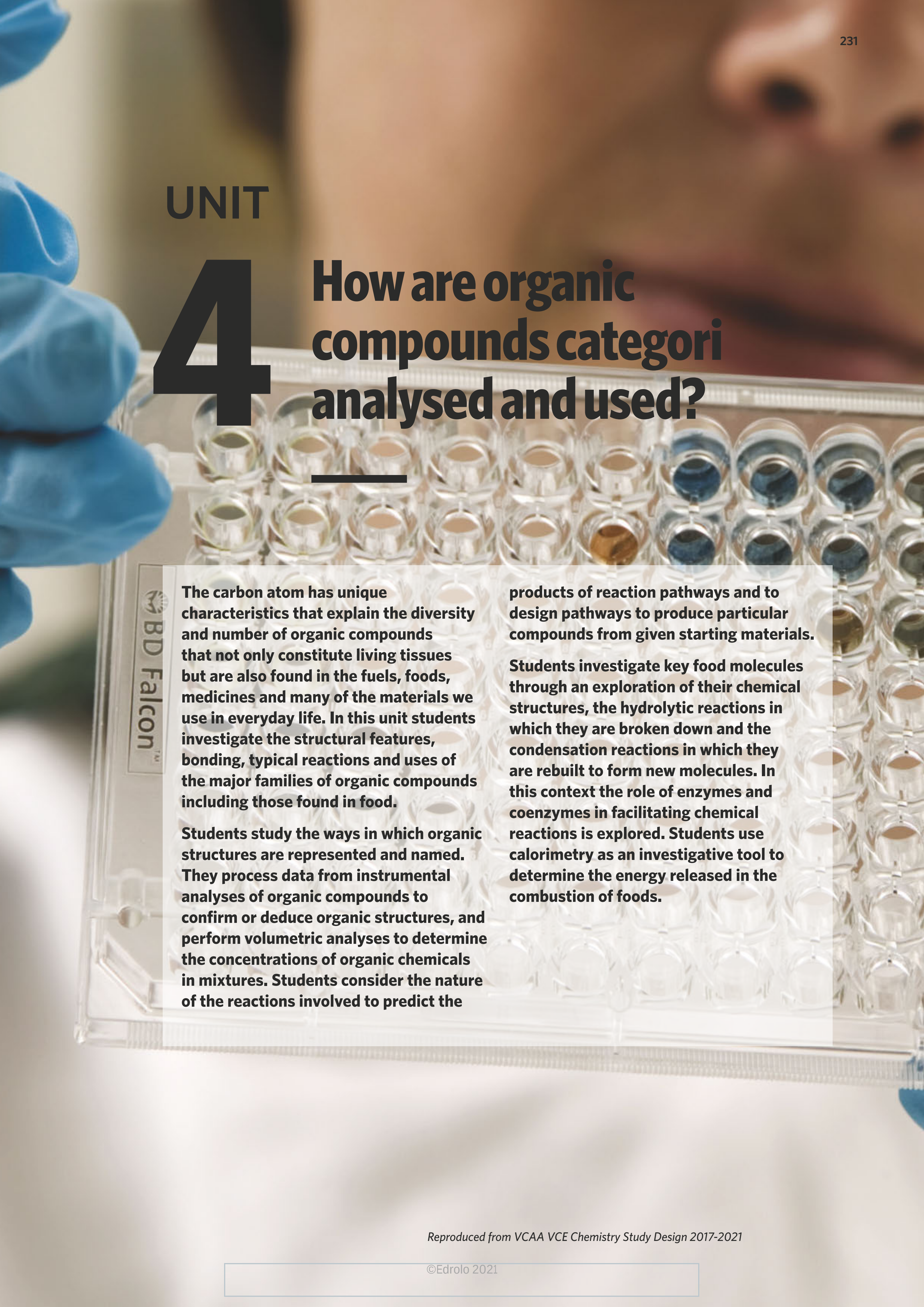
Short answer questions

Question 3 (3 MARKS)

Identify three key differences between secondary cells, like Boop, and primary cells.

Question 4 (4 MARKS)

In the cartoon, Beep recharges Boop. What makes a battery rechargeable?



UNIT

4

How are organic compounds categori analysed and used?

The carbon atom has unique characteristics that explain the diversity and number of organic compounds that not only constitute living tissues but are also found in the fuels, foods, medicines and many of the materials we use in everyday life. In this unit students investigate the structural features, bonding, typical reactions and uses of the major families of organic compounds including those found in food.

Students study the ways in which organic structures are represented and named. They process data from instrumental analyses of organic compounds to confirm or deduce organic structures, and perform volumetric analyses to determine the concentrations of organic chemicals in mixtures. Students consider the nature of the reactions involved to predict the products of reaction pathways and to design pathways to produce particular compounds from given starting materials.

Students investigate key food molecules through an exploration of their chemical structures, the hydrolytic reactions in which they are broken down and the condensation reactions in which they are rebuilt to form new molecules. In this context the role of enzymes and coenzymes in facilitating chemical reactions is explored. Students use calorimetry as an investigative tool to determine the energy released in the combustion of foods.

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UNIT 4

AOS1

How can the diversity of carbon compounds be explained and categorised?

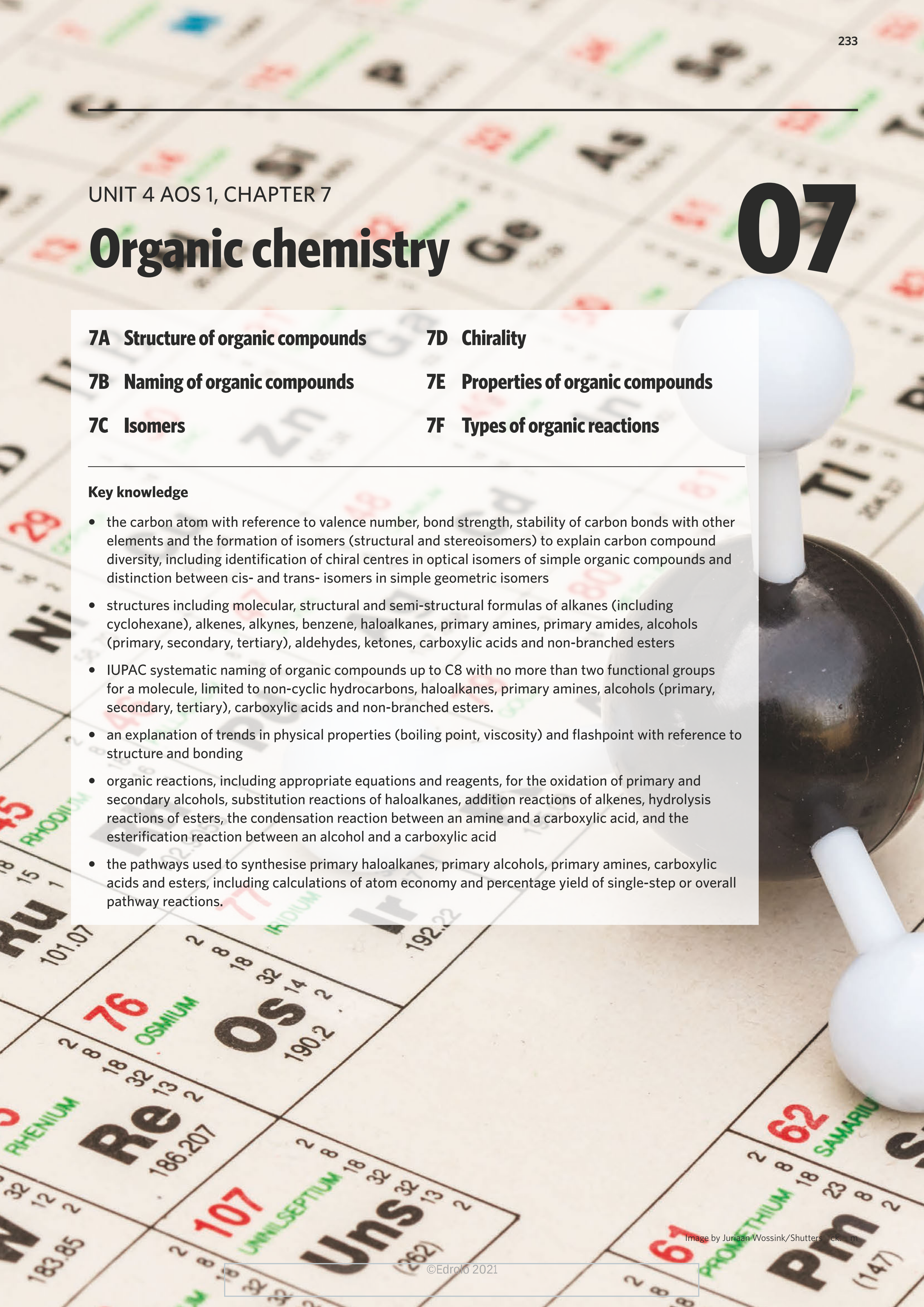
In this area of study students explore why such a vast range of carbon compounds is possible. They examine the structural features of members of several homologous series of compounds, including some of the simpler structural isomers, and learn how they are represented and named.

Students investigate trends in the physical and chemical properties of various organic families of compounds. They study typical reactions of organic families and some of their reaction pathways, and write balanced chemical equations for organic syntheses.

Students learn to deduce or confirm the structure and identity of organic compounds by interpreting data from mass spectrometry, infrared spectroscopy and proton and carbon-13 nuclear magnetic resonance spectroscopy.

Outcome 1

On completion of this unit the student should be able to compare the general structures and reactions of the major organic families of compounds, deduce structures of organic compounds using instrumental analysis data, and design reaction pathways for the synthesis of organic molecules.



UNIT 4 AOS 1, CHAPTER 7

Organic chemistry

07

7A Structure of organic compounds

7B Naming of organic compounds

7C Isomers

7D Chirality

7E Properties of organic compounds

7F Types of organic reactions

Key knowledge

- the carbon atom with reference to valence number, bond strength, stability of carbon bonds with other elements and the formation of isomers (structural and stereoisomers) to explain carbon compound diversity, including identification of chiral centres in optical isomers of simple organic compounds and distinction between cis- and trans- isomers in simple geometric isomers
- structures including molecular, structural and semi-structural formulas of alkanes (including cyclohexane), alkenes, alkynes, benzene, haloalkanes, primary amines, primary amides, alcohols (primary, secondary, tertiary), aldehydes, ketones, carboxylic acids and non-branched esters
- IUPAC systematic naming of organic compounds up to C8 with no more than two functional groups for a molecule, limited to non-cyclic hydrocarbons, haloalkanes, primary amines, alcohols (primary, secondary, tertiary), carboxylic acids and non-branched esters.
- an explanation of trends in physical properties (boiling point, viscosity) and flashpoint with reference to structure and bonding
- organic reactions, including appropriate equations and reagents, for the oxidation of primary and secondary alcohols, substitution reactions of haloalkanes, addition reactions of alkenes, hydrolysis reactions of esters, the condensation reaction between an amine and a carboxylic acid, and the esterification reaction between an alcohol and a carboxylic acid
- the pathways used to synthesise primary haloalkanes, primary alcohols, primary amines, carboxylic acids and esters, including calculations of atom economy and percentage yield of single-step or overall pathway reactions.

Image by Juriaan Wossink/Shutterstock.com

7A STRUCTURE OF ORGANIC COMPOUNDS

In this lesson we will be unpacking the different types of organic compounds and the structural features of each. In particular, we will look at the functional groups that help to define the type of organic compound.

This lesson will provide us with the basics on the structure of organic compounds. This knowledge will be built upon as we progress through the chapter.

7A Structure of organic compounds	7B Naming of organic compounds	7C Isomers	7D Chirality	7E Properties of organic compounds	7F Types of organic reactions

Study design dot points

- the carbon atom with reference to valence number, bond strength, stability of carbon bonds with other elements and the formation of isomers (structural and stereoisomers) to explain carbon compound diversity, including identification of chiral centres in optical isomers of simple organic compounds and distinction between cis- and trans- isomers in simple geometric isomers
- structures including molecular, structural and semi-structural formulas of alkanes (including cyclohexane), alkenes, alkynes, benzene, haloalkanes, primary amines, primary amides, alcohols (primary, secondary, tertiary), aldehydes, ketones, carboxylic acids and non-branched esters

Key knowledge units

Carbon bonds	4.1.1.1
Alkanes, alkenes and alkynes	4.1.2.1.1
Haloalkanes	4.1.2.1.2
Primary amines and amides	4.1.2.1.3
Alcohols	4.1.2.1.4
Aldehydes and ketones	4.1.2.1.5
Carboxylic acids	4.1.2.1.6
Esters	4.1.2.1.7

Key terms and definitions

- **Bond strength** how strongly bonds hold atoms together
- **Bond length** length of a bond
- **Bond energy** measurement used to indicate the amount of energy needed to break bonds, measured in kJ/mol
- **Electronegativity** tendency of an atom to attract a pair of bonding electrons
- **Hydrocarbons** organic compounds consisting of carbon and hydrogen
- **Valence number** number of electrons in the outer shell (valence shell) of an atom
- **Saturated hydrocarbons** molecules that have only single carbon-carbon bonds
- **Unsaturated hydrocarbons** molecules that have at least one double or triple carbon-carbon bond
- **Molecular formula** formula that shows the number of atoms of every element in a molecule
- **Structural formula** structural representation of a molecule that shows the atoms in the compound, the number of each atom, and how atoms are arranged and bonded to each other
- **Semi-structural formula** condensed form of a structural formula that does not show all bonds between atoms in a compound
- **Skeletal structure** representation of a molecular structure where covalent bonds are shown as lines. Carbon atoms are shown as vertices and hydrogen atoms bonded to carbon atoms are not shown
- **Terminal carbon** found at the end of the carbon parent chain and is bonded to one other carbon
- **Alkyl groups** groups formed by removing one hydrogen atom from the equivalent alkane chain

- **Functional groups** specific groups of atoms within a compound that affect the properties of the compound. Compounds containing the same functional group have similar chemical properties
- **Primary amine** compound with an amino functional group (NH_2) where the nitrogen atom is only bonded to one carbon atom
- **Amide** compound that has the amide functional group (CON)
- **Aldehydes** compounds that contain an aldehyde functional group (CHO)
- **Ketones** compounds that contain a carbonyl (CO) functional group. The carbon atom in the CO group is attached to 2 alkyl groups
- **Carboxylic acids** compounds that contain a carboxyl functional group (COOH)
- **Esters** compounds that contain an ester functional group (COO)
- **Haloalkanes** alkanes that contain a halogen
- **Alcohols** compounds that contain a hydroxyl functional group (OH) bonded to a carbon atom in the carbon chain
- **Primary alcohols** alcohols where the hydroxyl functional group (OH) is bonded to a carbon with only 1 alkyl group
- **Secondary alcohols** alcohols where the hydroxyl functional group (OH) is bonded to a carbon with 2 alkyl groups
- **Tertiary alcohols** alcohols where the hydroxyl functional group (OH) is bonded to a carbon with 3 alkyl groups

Carbon bonds 4.1.1.1

OVERVIEW

The bonding between carbon and other atoms can have different characteristics. The strength of these bonds depends on the interaction of various factors including bond length and bond energy.

THEORY DETAILS

Carbon bonding is the foundation of all organic compounds. As a result, exploring the nature of these bonds provides us with a solid basis to develop an understanding of the different types of organic compounds that exist.

Organic compounds are identified as those where carbon is covalently bonded to other atoms. Most often this involves hydrogen, nitrogen, or oxygen. **Hydrocarbons**, made up of only carbon and hydrogen atoms, are an important set of organic molecules that are predominantly found in naturally occurring fuel sources.

The ability of carbon to bond to a variety of different atoms is due to the fact that it has a **valence number** of four and can therefore form four covalent bonds in a tetrahedral arrangement. The strength of the bonds however may vary depending on the atoms involved.

The **bond strength** of a particular carbon bond depends on the **bond energy**, measured in kJ/mol. There are various factors that impact the amount of energy required to break a bond, including:

- bond length.
- the difference in **electronegativity** of the atoms involved.
- size of the atoms.

It is important to note that it is the combination of these factors that results in overall bond energy, and therefore we will not be able to obtain a definitive answer if we only look at each factor in isolation.

As shown in figure 1, the distance between the nuclei of the two bonding atoms is known as the **bond length**. The length of the bond will vary depending on the attraction between the nuclei of the bonding atoms and the shared pair of electrons. Also, the size of the atoms involved in the bond also impacts the bond length, where bonds between larger atoms result in longer bond lengths. Looking at the values in table 1, we can identify a relationship between bond length and bond energy.

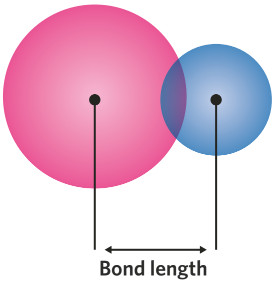


Figure 1 Illustration of how bond length is measured

Table 1 Bond energies for common bonds

Bond	Energy kJ/mol	Length	Bond	Energy kJ/mol	Length	Bond	Energy kJ/mol	Length
Single bonds						**Multiple bonds**		
H—H	432	74	C—N	305	147	C=C	614	134
H—F	565	92	C—O	358	143	C=N	615	127
H—Cl	427	127	C—P	264	187	C=O	745 (779 in CO_2)	123
H—Br	363	141	C—S	259	181			
H—I	295	161	C—F	453	133			
C—H	413	109	C—Cl	339	177			
C—C	347	154	C—Br	276	194			
C—Si	301	186	C—I	216	213			

In general, the bond energy (and thus the bond strength) increases as the length of the bond decreases.

Taking a closer look at the table we can see that there is a relationship between bond energy and electronegativity. As we know, electronegativity increases as we move across a period from left to right, with fluorine being the most electronegative of all elements followed by oxygen, chlorine and nitrogen. Based on the values in the table, we can see that bond energy also follows this trend in descending order.

Not only can bond energy indicate how strong a bond is, it also gives us information about the stability of bonds. As summarised in figure 2, bonds with high bond energy are more stable than those with low bond energies. These factors have important implications on the stability of the different types of organic molecules that we will investigate in this lesson.

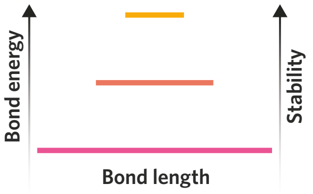


Figure 2 The relationship between bond length, energy and stability

Alkanes, alkenes and alkynes 4.1.2.1.1

OVERVIEW

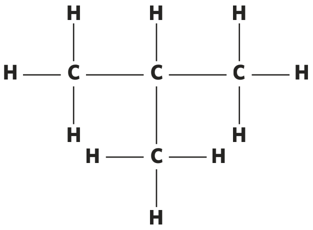
Alkanes, alkenes and alkynes are hydrocarbons with different carbon bonding structures.

THEORY DETAILS

As we learned in Unit 1, alkanes are **saturated hydrocarbons** that have only single carbon-carbon bonds in their structures. The general formula of alkanes is C_nH_{2n+2}, where *n* represents the number of carbon atoms present in the structure.

As seen in figure 3, alkanes are usually arranged as linear chains or branched chains (due to the presence of side chains); however, some alkanes can be organised in a cyclic manner.

Branched arrangement



Linear chain arrangement

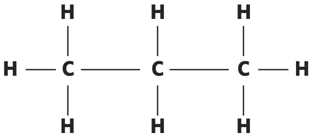


Figure 3 Common structural arrangements of alkanes

As shown in figure 4, the two terminal carbon atoms in a cycloalkane bond to form a closed ring with no **terminal carbon**. In this structure, each carbon atom is bonded to two adjacent carbon atoms and two hydrogen atoms. Unlike straight-chain alkanes and branched alkanes, cycloalkanes have the general formula as C_nH_{2n}. Benzene is a cyclic compound which has 6 carbons in the ring structure, each bonded to one hydrogen and two carbon atoms. It looks like it is lacking bonds but in fact, one electron from each carbon atom is shared (delocalised), resulting in a very stable formation. Two representations of benzene are shown in figure 7.

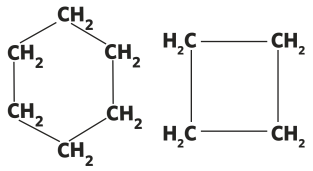


Figure 4 Examples of cycloalkanes, cyclohexane (left) cyclobutane (right)

Alkenes are **unsaturated hydrocarbons** that have at least one carbon-carbon double bond in their carbon chain. The general formula of alkenes is C_nH_{2n} which is similar to the general formula of cycloalkanes however it is important to note that both are structurally quite different and therefore would behave differently. Although we often see and draw alkenes as linear structures, in reality the double bond causes a 'kink' in the carbon chain, as shown in figure 5.

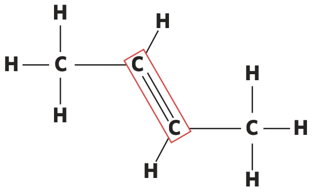


Figure 5 Structural formula of but-2-ene, an example of an alkene. The red box indicates the carbon-carbon double bond.

Alkynes are also unsaturated hydrocarbons but, as shown in figure 6, they have at least one carbon-carbon triple bond in their carbon chain. The general formula of alkynes is C_nH_{2n-2}. As we know from Unit 1, all of these hydrocarbons have the capacity to be bonded to alkyl and functional groups, a concept that we will work through during the course of this lesson.

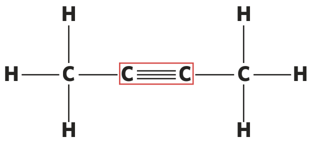


Figure 6 The structural formula of but-2-yne, an example of an alkyne. The red box indicates the carbon-carbon triple bond.

The organic compounds shown above have been represented as structural formulas. Although this is one of the most common forms of representing the structure of these compounds, there are other ways in which these structures can be represented. Table 2 is a summary table of four formula types.

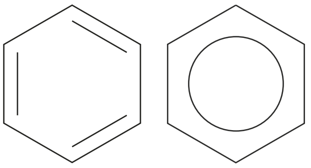
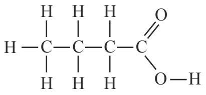
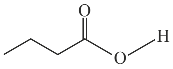


Figure 7 Structural representations of benzene

Table 2 Different types of formulas and their representations

Formula	Representation
molecular formula	$C_4H_8O_2$
structural formula	
semi-structural (condensed) formula	$CH_3CH_2CH_2COOH$ or $CH_3(CH_2)_2COOH$
skeletal structure	

Source: VCAA data book

The first three formula types should be quite familiar as they are often used throughout chemistry books and resources. Skeletal structures however are not as widely used as the first three. With skeletal structures, the main elements to be aware of are:

- carbons in the carbon chain are represented as vertices.
- hydrogens are generally omitted unless part of a functional group.
- atoms in a functional group are shown.

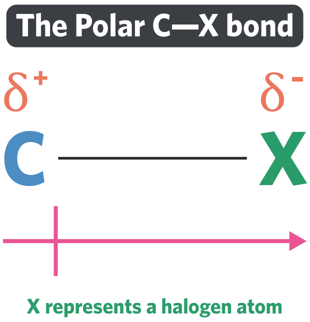


Figure 8 Representation of a polar bond between a carbon and halogen atom

Haloalkanes 4.1.2.1.2

OVERVIEW

Haloalkanes are alkane-based compounds which have one or more halogen atoms bonded to the carbon chain.

THEORY DETAILS

Haloalkanes are formed by replacing one or more hydrogen atoms in the carbon chain of alkanes with a halogen; atoms found in group 17 of the periodic table. As halogens are more electronegative than carbons, they have a greater tendency to attract the shared pair of electrons to their own nucleus. This results in a polar bond. As shown in figure 8, the carbon atom has a partial positive charge, while the halogen atom has a partial negative charge, thereby making the bond polar.

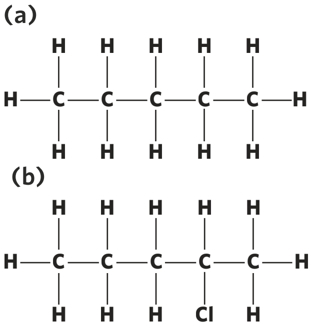


Figure 9 **(a)** Structural formula of pentane; **(b)** Structural formula of 2-chloropentane, an example of a haloalkane

As shown in figure 9, haloalkanes look similar to their alkane counterpart; however, the polar nature of the carbon-halogen bond causes the molecule to have slightly different properties to its comparable alkane. We will discuss this further in a later lesson.

In addition to halogens, organic compounds can also have other **functional groups** as part of their structures. In the next sections of this lesson, we will investigate functional groups of common organic compounds.

Primary amines and amides 4.1.2.1.3

OVERVIEW

Amines and amides are compounds whose functional group contain a carbon-nitrogen bond. In this lesson, we will focus on primary amines and amides.

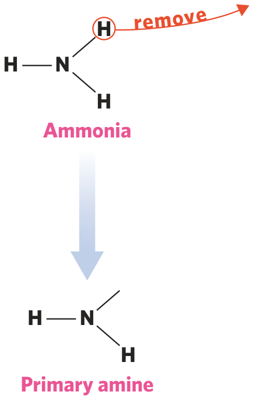
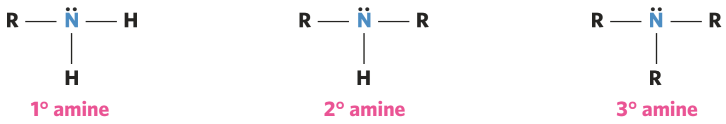


Figure 10 The formation of a primary amine from ammonia

THEORY DETAILS

Due to the similarity in structure, amines are thought to be derived from ammonia. As seen in figure 10, a hydrogen atom found in ammonia is removed, resulting in the formation of an amino group (NH_2). The nitrogen in the amino group is then able to bond to an **alkyl group**. Therefore, molecules with this functional group are considered as amines.

As nitrogen can take part in three bonds, it can potentially bond to three alkyl groups. The number of alkyl groups bonded to the nitrogen atom determines the nature of the amine. Figure 11 shows three types of possible amines that exist; however, we will only focus on primary amines.



1° amine 2° amine 3° amine

Figure 11 Representations of different types of amines. R represents an alkyl group.

Primary amines have two hydrogen atoms and one alkyl group bonded to the nitrogen atom, whereas secondary and tertiary amines have two and three alkyl groups bonded to the nitrogen respectively. It is not often mentioned that the nitrogen atom in the amino group has a lone pair of electrons which affect the properties of amines. Similar to ammonia, the lone pair of electrons helps amines such as ethanamine (figure 12) act as weak bases.

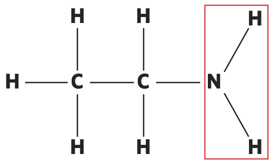


Figure 12 Structural formula of ethanamine, an example of an amine. The red box indicates the amino functional group.

Compared to the amino group (NH_2), **amides** also have oxygen in their structures. The carbon, oxygen and nitrogen form the functional group of an amide. Below is an illustration of the amide functional group.

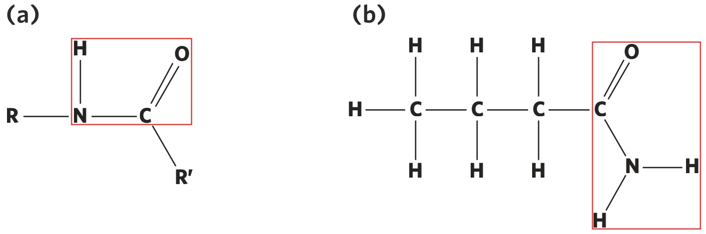
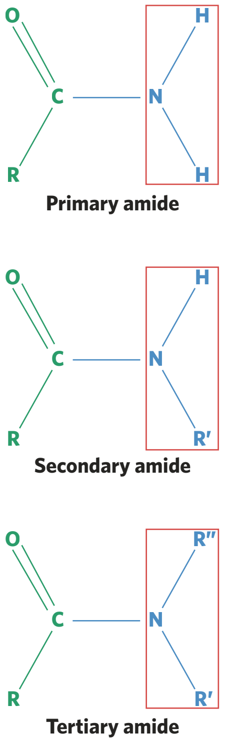


Figure 13 **(a)** Structural representation of the amide functional group where R and R′ both represent different alkyl groups and **(b)** Structural formula of butanamide, an example of an amide. The red box indicates the amide functional group.

It is important to note that the oxygen atom in the functional group is directly bonded to the carbon atom, not the nitrogen atom and the remaining bond on the carbon atom in the functional group is bonded to an alkyl group. The two remaining bonds on the nitrogen atom in the functional group can bond to a combination of hydrogen atoms and alkyl groups. As shown in figure 14, the number of alkyl groups bonded to the nitrogen of the amide group determines the type of amide it is. As mentioned, we will only focus on primary amides.

Due to the nature of primary amides, the amide functional group is always found on the end of a carbon chain. This can be seen in figure 13(b).



Primary amide

Secondary amide

Tertiary amide

Figure 14 Structural representation of different types of amides. R, R′ and R″ represent alkyl groups. The red squares shows the structural differences between primary, secondary and tertiary amide groups.

Alcohols 4.1.2.1.4

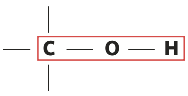
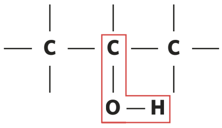
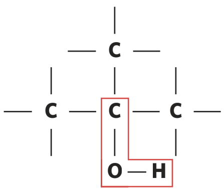
OVERVIEW

Alcohols are derivatives of hydrocarbons with hydroxyl (OH) group(s) bonded to the carbon atom(s) in the carbon chain. There are 3 types of alcohols – primary alcohols, secondary alcohols, and tertiary alcohols.

THEORY DETAILS

Alcohols are formed when hydrocarbons have one or more of their hydrogen atoms replaced by a hydroxyl (OH) group(s). Table 3 is a summary table of these three types of alcohol.

Table 3 Structural representation of primary, secondary and tertiary alcohols

Types of alcohols		
Primary	Secondary	Tertiary
		

As we can see, the categorisation of an alcohol depends on the number of alkyl groups bonded to the carbon to which the hydroxyl group is bonded to. In a **primary alcohol**, the carbon bonded to the hydroxyl group is bonded to only one alkyl group. The carbon bonded to the hydroxyl group in a **secondary and tertiary alcohol** is bonded to two and three alkyl groups respectively.

Tip Carbon bonded to OH group linked to **one** carbon – **primary**

Carbon bonded to OH group linked to **two** carbons – **secondary**

Carbon bonded to OH group linked to **three** carbons – **tertiary**

The primary alcohol ethanol, as shown in figure 15, is an alcohol that has a variety of everyday uses, including as a fuel source and as an ingredient in anti-bacterial cleansing wipes.

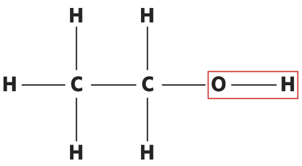


Figure 15 Structural formula of ethanol, an example of an alcohol. The red box indicates the hydroxyl functional group.

Aldehydes and ketones 4.1.2.1.5

OVERVIEW

Aldehydes and ketones are compounds that have a carbonyl group (C=O) in their structures. However, the remaining bonds on the carbon of the carbonyl group are bonded to different atoms in aldehydes and ketones.

THEORY DETAILS

Both **aldehydes** and **ketones** contain a carbon-to-oxygen double bond. As seen in figure 16, the carbon in the carbonyl group can still take part in two covalent bonds.

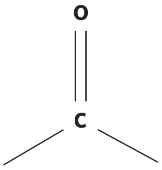


Figure 16 Carbonyl functional group

In aldehydes, one of the remaining bonds on the carbon atom in CO group is bonded to a hydrogen atom, which forms the aldehyde functional group CHO. The other remaining bond on the carbon atom can be bonded to either a hydrogen atom or an alkyl group. Figure 17 shows these two possible types of aldehyde structures.

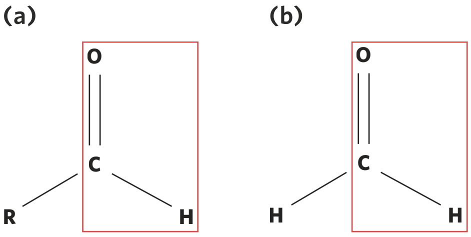


Figure 17 **(a)** The structure for the aldehyde functional group where R represents an alkyl group; **(b)** structural formula for methanal, an example of an aldehyde. The red box indicates the aldehyde group.

In ketones, each of the two remaining bonds on the carbon in the carbonyl group are bonded to an alkyl group. As shown in figure 18, the two alkyl groups bonded to the carbon in the CO group do not have to be the same.

▶ **Important note**

The hydrogen atom in the aldehyde functional group (CHO) is bonded to the carbon atom, not the oxygen atom.

As both aldehydes and ketones have a carbonyl group (CO) in their structures, it is sometimes tricky to determine if a compound is an aldehyde or a ketone. The key distinguishing characteristic between ketones and aldehydes is that the carbonyl group in aldehydes is found at the end of the carbon chain whereas in ketones, the carbonyl group is bonded to a carbon within the carbon chain.

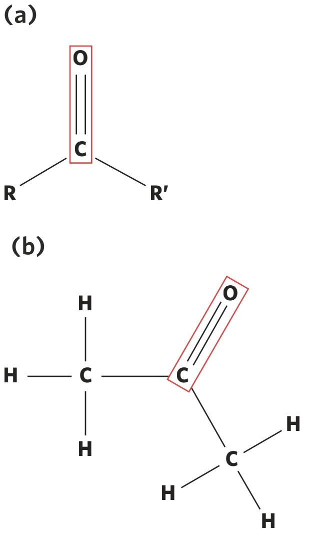


Figure 18 **(a)** Structure of a ketone functional group where R and R′ represent two different alkyl groups **(b)** Structural formula of propanone, an example of a ketone where both alkyl groups bonded to the carbonyl group are the same. The red box indicates the ketone functional group.

Carboxylic acids 4.1.2.1.6

OVERVIEW

Carboxylic acids are another type of organic compound that contains a functional group involving oxygen.

THEORY DETAILS

Carboxylic acids contain a carboxyl group (COOH) always found at the end of the carbon chain. As the carboxyl group has the capacity to donate its H^+ into a solution, it is able to act as a weak acid.

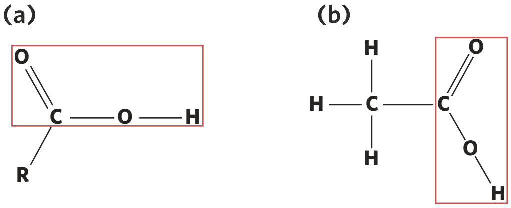


Figure 19 **(a)** Structure of a carboxylic functional group where R represents an alkyl group; **(b)** Structural formula for ethanoic acid, an example of a carboxylic acid. The red box indicates the carboxyl functional group.

As seen in the figure above, the carboxyl group consists of a carbonyl group whose carbon is bonded to a hydroxyl group; hence its name. The carbon in the carboxyl group can bond to either a hydrogen or alkyl group.

Esters 4.1.2.1.7

OVERVIEW

Similar to alcohols, aldehydes, ketones and carboxylic acids, esters contain a functional group involving an oxygen atom.

THEORY DETAILS

Due to their structure, **esters** are often used in perfumes and synthetic flavouring. The distinguishing structural feature of an ester is that it has a COO group in its structure that can be found within the carbon chain.

As we can see in figure 20, the carbon atom in the ester COO group is linked to one oxygen atom through a double bond and to another oxygen atom through a single bond. The oxygen atom in the single carbon-to-oxygen bond and the carbon itself is then bonded to an alkyl group. At first glance, this may seem similar to a carboxyl group (COOH) however unlike the carboxyl functional group, the ester group is found within a carbon chain with alkyl groups bonded on either side. Figure 21 shows structures of some esters that you may have encountered.

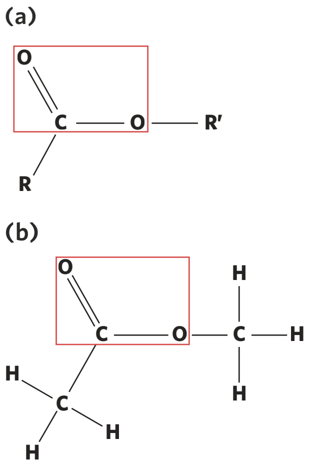


Figure 20 **(a)** Structure of an ester functional group; **(b)** Structural formula for methyl ethanoate, an example of an ester. The red box indicates the ester functional group and R/R′s represent alkyl groups.

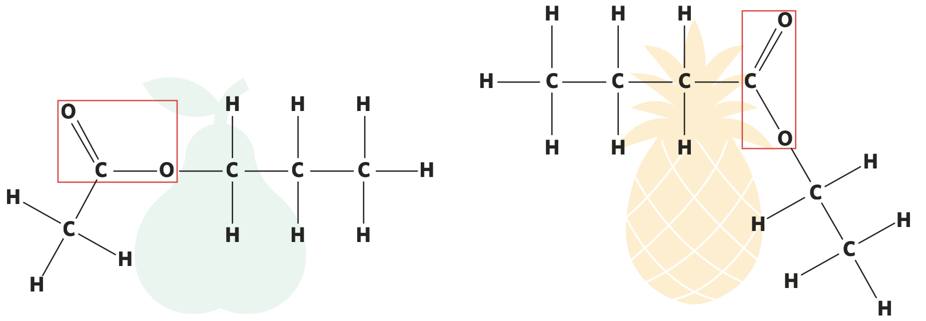


Figure 21 Structural formula of propyl ethanoate and ethyl butanoate, esters responsible for pear and pineapple smells respectively. The red box indicates the ester functional group.

Theory summary

Bond length	C—F	<	C—Cl	<	C—Br	<	C—I
Bond strength	C—I	<	C—Br	<	C—Cl	<	C—F
Molecular size	F	<	Cl	<	Br	<	I

- Alkanes, alkenes and alkynes are hydrocarbons with carbon and hydrogen atoms in their structure.
- Alkanes are saturated hydrocarbons with only single carbon-carbon bonds.
- Alkenes are unsaturated hydrocarbons with at least one carbon-carbon double bond.
- Alkynes are unsaturated hydrocarbons with at least one carbon-carbon triple bond.
- Haloalkanes are compounds where halogen atoms are bonded to carbon atoms in the carbon chain.
- In primary amines, the nitrogen atom is bonded to two hydrogen atoms and one alkyl group. The amino functional group is NH_2.
- In primary amides, the nitrogen atom is bonded to two hydrogen atoms and one C═O bond. The primary amide functional group is $CONH_2$.
- Alcohols are organic compounds that contain a hydroxyl functional group (OH).
- Based on the number of alkyl groups connected to the carbon bonded to the hydroxyl group, there are three types of alcohols – primary alcohols, secondary alcohols and tertiary alcohols.
- Both an aldehyde and a ketone have one CO group in their structures but it is located differently.
- Carboxylic acids contain a carboxyl functional group (COOH).
- The carbon atom in COOH group can be bonded to either a hydrogen atom or an alkyl group.
- The ester functional group (COO) is found within the carbon chain of an organic compound.

7A QUESTIONS

Theory review questions

Question 1

Which of the following factors affects bond strength?

I Bond length **II** Atomic number **III** Electronegativity

A I only
B I & II only
C II & III only
D I and III only

Question 2

Which statement is **false** about the structure of haloalkanes?

A Haloalkanes are formed by replacing one or more hydrogen atoms in the carbon chain of alkanes with halogen atoms (Cl, Br, I, F, ...).
B The carbon-halogen bond in a haloalkane is polar.
C The position and number of halogen atoms are the same for each haloalkane compound.
D The 3 types of haloalkanes are linear straight-chain haloalkanes, branched haloalkanes and cyclohaloalkanes.

Question 3

Which statement is true about the structure of primary amides?

A The oxygen atom in the amide functional group is directly bonded to the carbon atom.
B The oxygen atom in the amide functional group is directly bonded to the hydrogen atom.
C The functional group of a primary amide is CO.
D The nitrogen atom in the primary amide functional group is linked to three alkyl groups.

Question 4

Fill in the blanks with the correct words that describe the structure of a primary amine. More than one word may be required for each space.

A primary amine has two ___________ atoms and ___________ attached to the nitrogen atom, which forms an ___________ group ___________.

Question 5

Fill in the blanks with the correct words that describe the structure of alcohols.

Alcohols are also classified based on the number of alkyl groups connected to the carbon bonded to the OH group. There are three types of alcohols: ___________ alcohols, ___________ alcohols and ___________ alcohols. In a primary alcohol, carbon connected to the OH group is bonded to ___________ alkyl group. The carbon connected to the OH group in a secondary alcohol is bonded to ___________ alkyl groups. In a tertiary alcohol, the carbon connected to the OH group is bonded to ___________ alkyl groups.

Question 6

Fill in the correct types of compounds and functional groups in the table below.

Type of compound	Functional group
Alkene	$C{=}C$
	$C{\equiv}C$
Aldehyde	CHO
Primary amide	
Ketone	

Type of compound	Functional group
Primary amine	NH_2
Alcohol	
Carboxylic acid	
Ester	

Exam-style questions

Within lesson

Question 7 (1 MARK)

Which statement is true about the structures shown?

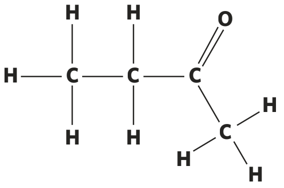
A Both compounds are aldehydes

B Both compounds are ketones

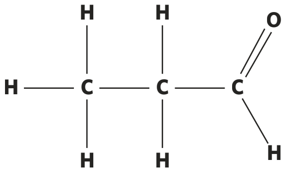
C Structure **(a)** is a ketone and structure **(b)** is an aldehyde

D Structure **(b)** is a ketone and structure **(a)** is an aldehyde

(a)



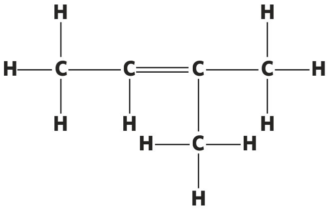
(b)



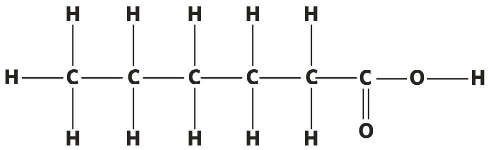
Question 8 (1 MARK)

Which one of the following structural formulas represents a primary alcohol?

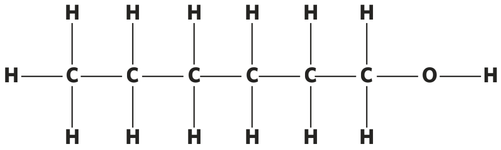
A



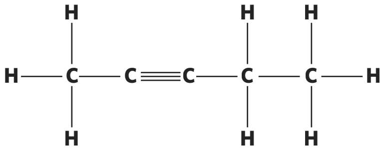
B



C



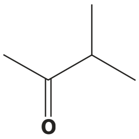
D



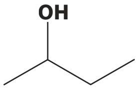
Question 9 (1 MARK)

Which one of the following skeletal formulas represents an ester?

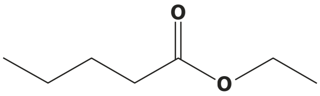
A



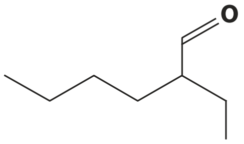
B



C



D



Question 10 (1 MARK)

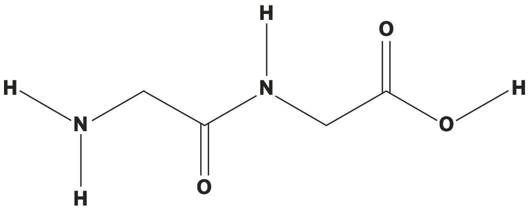
How many different functional groups can be found in the molecule shown?

A 4

B 3

C 2

D 1



Question 11 (2 MARKS)

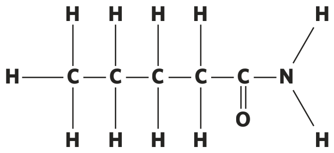
Carbon is able to bond to many different elements. The length of a carbon-nitrogen bond is 147 pm whereas the length of a carbon-hydrogen bond is only 109 pm. Which of the two bonds would have a higher bond energy? Explain.

Question 12 (2 MARKS)

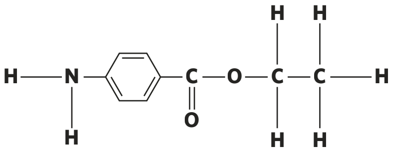
For the molecules shown,

a circle the functional group(s) present. (1 MARK)

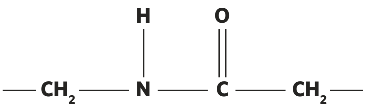
b identify the name of the functional group(s) in each molecule. (1 MARK) i



ii



iii



Question 13 (2 MARKS)

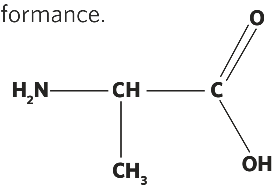
Aldehydes and ketones can have the same molecular formula but different structural formulas. From the molecular formula C_3H_6O, draw the structural formula of

a an aldehyde. (1 MARK)

b a ketone. (1 MARK)

Question 14 (3 MARKS)

The structure shown is an important molecule that is used in the body to help improve exercise performance.



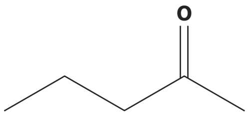
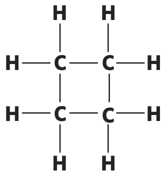
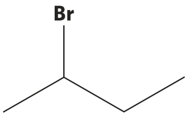
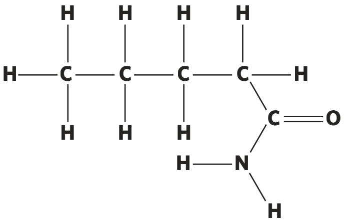
When asked to identify the functional group(s) present in the molecule, a student gave the following explanation:

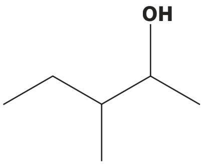
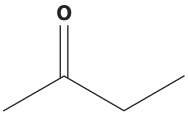
"This molecule has an amide functional group as there is a carbonyl group and a nitrogen-carbon bond found in the structure".

Comment on the accuracy of the statement above. Draw an image to support your answer.

Question 15 (16 MARKS)

Draw the correct semi-structural formula, structural formula and skeletal formula in the table below for each molecule.

Semi-structural formulas	Structural formulas	Skeletal formulas
$CH_3CHC(CH_3)CH_3$		
$CH_3CH_2CH_2COCH_3$		
$CH_2CH_2CH_2CH_2$		
		
$CH_3CH_2CH_2CH_2NH_2$		
		

Semi-structural formulas	Structural formulas	Skeletal formulas
		
		
$CH_3CH(CH_3)CH_2CH_2COOH$		
$CH_3CH_2CH_2COOCH_3$		

Multiple lessons

Question 16 (6 MARKS)

Biobutanol, produced through the fermentation of biomass, can be blended with petrol and used as a car fuel.
The semi-structural formula of biobutanol is below.

$CH_3CH_2CH_2CH_2OH$

a Identify whether this biobutanol is a renewable or non-renewable resource. (1 MARK)

b Identify the type of alcohol that biobutanol would be classified as. Explain. (2 MARKS)

Biobutanol undergoes combustion as follows.
$C_4H_9OH_{(l)} + 6O_{2(g)} \rightarrow 4CO_{2(g)} + 5H_2O_{(g)}$

c Given that the heat of combustion of butanol is 2676kJ mol^{-1}, determine the mass of oxygen that would be used up if 1033 kJ of energy was released from the reaction. (3 MARKS)

7B NAMING OF ORGANIC COMPOUNDS

In this lesson we will go through the rules and the steps of writing names for organic compounds based on their structures. More specifically, we will use our knowledge of functional groups, carbon bonds, and substituents of organic compounds to write their systematic names.

7A Structure of organic compounds	7B Naming of organic compounds	7C Isomers	7D Chirality	7E Properties of organic compounds	7F Types of organic reactions

Study design dot point

- IUPAC systematic naming of organic compounds up to C8 with no more than two functional groups for a molecule, limited to non-cyclic hydrocarbons, haloalkanes, primary amines, alcohols (primary, secondary, tertiary), carboxylic acids and non-branched esters.

Key knowledge units

Naming of organic compounds	4.1.3.1

Key terms and definitions

- **Parent carbon chain** longest continuous chain of carbon-carbon bonds. This needs to include any carbon double/triple bonds if present
- **Substituents** single atoms or groups of atoms which are attached to the parent carbon chain
- **IUPAC naming** set of rules used to name organic compounds according to the International Union of Pure and Applied Chemistry (IUPAC)

Lesson links

This lesson builds on:

- 7A – Structure of organic compounds

Recognition of carbon bonds and functional groups is required to name organic compounds.

Naming of organic compounds 4.1.3.1

OVERVIEW

In Chemistry, we use a particular system to name compounds depending on their molecular structure.

THEORY DETAILS

As discussed in the previous lesson, there are many types of organic compounds with different types of carbon bonds, functional groups, and branches. We use a set of guidelines outlined by **IUPAC** to systematically name organic compounds. Using this system, the names given to compounds tell us what the compound looks like by identifying the type of carbon bonds involved and the types of functional group(s) present. Understanding the naming rules for organic compounds can allow us to determine the overall structure of the compounds. To write the correct name for an organic compound, we need to work through the following steps.

1. Identify and name the parent carbon chain.
2. Identify the functional group present (if any) and thereby the appropriate suffix (ending) of the name.
3. Number the positions of the carbons in parent chain. This will be affected by the priority of the functional group(s)/side chains present.
4. Identify the number and position(s) of the functional group(s).
5. Identify the position(s) and name(s) of the **substituent(s)**.
6. Combine the above to write the complete name of the organic compound.

The name that is identified through this process can be broken down as follows.

Position of substituents	-	Substituent counter	Substituent name	Parent chain prefix	Carbon bond type (ane/ene/yne)	-	Position of functional group	-	Functional group naming convention

Not all of the organic compounds that we will come across will have all of these components however it is important for us to understand how all of the structural features contribute to the name of a compound.

The following tables outline the key ideas that we need to know in order to successfully name organic compounds.

Table 1 Summary of the prefixes that represent different carbon chain lengths

Prefix	**meth**	**eth**	**prop**	**but**	**pent**	**hex**	**hept**	**oct**
The number of carbon atoms in the parent chain	1	2	3	4	5	6	7	8

Table 2 Carbon bonds/functional groups with their associated suffix (ending)

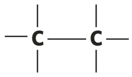
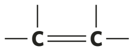
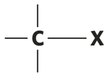
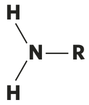
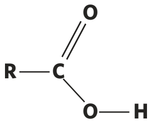
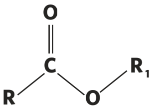
Carbon bonds/functional groups	**Type of compound**	**Ending (Suffix)**
	Alkane	-ane
	Alkene	-ene
$-C\equiv C-$	Alkyne	-yne
 (X represents a halogen)	Haloalkane	-ane
 (R represents an alkyl group)	Primary amine	-amine
$R-O-H$	Primary alcohol	-ol
	Carboxylic acid	-oic acid
 R represents an alkyl group	Ester	-yl -oate

Table 3 Name of common substituents

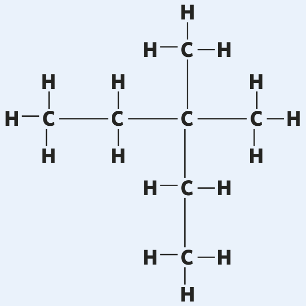
Alkyl groups/Halogen	**Name**
CH_3 -	methyl
CH_3CH_2 -	ethyl
$CH_3CH_2CH_2$ -	propyl
$CH_3CH_2CH_2CH_2$ -	butyl
Cl -	chloro
Br -	bromo
I -	iodo
F -	fluoro

Table 4 Counters used to signify multiples of the same substituent.

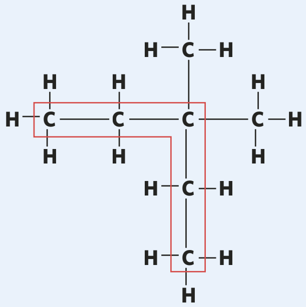
Number of times the same substituent is found in the molecule	**Substituent prefix**
2	di
3	tri
4	tetra

1 Worked example

Identify the IUPAC name for this molecule.



Step 1: Identify and name the parent carbon chain.

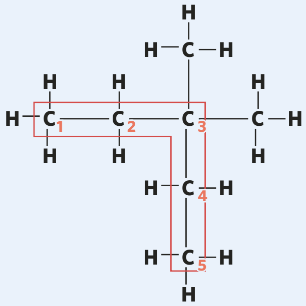


The red outline shows the longest unbroken chain of carbon-carbon bonds and therefore is the parent chain.

Step 2: Identify the type of the organic compound and thereby the appropriate suffix (ending) of its name.

As the chain contains only single carbon bonds, the suffix for this molecule will be **-ane**.

Step 3: Number the positions of the carbons in parent carbon chain. This will be affected by the the priority of the functional group(s)/side chains present.

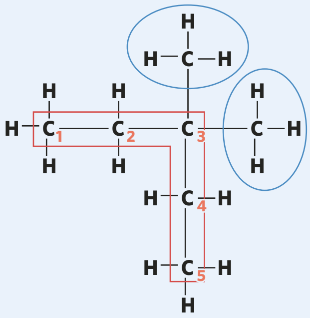


The carbons need to be numbered in a way that the functional group/side chain present occurs at the lowest carbon number.

Step 4: Identify the number and position(s) of the functional group(s).

N/A

Step 5: Identify the number and position(s) of the substituent(s).



There are **two methyl groups** both at **carbon number 3**. We need to use '**di**' to signify there are 2 of the same group.

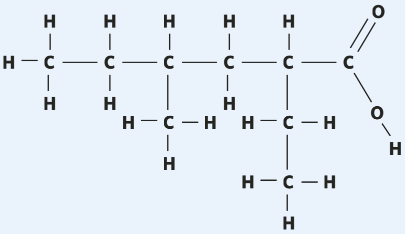
Step 6: Combine the above to write the complete name of the organic compound.

3,3-dimethylpentane

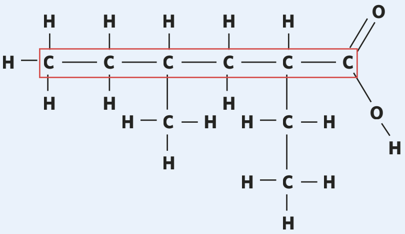
In most cases, the longest carbon chain is the **parent chain** however if there are double or triple bonds present these need to be included as part of the chain. The presence of functional groups also affects both the parent chain and the naming priorities of an organic compound.

2 Worked example

Identify the systematic name for the compound to the right.

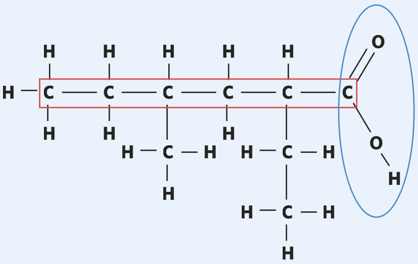


Step 1: Identify and name the parent carbon chain.



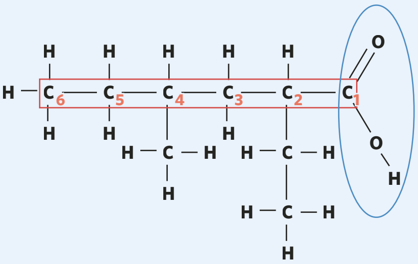
We can see that this is not the longest carbon-carbon chain however due to the presence of the carboxyl functional group, the parent chain must include this functional group. The chain identified in red is the longest carbon chain including the carboxyl function group.

Step 2: Identify the type of organic compound and thereby the appropriate suffix (ending) of its name.



This molecule contains a carboxyl functional group (COOH) therefore the suffix for this molecule will be **-oic acid**.

Step 3: Number the parent carbon chain.

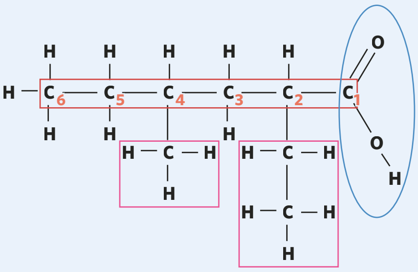


The carbon atom in the functional group is always marked as carbon number 1.

Step 4: Identify the number and position of the functional group(s).

In a carboxylic acid, position of the COOH group is 1 and therefore does not need to be noted in its name.

Step 5: Identify the position and name of the substituent(s).



There are **two alkyl groups** present – methyl and ethyl. The methyl group is bonded to carbon number 4 and ethyl is bonded to carbon number 2. In alphabetical order, the positions and names of the substituents are written as **2-ethyl-4-methyl**.

Step 6: Write the complete name of the organic compound.

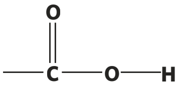
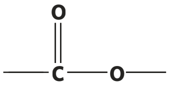
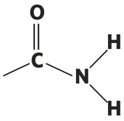
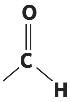
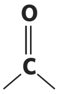
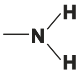
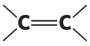
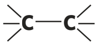
2-ethyl-4-methylhexanoic acid

For compounds with two functional groups, the suffix of the name of the compound is derived from the functional group with the highest priority as outlined in table 5. The remaining functional group(s) with a lower priority then act as the substituent and therefore form the prefix. The effect of this can be seen in table 5.

Table 5 Priorities of functional groups

Highest priority

Least priority

Functional groups	Types of Compound	If used to determine the prefix	If used to determine the suffix
 $\mathrm{-C(=O)-O-H}$	Carboxylic acid	carboxy- *	-oic acid
 $\mathrm{-C(=O)-O-}$	Ester	N/A	-yl -oate
	Primary amide	N/A	-amide
	Aldehyde	formyl- *	-al
	Ketone	oxo- *	-one
$\mathrm{-O-H}$	Alcohol	hydroxy-	-ol
	Amine	amino-	-amine
	Alkene	N/A	-ene
$\mathrm{-C{\equiv}C-}$	Alkyne	N/A	-yne
	Alkane	N/A	-ane
$-X$ (*x* represents a halogen)	Haloalkane	depends on halogen	-

* = outside the scope of the VCE study design

When finalising the name of the organic compound, we need to ensure that we include the following conventions.

- Commas "," are used to separate numbers representing positions of substituents or functional groups.
- "-" is used to separate numbers from words.
- There is no blank space between names of substituent/functional groups and parent chain name.
- Names of substituents need to be written in alphabetical order (not including prefixes such as di/tri, etc.).

Theory summary

- To name all organic compounds, we need to go through 6 steps.
  1. Identify and name the parent carbon chain.
  2. Identify the type of the organic compound and ending of its name.
  3. Number the parent carbon chain.
  4. Identify the number and position(s) of the functional group(s).
  5. Identify the position and name of the substituent(s).
  6. Write the complete name of the organic compound.
- If a compound has 2 functional groups, the parent carbon chain and substituent are determined based on the priorities of functional groups.

7B QUESTIONS

Theory review questions

Question 1 (1 MARK)

Which of the following statements is **false**?

A The parent chain is the longest carbon chain if there is no double bond, triple bond or functional group in the compound.

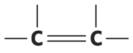
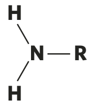
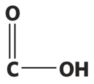
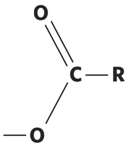
B The parent chain is always the longest carbon chain.

C Comma is used to separate 2 numbers presenting positions of a substituent.

D "-" is used to separate numbers from words in names of organic compounds.

Question 2 (12 MARKS)

Fill in the blanks with the correct carbon bonds, functional groups, type of compound and suffix.

Carbon bonds/functional groups	Type of compound	Ending (suffix)
	Alkane	
 $-C=C-$		
	Alkyne	-yne
C—X (*X* is a halogen ie. Cl, Br, I,...)		
 (R represents an alkyl group)	Primary amine	
	Alcohol	-ol
 $-C(=O)OH$		-oic acid
		

Question 3 (1 MARK)

Choose the option with the correct words to fill in the blanks.

If a compound has 2 functional groups, we need to consider the ______ to determine the parent carbon chain and substituents. The parent carbon chain is determined based on the group with ____ priority and the substituent is the group with ______ priority.

A Parent carbon chain, higher, lower

B Priorities of functional groups and carbon bonds, lower, higher

C Properties of the compound, lower, higher

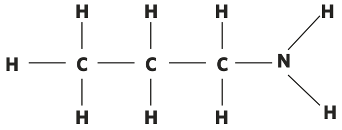
D Priorities of functional groups and carbon bonds, higher, lower

Exam-style questions

Within lesson

Question 4 (1 MARK)

What is the correct IUPAC name for the compound to the right?



A Propan-1-amine

B Amine propane

C Amyl propane

D Ethylamine

Question 5 (1 MARK)

Which of the following is the correct systematic name for the semi-structural formula $CH_3CH_2CHCHCH_3$?

A Pent-3-ene

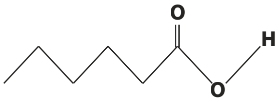
B Pent-2-ene

C But-2-ene

D Pentane

Question 6 (1 MARK)

What is the correct IUPAC name for the skeletal structure shown?



A Pentanoic acid

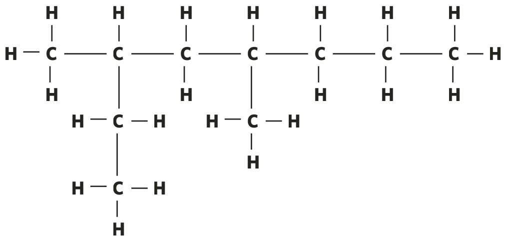
B Hexanone

C Butanoic acid

D Hexanoic acid

Question 7 (1 MARK)

Which option represents the correct positions and names of the substituents on the given compound?



A 1-methyl

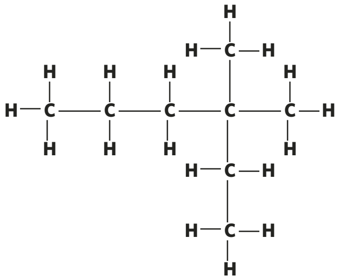
B 3,5-dimethyl

C 4,6-methyl

D 4-ethyl-2-methyl

Question 8 (3 MARKS)

This compound is a structural isomer of octane.



a How many carbons can be found in the parent chain? (1 MARK)

b Identify any substituent(s) present. (1 MARK)

c Write the systematic name of the compound above. (1 MARK)

Question 9 (3 MARKS)

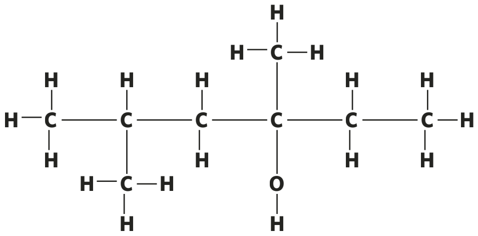
a What is the length of the carbon chain of this molecule? (1 MARK)

b Identify the name of the functional group found in this molecule. (1 MARK)

c What is the name of the molecule shown? (1 MARK)

Question 10 (4 MARKS)

For the molecule shown:



a Identify the functional group present in this compound. (1 MARK)

b What type of alcohol can this compound be classified as? Explain. (2 MARKS)

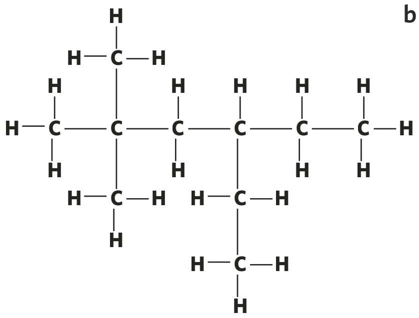
c What is the name of this compound? (1 MARK)

Multiple lessons

Question 11 (5 MARKS)

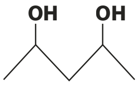
Write the correct IUPAC name for the compounds below.

a



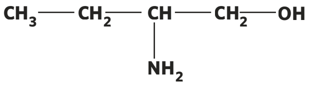
b $CH_2CHCH(CH_3)CH(CH_3)CH_3$

c



d $CH_3CH(Br)CH(Br)CH_3$

e



$CH_3-CH_2-CH(NH_2)-CH_2-OH$

Question 12 (3 MARKS)

Complete the table.

Name	Structural formula
2,4-dimethylpentane	
2-aminopropanoic acid	
3-aminopentan-2-ol	

7C ISOMERS

In this lesson, we will learn how a single organic compound can have different arrangements of its atoms. This will be an extension of the knowledge we learned from 7A.

7A Structure of organic compounds	7B Naming of organic compounds	7C Isomers	7D Chirality	7E Properties of organic compounds	7F Types of organic reactions

Study design dot point

- the carbon atom with reference to valence number, bond strength, stability of carbon bonds with other elements and the formation of isomers (structural and stereoisomers) to explain carbon compound diversity, including identification of chiral centres in optical isomers of simple organic compounds and distinction between cis- and trans- isomers in simple geometric isomers

Key knowledge unit

Types of isomers	4.1.1.2

Key terms and definitions

- **Isomers** molecules with the same molecular formula but different structures
- **Structural isomers** isomers that have the same molecular formula but the atoms are arranged in different orders
- **Spatial orientation** direction and position in space
- **Stereoisomers** isomers with the same order of atoms but have different spatial orientations
- **Geometric isomers** *cis* and *trans* isomers which are formed due to the inability for double bonds to rotate
- **Enantiomers (optical isomers)** pairs of chiral compounds that are mirror images of each other

Lesson links

This lesson builds on:

- ▶ 7A – Structure of organic compounds

Formation of isomers explains carbon compound diversity.

Types of isomers 4.1.1.2

OVERVIEW

Isomers are molecules with the same molecular formula but with different atom arrangements or different **spatial orientations**. Figure 1 shows a mind map that summarises the types of isomers. As we go through this lesson, we will see how different types of isomers are formed, and how to identify and draw them.

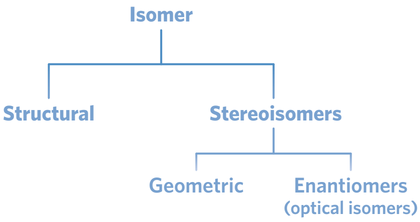


Figure 1 Different types of isomers relevant to the study design

THEORY DETAILS

As we learned from lesson 7A, atoms in a molecule can bond to each other in many different ways. This leads to the concept of isomers. There are two main types of isomers – **structural isomers** and **stereoisomers**.

Structural isomers

Structural isomers are molecules that have the same molecular formula but differ in the arrangement of atoms. The three molecules in figure 2 have the same molecular formula C_5H_{12}, however their structural formulas are different. Pentane has a linear straight carbon chain, while 2-methylbutane has a methyl group bonded to the second carbon of the linear carbon chain and 2,2-dimethylpropane has two methyl groups bonded to the central carbon of the linear carbon chain. Therefore, we can say that these three molecules are structural isomers of C_5H_{12}.

When it comes to larger molecules with more carbon atoms, it can be tricky to identify all of the possible structural isomers. There are some strategies that can be used to determine possible structural isomers of a molecule.

- Changing the position of a substituent/functional group (positional isomer)
- Arranging available atoms into a branch/side chain (chain isomer)
- Changing the identity of the functional group (functional isomer)

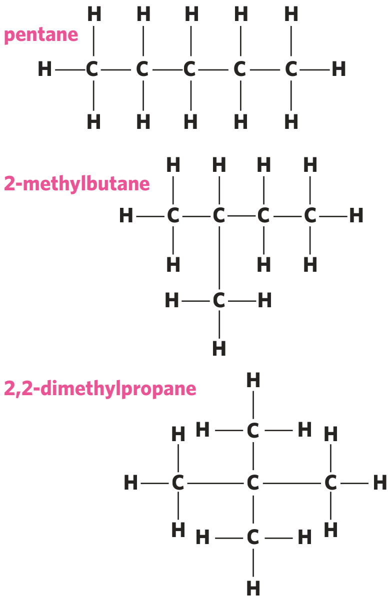


Figure 2 Structural isomers of C_5H_{12}

1 Worked example

Identify all structural isomers for C_4H_9Cl.

What information is presented in the question?

The molecular formula of the compound is C_4H_9Cl

What is the question asking us to do?

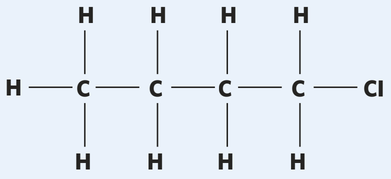
Find the isomers of C_4H_9Cl

What strategy(ies) do we need in order to answer the question?

1. Draw a straight chain structure of the molecule with the formula C_4H_9Cl
2. Identify if the halogen can be attached to other carbons in the chain
3. Identify if any side chains can be made from the atoms available
4. Draw the different possible structures based on the details above

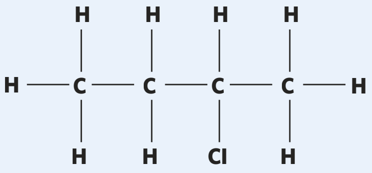
Answer

Straight chain structure



1-chlorobutane

Moving the position of the halogen

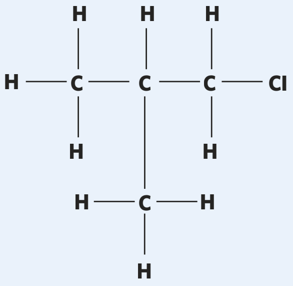


2-chlorobutane

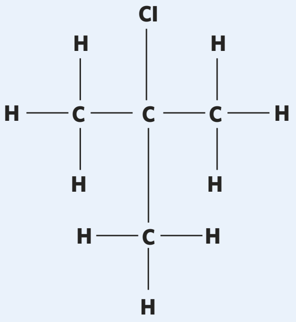
If we continue to shift Cl to the carbons on the left we would be recreating both 1-chloro and 2-chlorobutane.

Possible alkyl groups

We can rearrange atoms to make a methyl group with a three carbon parent chain.



1-chloro-2-methylpropane



2-chloro-2-methylpropane

Therefore, there are four structural isomers for C_4H_9Cl.

Stereoisomers

Stereoisomers are isomers where all atoms are bonded in the same order but arranged differently in a three-dimensional space. There are two main types of stereoisomers – geometric and enantiomers.

Geometric isomers occur when there is a restriction in the ability of a carbon-carbon bond to be rotated in a way that changes the spatial arrangement of the alkyl/functional groups bonded to that carbon, as shown in figure 3. In the context of the study design, we will only make reference to carbon-carbon double bonds.

With reference to carbon-carbon double bonds, we can classify the geometric isomers into two groups – *cis* or *trans* isomers. This depends on the orientation of substituents/functional groups bonded to the carbons involved in the double bond. A molecule is classified as a *cis* molecule if it has the substituents or functional groups bonded to each carbon in the carbon-carbon double bond located on the same side. As shown in figure 4a, the CH_3 groups bonded to the carbons in the double bond are located on the same side of the double bond. Hence, we call this *cis*-but-2-ene. In contrast, the CH_3 groups bonded to the carbons in the double bond in figure 4b are found on the opposite sides of the double bond. Therefore we call this *trans*-but-2-ene.

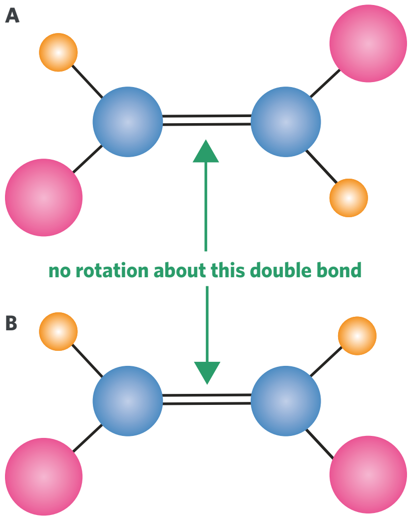


Figure 3 Illustration of the inability to rotate a double bond

Although they may look similar, geometric isomers have different physical properties and reactivity.

Tip Draw a horizontal line across the carbon double bond to see the position of the functional group/substituent/carbon chain.

Enantiomers

Enantiomers are molecules whose mirror images cannot be placed on top of each other even though their atoms are connected in the same order. We will discuss further about enantiomers and how to identify them in the next lesson in the context of chirality.

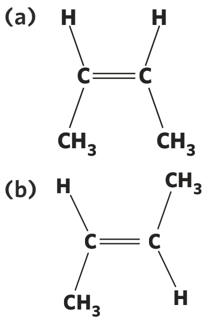


Figure 4 **(a)** *Cis*-but-2-ene
(b) *Trans*-but-2-ene

Theory summary

- Structural isomers molecules that have molecular formula but the atoms are connected differently.
- Stereoisomers are isomers with the same order of atoms but have different orientations in three-dimensional space.
- Enantiomers are isomers whose structures cannot be placed on top of each other.
- *Cis* and *trans* isomers result from the inability for a carbon-carbon double bond to rotate.

7C QUESTIONS

Theory review questions

Question 1

Which of the following statements is **not** true about isomers?

A Isomers are molecules with the same molecular formula but have different atom arrangement or different spatial orientation.

B Structural isomers and stereoisomers are the two main types of isomers.

C Geometric isomers are a type of stereoisomers.

D Enantiomers are a type of structural isomers.

Question 2

Fill in the blanks with correct words about stereoisomers.

There are two main types of stereoisomers which are ___________ and ___________. ___________ are formed due to the inability to rotate a ___________ bond. ___________ are molecules whose structures cannot be placed on top of each other even though their atoms are connected in the same order.

Question 3

Which of the following statements is true about geometric isomers?

A If one of the carbon atoms in the carbon-carbon double bond has two different groups bonded to it, the molecule can exist as *cis*- and *trans*- isomers.

B A *trans*- isomer has two different groups on the same side of the carbon-carbon double bond.

C Geometric isomers are isomers that have the same molecular formula but differ in the atom order.

D A *cis*- isomer has two different groups on the same side of the carbon-carbon double bond.

Exam-style questions

Within lesson

Question 4 (1 MARK)

The number of structural isomers that are carboxylic acids of the formula $C_5H_{10}O_2$ is

A 2

B 3

C 4

D 5

Question 5 (1 MARK)

For which one of the following molecular formulas is there only one possible structure?

A C_3H_7OH

B $C_2H_2F_2$

C C_4H_8

D C_2HF_3

Question 6 (1 MARK)

Which one of the following compounds can exist as *cis*- and *trans*- isomers?

A $CH_3CH_2C(CH_3)C(CH_3)CH_2CH_3$

B $CH_2C(OH)CH_3$

C $CH_3CH(CH_3)CH_2CH_2COOH$

D $CH_3C(CH_3)C(CH_3)(CH_2)_{10}NH_2$

Question 7 (14 MARKS)

Draw all possible structures for the molecular formulas below.

a $C_2H_2Br_2$ (3 MARKS)

b C_2HCl_3 (1 MARK)

c $C_2H_4Br_2$ (2 MARKS)

d $C_5H_{12}O$ (excluding geometric isomers) (8 MARKS)

Question 8 (4 MARKS)

For each semi-structural formula given,

i draw the structural formula.

ii identify whether or not it can exist as *cis*-*trans* isomers.

a $CH_3C(OH)C(OH)CH_3$ (2 MARKS)

b $CH_3CH_2COOCH_3$ (2 MARKS)

Multiple lessons

Question 9 (6 MARKS)

Draw all possible structural isomers of C_4H_8 and give the correct IUPAC name for each isomer.

Question 10 (4 MARKS)

For the semi-structural formula $CH_3C(Br)C(Br)CH_3$,

a draw *cis*- and *trans*- isomers. (2 MARKS)

b write the correct IUPAC name for each isomer. (2 MARKS)

7D CHIRALITY

In this lesson, we will develop a deeper understanding of isomers by investigating chirality.

The concept of chirality allows us to further understand the importance and function of isomers.

7A Structure of organic compounds	7B Naming of organic compounds	7C Isomers	7D Chirality	7E Properties of organic compounds	7F Types of organic reactions

Study design dot point

- the carbon atom with reference to valence number, bond strength, stability of carbon bonds with other elements and the formation of isomers (structural and stereoisomers) to explain carbon compound diversity, including identification of chiral centres in optical isomers of simple organic compounds and distinction between cis- and trans- isomers in simple geometric isomers

Key knowledge units

Properties of chiral compounds	4.1.1.3.1
Chiral centres	4.1.1.3.2

Key terms and definitions

- **Achiral compounds** compounds that can be superimposed onto their mirror image
- **Chiral compounds** compounds that cannot be superimposed onto their mirror image
- **Chiral centre** atom that has four different groups bonded to it
- **Superimposable** the ability for a molecule to be placed over its mirror image

Lesson links

This lesson builds on:

- 7A – Structure of organic compounds

Chirality affects the structure of organic compounds.

- 7B – Naming organic compounds

Although they have the same formula, chiral compounds can have different systematic names.

- 7C – Isomers

Particular isomers can also be referred to as chiral compounds.

Properties of chiral compounds 4.1.1.3.1

OVERVIEW

Isomers can be further categorised based on their structural compatibility with their mirror images.

THEORY DETAILS

As mentioned in lesson 7C, enantiomers are a subset of stereoisomers. In particular, **enantiomers** are molecules whose structures and mirror images are not superimposable.

Compounds are described as being **chiral** if they cannot be placed on top of their mirror image, with all of the functional groups in the same three-dimensional arrangement, no matter how much we rotate the compound. These compounds are considered to be 'non-superimposable'. Compounds that align with their mirror image are known to be **achiral.** Figure 1 shows a simple illustration of chiral and achiral objects.

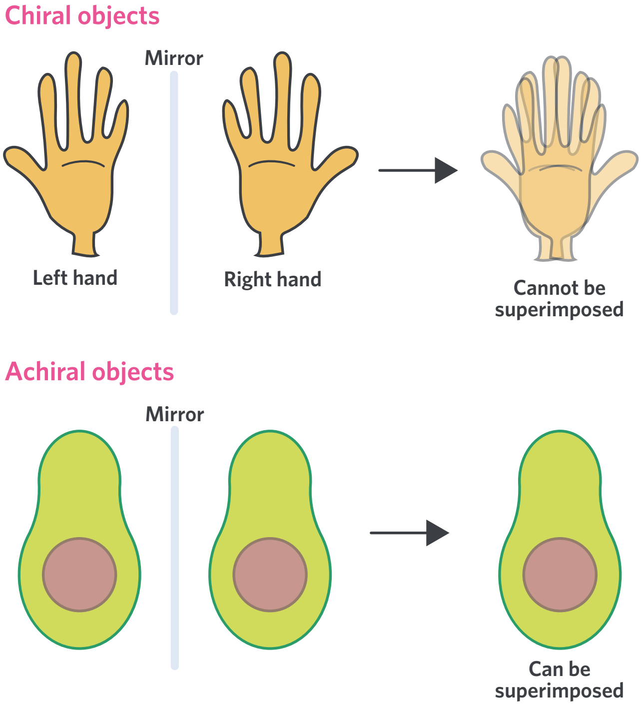


Figure 1 Examples of chiral and achiral objects

We apply the same concept to test the chirality of chemical compounds. Figure 2 shows the process that needs to be taken to determine whether or not molecule A and its mirror image are chiral. When analysing the molecules in the figure, imagine the solid dark wedge bond moving towards you whilst the bond with the dashed lines moves away from you.

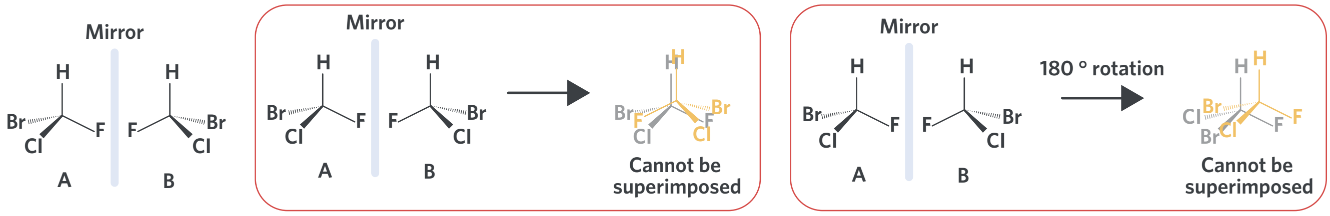


Figure 2 Process involved in determining the chirality of compounds A and B

As seen in figure 2, molecules A and B do not align when placed on top of each other even when molecule B has been rotated 180 °. Therefore, we can say that molecule A is chiral and that A and B are **enantiomers** of each other. In contrast, molecules whose mirror images align cannot be considered as enantiomers and are therefore referred to as being achiral. As can be seen in figure 3, molecule B is able to be superimposed on top of the molecule A when rotated.

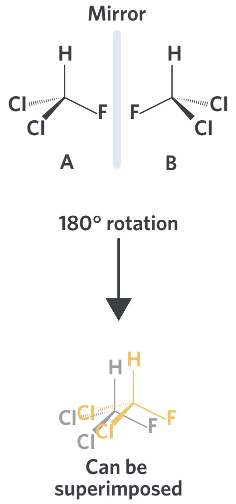


Figure 3 Illustration showing the alignment of molecules A and B when placed on top of each other

Enantiomers have the same chemical and physical properties (except when interacting with light) such as melting and boiling points; however, will interact differently with the same molecule and/or structure. This concept is really important in drug design.

The effectiveness of drugs depends on the interaction between the drug molecules and corresponding binding sites in the body. As shown in figure 4, a drug molecule can only bind to the drug binding site when their structures match. The molecule which can bind to the drug binding site is called an active enantiomer. An inactive enantiomer, which is the mirror image of the active enantiomer, cannot bind to the drug binding site because of their unmatched structures.

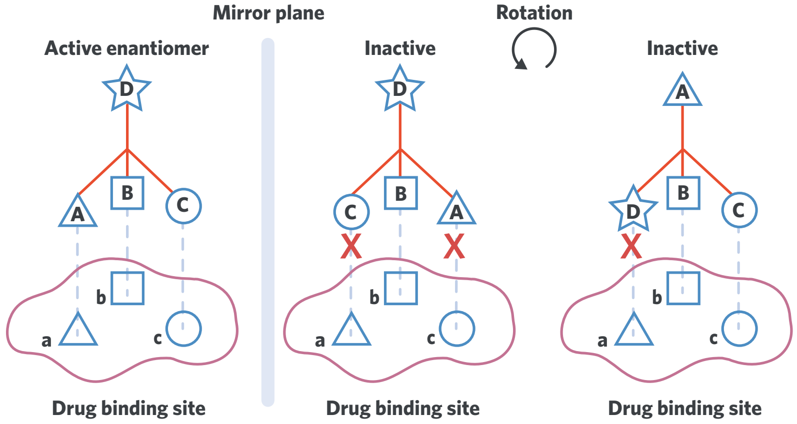


Figure 4 Interaction of enantiomers on drug binding sites

Sometimes, both enantiomers can be functional however depending on the molecule, can have different effects. An example of this is the drug thalidomide, which was originally developed and used as a sedative to help with morning sickness. What scientists didn't know at the time was that the original molecule could be converted to its enantiomer in the body. The enantiomer affected the development of the fetus during pregnancy, resulting in babies with severe limb deformities.

Chiral centres 4.1.1.3.2

OVERVIEW

The presence of chiral centres can help us to determine whether or not a molecule is chiral.

THEORY DETAILS

A chiral compound must contain a **chiral centre**. In the context of organic compounds, a **chiral centre** is a carbon that is attached to four different groups. It is important to note that we are looking for four different groups, and not just looking for a carbon atom being attached to four groups.

The molecule in figure 5 contains two carbons. In order to determine whether it contains a chiral centre, we can analyse the environment of each carbon in the parent chain.

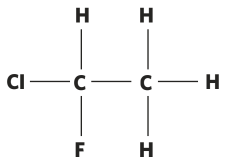


Figure 5 Structural formula for 1-chloro-1-fluoroethane

As shown in figure 6, structure **(a)** has four different groups – CH_3, H, Cl and F – bonded to carbon number one. Therefore, this carbon is a chiral center. However in figure **(b)**, there are only two different groups – CHClF and H – bonded to carbon number two. This means that carbon number 2 is not a chiral centre.

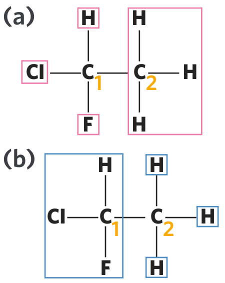


Figure 6 **(a)** & **(b)** show the environments surrounding carbons present in 1-chloro-1-fluoroethane

Although chiral compounds always contain at least one chiral centre, achiral compounds can have multiple chiral centres. Therefore, a molecule with multiple chiral centers is not always chiral. However, we still need to check to make sure that the mirror images are superimposable.

Another way to confirm if molecules are chiral, especially large molecules, is to identify if the molecule has a plane of symmetry.

In figure 7, the red dotted line divides the molecule into two halves that are mirror images of each other. The red dotted line represents the plane of symmetry. If the molecule is symmetrical then it is said to be achiral. We can use this concept to determine whether or not a molecule with multiple chiral centres is chiral or achiral. Although the molecule in figure 7 has multiple chiral centres, it is achiral as it can be superimposed on its mirror image.

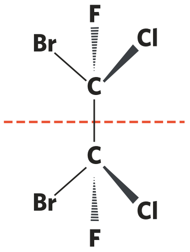
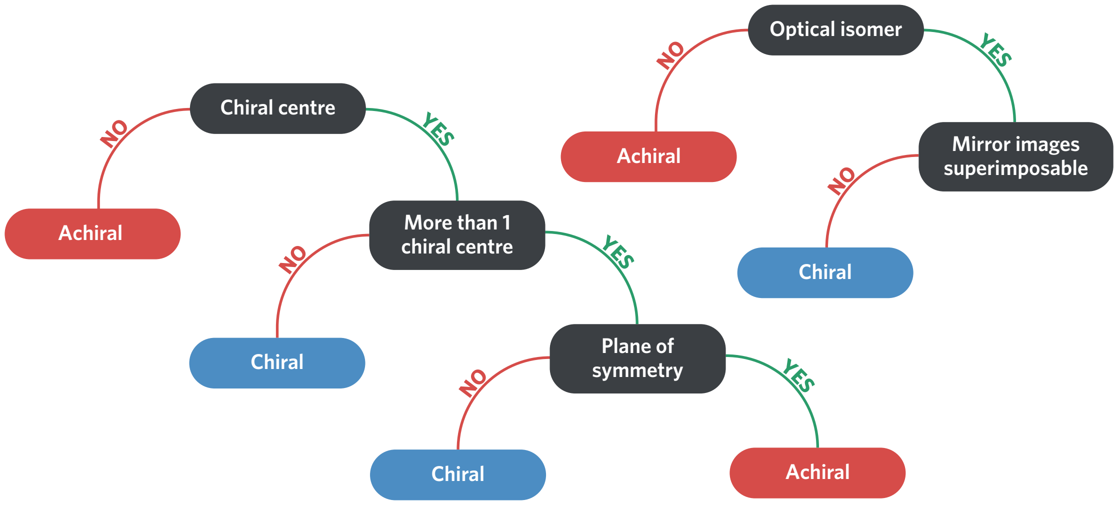


Figure 7 Complicated molecule bisected by a plane of symmetry

Theory summary

- A chiral compound is a compound whose structure and mirror image are non-superimposable.
- Achiral compounds have superimposable mirror images.
- Pairs of chiral compounds are called enantiomers.
- Enantiomers have the same chemical and physical properties but interact differently with other chiral compounds and light.
- A chiral center is a carbon atom that has four different groups attached to it.
- Chiral compounds have chiral centres however molecules with multiple chiral compounds aren't always chiral. Therefore, we can use plane of symmetry to determine if a compound is chiral.

A flow chart of the possible methods to determine if a compound is chiral.



7D QUESTIONS

Theory review questions

Question 1

Pairs of molecules can be considered as enantiomers if

A both molecules look exactly the same.

B they are stereoisomers of each other however are not superimposable.

C they are stereoisomers of each other and can be superimposed on each other.

D they have different molecular formulas.

Question 2

Which of the following statements about chirality is true?

I Molecules that have only one chiral centre are all considered to be chiral compounds.

II Achiral compounds have a line of symmetry.

III Chiral carbons are found in all carbon compounds.

A I only

B II & III only

C I & II only

D II only

Question 3

Consider the statement “Achiral compounds can have chiral centres”. Which of the following comments is accurate regarding this sentence?

A The sentence is incorrect as only chiral compounds have chiral centres.

B The sentence is incorrect as chiral centres are only present in non-superimposable compounds.

C This sentence is correct as both chiral and achiral compounds can have chiral centres.

D This sentence is correct as achiral compounds all have one chiral centre.

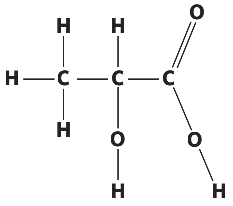
Exam-style questions

Within lesson

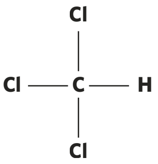
Question 4 (1 MARK)

Which of the following molecules has a chiral centre?

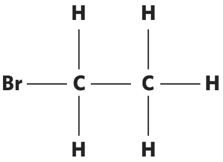
I



II



III

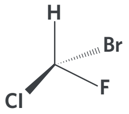


A I & II only **B** II only **C** I & III only **D** I only

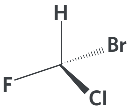
Question 5 (1 MARK)

The highlighted molecule is considered to be chiral. Which of the following molecules would be its enantiomer?

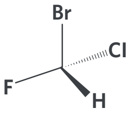
A



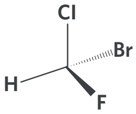
B

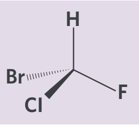


C



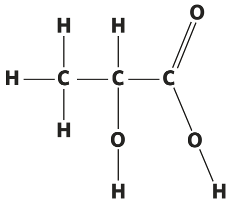
D





Question 6 (1 MARK)

How many chiral centres are present in the molecule shown?



A 1

B 2

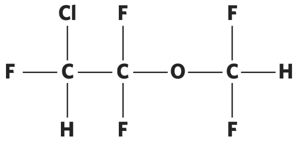
C 3

D 4

Question 7 (1 MARK)

Enflurane was first discovered during the 1960s and can be used as an inhaled anesthesia.

Identify the chiral centre(s) in this molecule.



Question 8 (2 MARKS)

The semi-structural formula for a haloalkane is $CH_3CHBrCH_2CHClCH_3$.

a Draw the structural formula for the compound. (1 MARK)

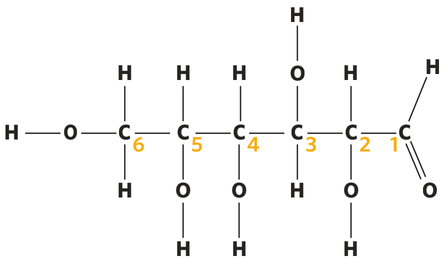
b Identify the chiral centre(s) present. (1 MARK)

Question 9 (3 MARKS)

A glucose molecule is shown.

a Which carbon(s) can be considered as a chiral centre? (1 MARK)

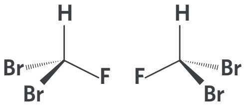
b While examining the molecule above, a student made the comment: "This compound has a chiral centre therefore it must be chiral". Comment on the accuracy of this statement. (2 MARKS)



Question 10 (3 MARKS)

Lizzy was asked to examine these molecules to determine whether they are chiral. She concluded that these compounds are in fact chiral.

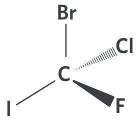
Comment on the accuracy of her statement.



Question 11 (4 MARKS)

a Explain why the molecule shown is considered a chiral compound. Include a diagram in your answer. (3 MARKS)

b Draw the structural formula for the enantiomer of this compound. (1 MARK)



Multiple lessons

Question 12 (5 MARKS)

Butanol is often used to produce a compound that is an ingredient in paint.

a Draw the structural formula for butan-1-ol. (1 MARK)

b If present, circle the chiral centre(s) in butan-1-ol. (1 MARK)

c Butan-2-ol is considered to be an isomer of butan-1-ol. Draw the other isomer(s) of butan-1-ol. (2 MARKS)

d Give the systematic name for the molecule(s) above. (1 MARK)

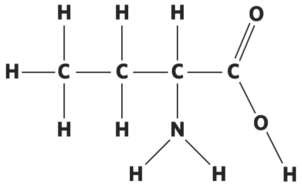
Question 13 (6 MARKS)

The molecule shown can be used to produce proteins in the body.

a Draw the structural isomers of the compound. (4 MARKS)

b How many chiral centres can be found in the molecule shown? (1 MARK)

c Give the systematic name for this compound. (1 MARK)



7E PROPERTIES OF ORGANIC COMPOUNDS

In this lesson, we will apply our understanding of the structure of organic compounds to investigate the properties of these compounds. In particular, we will be investigating how bonding affects the boiling point, flashpoint and viscosity of different organic compounds.

7A Structure of organic compounds	7B Naming of organic compounds	7C Isomers	7D Chirality	7E Properties of organic compounds	7F Types of organic reactions

Study design dot point

- an explanation of trends in physical properties (boiling point, viscosity) and flashpoint with reference to structure and bonding

Key knowledge units

Boiling point	4.1.4.1.1
Flashpoint and viscosity	4.1.4.1.2

Key terms and definitions

- **Boiling point** temperature required to turn a substance from a liquid to its gaseous state
- **Flash point** lowest temperature at which an organic compound gives off sufficient vapour to ignite in air
- **Viscosity** resistance of a substance to flow
- **Volatility** tendency of a substance to be vapourised

Lesson links

This lesson builds on:

- 7A – Structure of organic compounds

Structure helps to determine the properties of organic compounds.

Boiling point 4.1.4.1.1

OVERVIEW

The boiling point of a compound can give important information about the physical properties and structural characteristics of the compound.

THEORY DETAILS

Substances are often represented as a single compound. However, they are actually made up of millions of the same compound bonded together by intermolecular bonding.

The liquid water that we see in figure 1 consists of millions and millions of H_2O molecules bonded together, specifically via hydrogen bonds, permanent dipole-dipole bonds and dispersion forces. Therefore to boil water, the intermolecular bonds between these molecules need to be broken in order for water to change from a liquid to a gas. The point at which this occurs is known as the **boiling point**.

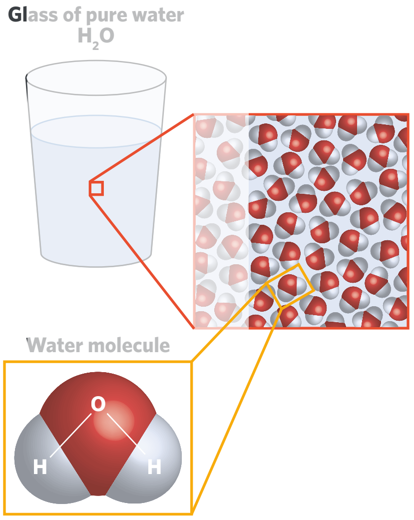


Figure 1 A visual representation of the composition of a glass of water

The boiling point of a liquid is defined as the temperature at which it changes from its liquid state to a gaseous state. The temperature at which these bonds break is dependent upon the strength of intermolecular forces between molecules, the length of the carbon-carbon chains, the amount of branching within the compound and the polarity of the compound. We can use this information to differentiate and compare different molecules.

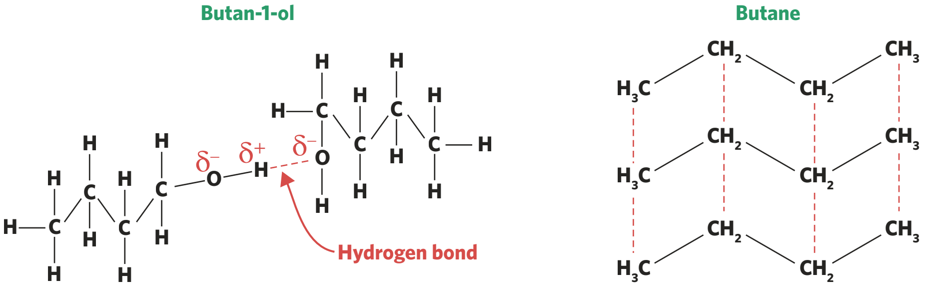
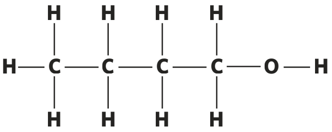
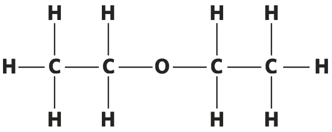
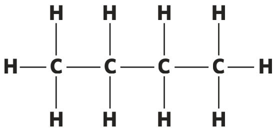


Figure 2 Structural formula and intermolecular forces between butan-1-ol and butane molecules, respectively

The strength of intermolecular forces between molecules affects the boiling point as it determines how much energy (heat) is needed to disrupt the forces between molecules. Compounds with strong intermolecular forces, like hydrogen bonds, tend to have higher boiling points as more energy is required to break the bonds. Whilst compounds with weaker intermolecular forces, like dispersion forces, have lower boiling points as not as much heat is required to break the bonds. An example of this is the oxygen-hydrogen bond in compounds, like butan-1-ol, as shown in figure 2. Due to the hydroxyl (–OH) group, butan-1-ol can form hydrogen bonds with the same groups in another butan-1-ol molecule whereas butane, a non-polar molecule, is held together solely by dispersion forces. As a result, the boiling point of butan-1-ol is higher than butane.

Table 1 Common compounds and their respective molecular weights, strongest intermolecular forces and boiling points

Structure	Butan-1-ol 	Diethyl ether 	Butane 
Molecular weight (g/mol)	74.12	74.12	58.12
Intermolecular forces	Hydrogen bonding, permanent dipole-dipole bonding, dispersion forces	Permanent dipole-dipole bonding, dispersion forces	Dispersion forces
Boiling point (°C)	117	35	-1

As a general rule, the boiling point decreases based on intermolecular forces in the following order – hydrogen bonding → permanent dipole-dipole bonding → dispersion forces.

The length of the carbon-carbon chain also affects the boiling point as the intermolecular forces of attraction between molecules increases with molecular size. This occurs particularly in a homologous series of non-polar substances like alkanes, where with each added CH_2 group, the strength of the dispersion forces increases. This occurs because the more electrons there are, the greater the chance that a spontaneous dipole moment can arise. Hence, as we go through a homologous series, increasing the length of the hydrocarbon chain, dispersion forces increase. More energy is therefore required to overcome this increase in strength of dispersion forces and so the boiling point rises. As a result, boiling point increases as the length of the chain increases.

Branching in molecules negatively affects the boiling point as it decreases the surface area of the compound. This is because branched molecules can't pack as tightly together as there is more space between the molecules, reducing the surface area of the compound. As a result, there is less opportunity for bonds to be formed between the molecules, therefore the overall bonding is weaker. In contrast, molecules like straight-chain alkanes can pack tightly together, increasing the overall surface area and strength of bonding between the molecules and thereby increasing its boiling point. We can use these properties to differentiate isomers of a compound. For example, if we take the two other isomers of 2,2-dimethylpropane, pentane and 2-methylbutane, branching reduces the boiling point of 2-methylbutane when compared to pentane.

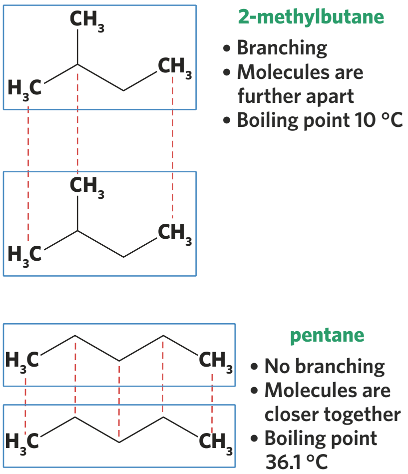


Figure 3 Structural formula and characteristics of 2-methylbutane and pentane.

Difference in electronegativity between covalently bonded atoms results in polar bonds. This results in a bond that is a dipole; the presence of two poles where one is partially positive and the other partially negative. The oppositely charged poles of different molecules can be attracted to each other, resulting in a dipole-dipole interaction. In aldehydes, ketones and esters, this occurs between the carbon-oxygen double bond, as shown in figure 4. Molecules that take part in dipole-dipole interactions have a higher boiling point than molecules held together by only dispersion forces.

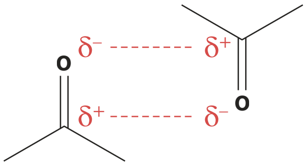


Figure 4 Dipole-dipole attraction between polar carbonyl groups

The boiling point of a compound can also give an indication of its **volatility**. Like boiling point, volatility depends on the strength of the intermolecular bonds holding the molecules together where more volatile substances have weaker intermolecular bonds compared to less volatile substances.

Tip As a general rule, boiling points increase in the order:

Alkanes, alkenes, alkynes < aldehydes, ketones, esters < alcohols, carboxylic acids, amines, amides.

Flashpoint and viscosity 4.1.4.1.2

OVERVIEW

Flashpoint and viscosity give an indication of the physical and structural characteristics of organic compounds.

THEORY DETAILS

Flashpoint

Flashpoint is the lowest temperature at which the vapours of a liquid will ignite in the presence of oxygen and an ignition source. The lower the flash point of a liquid, the easier it is to ignite.

For example, petrol has a flashpoint of −43 °C, which means it will easily ignite if its vapour comes into contact with a flame at any temperature above −43 °C. This is what makes petrol useful for cars, as they will ignite readily in a combustion engine. However, it also means special precautions need to be taken when transporting and storing petrol so that its vapours can't easily come into contact with ignition sources. If the temperature of the petrol increases, like when the engine of a car is running, the concentration of the vapour increases making it a larger fire and explosion hazard.

The flashpoint is higher in substances with stronger intermolecular forces as more energy is required to break the bonds between molecules. Flashpoint also increases as carbon chain length increases as there are more interactions between larger molecules that need to be broken. Conversely, branching results in a lower flash point, as molecules are prevented from packing closely together. Hence, it takes less energy to break the molecules apart.

Viscosity

Viscosity measures the resistance to flow of substances and reflects the substance's structural properties. Liquids with a high viscosity, like honey, flow very slowly, whilst those with low viscosities, like water, flow more readily. This is due to the strength of intermolecular forces and the length of their molecular chains.

Viscosity of liquids depends on the interactions between molecules, increasing as the forces of attraction between molecules increases. As seen in figure 5, liquids with stronger polar intermolecular forces, like honey, have stronger attractive forces holding the molecules together making it harder for the substance to flow. Conversely, non-polar substances, like cooking oil, tend to be less viscous as their intermolecular forces are weaker, allowing them to flow more readily in comparison.

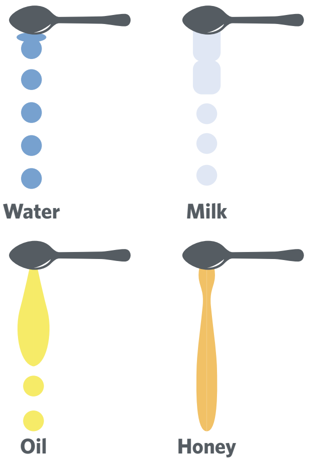


Figure 5 Diagram showing the viscosity of some common substances

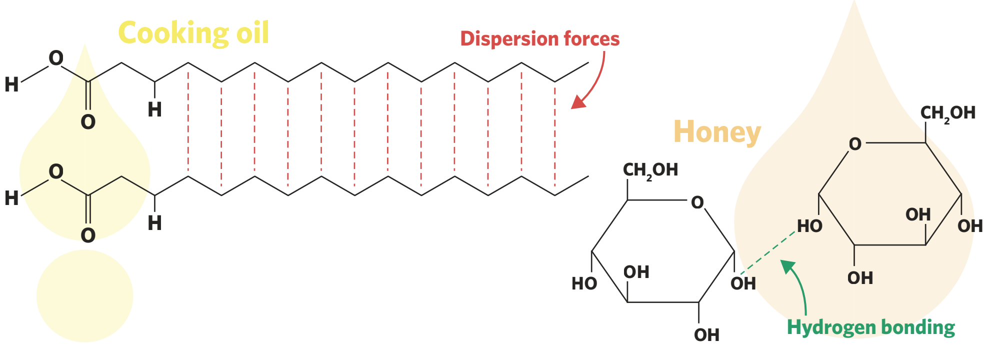


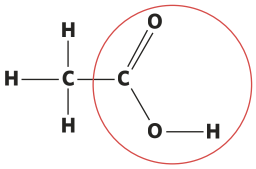
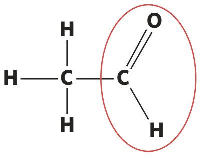
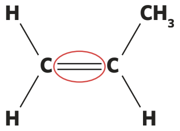
Figure 6 Diagram of intermolecular forces between cooking oil molecules and honey molecules. Note: not all bonds have been shown for both molecules.

Viscosity increases with chain length in a homologous series as the longer molecular chains have stronger intermolecular dispersion forces due to more electrons being present. On the other hand, substances with smaller chain lengths have weaker intermolecular dispersion forces thus can flow more readily.

As viscosity is dependent on the intermolecular reactions between molecules, changes in temperature (and therefore heat energy) can affect the ability of substances to flow. An increase in temperature results in a decrease in viscosity as there is more energy available to break the intermolecular bonds, allowing substances to flow more readily. Conversely, a decrease in temperature results in an increase in viscosity.

In summary, general trends can be identified between types of organic compounds and their physical properties, as shown in table 2.

Table 2 Trend of boiling point, flash point and viscosity in organic compounds

Types of organic compounds	Example	Intermolecular forces	Polarity
Alcohols, amines, amides, carboxylic acids	Ethanoic acid 	Hydrogen bonding, permanent dipole-dipole bonding, dispersion forces	Polar
Haloalkanes, aldehydes, ketones, esters	Ethanal 	Permanent dipole-dipole bonding, dispersion forces	Polar
Alkanes, alkenes, alkynes	Propene 	Dispersion forces	Non-polar

Real-life example

Using the example of fuels from Unit 3 AOS 1, we know that petrodiesel, a non-renewable fuel, is a nonpolar compound with the weakest type of intermolecular force, dispersion forces. However, biodiesel, a renewable fuel, is a polar compound that forms dipole-dipole interactions between molecules due to the presence of a polar ester functional group in the molecule. Biodiesel is also longer than petrodiesel and so has more dispersion forces, adding to the strength of its intermolecular forces. Therefore, biodiesel has a higher flashpoint and boiling point, making it safer for storage and transportation but not as desirable as a fuel as it is harder to vaporise. Biodiesel also has a higher viscosity because of those strong intermolecular forces, making it more difficult in cold climates both to transfer from storage and provide the fuel for a vehicle as it doesn't flow along fuel lines very well. Biodiesel is also more hygroscopic (the ability for a compound to attract water from its surrounding environment) than petrodiesel because of the presence of the polar ester functional group which can form hydrogen bonds and permanent dipole-dipole bonds with water molecules. This can be a problem if water gets into the fuel line as the biodiesel molecule will not combust as easily if surrounded by water.

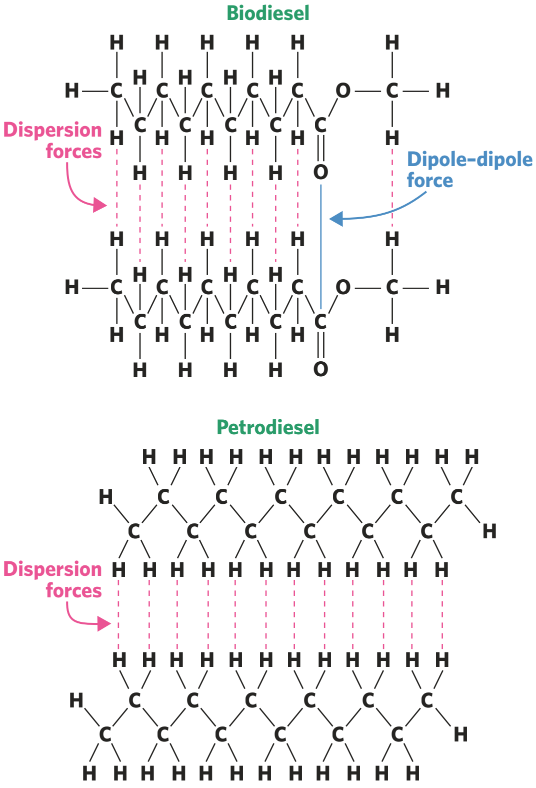


Figure 7 Diagram of intermolecular forces between biodiesel molecules and between petrodiesel molecules

Theory summary

- Compounds can be identified and categorised based on their physical and structural properties.
- Boiling point, flash point and viscosity are determined by a compound's intermolecular forces, length of carbon-carbon chain, branching and polarity.
- Boiling point is indicative of volatility – volatile compounds tend to have low boiling points because they easily release vapour.
- Stronger intermolecular forces, longer chain lengths and high polarity increase boiling point, flashpoint and viscosity.
- Increased branching of a compound decreases boiling point, flashpoint and viscosity.
- The flashpoint of a compound also gives an indication of the stability and safety of compounds for storage and transportation.
- Increasing the temperature of a liquid, decreases its viscosity as the intermolecular forces can be overcome more easily.

7E QUESTIONS

Theory review questions

Question 1

Complete the following paragraph.

Ethane is a member of the __________ homologous series. The forces of attraction holding the ethane molecules together are __________. As the chain length of this homologous series increases, their boiling points __________.

A	alkene	weak dispersion forces	increase
B	alkane	covalent bonds	decrease
C	alkene	dipole-dipole	decrease
D	alkane	weak dispersion forces	increase

Question 2

Which of the following does **not** relate to the process of boiling?

A It involves a phase change.
B The vapour pressure of a liquid becomes equal to the atmospheric pressure exerted on the liquid.
C It is a different process to evaporation.
D The substance changes from a low temperature to a higher temperature.

Question 3

Which of the following is incorrect about the bonds involved in the process of boiling?

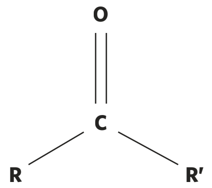
A Intramolecular forces are broken.
B The forces between molecules are broken.
C Intermolecular forces are broken.
D Hydrogen bonds break in pentan-1-ol.

Exam-style questions

Within lesson

Question 4 (1 MARK)

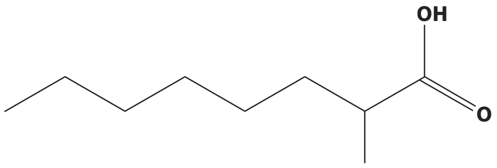
What is the strongest type of intermolecular bonding that exists between molecules that contain this functional group?



A Permanent dipole-dipole forces
B Hydrogen bonding
C Dispersion forces
D Cohesion

Question 5 (1 MARK)

Which is the strongest type of bonding that exists between these molecules?

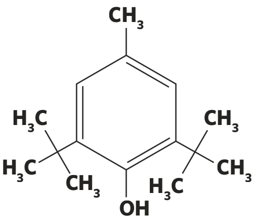


A Dispersion forces
B Dipole-dipole forces
C Hydrogen bonding
D Attractive forces

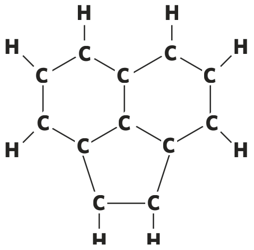
Question 6 (1 MARK)

Which of the following has a lower boiling point than Compound 1?

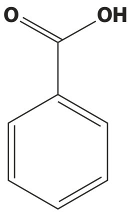
Compound 1



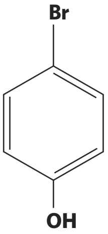
Compound 2



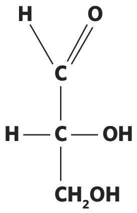
Compound 3



Compound 4



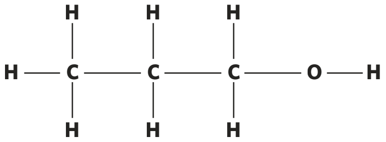
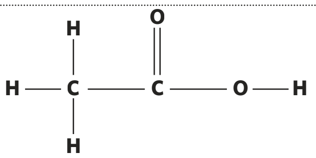
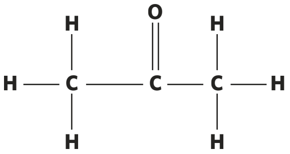
Compound 5



- **A** Compound 2
- **B** Compound 3
- **C** Compound 4
- **D** Compound 5

Question 7 (3 MARKS)

The table shows information about three organic carbon compounds.

Compound	Structural formula	Molecular weight	Boiling point (°C)
X	 $\mathrm{H-C-C-C-O-H}$	60	97
Y	 $\mathrm{H-C-C-O-H}$	60	118
Z	 $\mathrm{H-C-C-C-H}$	58	?

a What is the best estimate for the boiling point of compound Z? (1 MARK)

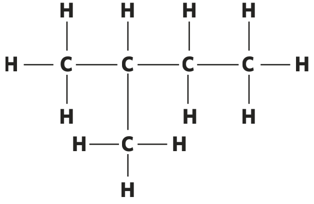
- **A** 22 °C
- **B** 56 °C
- **C** 100 °C
- **D** 125 °C

b Explain your answer to part a. (2 MARKS)

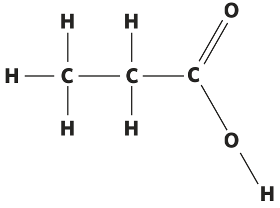
Question 8 (3 MARKS)

The structural formulas and names of two similarly sized and shaped compounds are shown below.

2-methylbutane



propanoic acid



Although they appear similar, the boiling points of these compounds are 28 °C and 141 °C.

Which compound, 2-methylbutane or propanoic acid, has the highest boiling point? Explain.

Question 9 (3 MARKS)

The following table gives the molar masses and boiling points of three organic compounds.

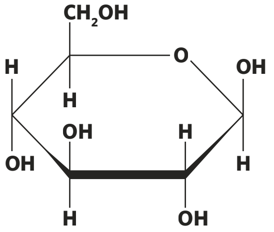
Compound	Molar mass	Boiling point (°C)
Butan-1-amine	73	78
Butan-2-amine	73	55
Butan-1-ol	74	118

Explain why, even though they have similar molecular masses, the boiling points are different.

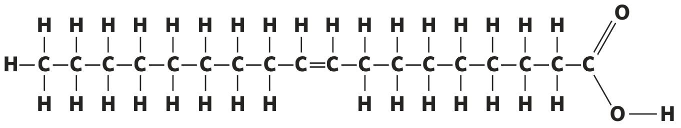
Question 10 (3 MARKS)

Explain why a substance made up of molecule **I** is more resistant to flow than a substance made up of molecule **II**.

I



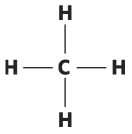
II



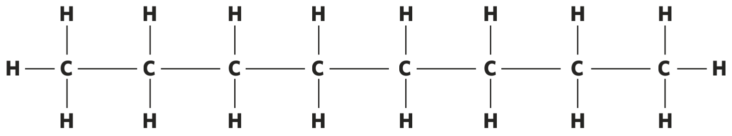
Question 11 (3 MARKS)

Both of the molecules shown below can be used as a fuel source.

Methane



Octane



Of the two, which molecule below would have a higher viscosity and boiling point? Explain.

Question 12 (2 MARKS)

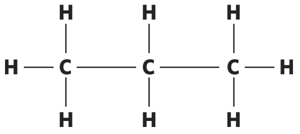
The United States generally experiences temperatures between 11 °C and 22 °C. Therefore in the United States, specific precautions are taken when the flash point of a liquid fuel is below 25 °C, for example the fuel containers must be secured from movement or accidental damage. Explain why it is important to have these safety precautions in place for liquids fuels with a flashpoint below 25 °C.

Multiple lessons

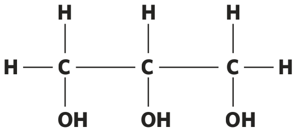
Question 13 (5 MARKS)

The molecular structures of three organic compounds are shown.

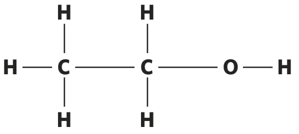
i



ii



iii



a Give the systematic name for each of the compounds. (3 MARKS)

b Which of the molecules above would have an associated isomer(s)? (1 MARK)

c List the compounds in increasing order of viscosity and boiling point. (1 MARK)

7F TYPES OF ORGANIC REACTIONS

In this lesson, we will be learning about reactions between organic compounds and how to measure the efficiency of a chemical reaction.

7A Structure of organic compounds	**7B Naming of organic compounds**	**7C Isomers**	**7D Chirality**	**7E Properties of organic compounds**	**7F Types of organic reactions**

Study design dot points

- organic reactions, including appropriate equations and reagents, for the oxidation of primary and secondary alcohols, substitution reactions of haloalkanes, addition reactions of alkenes, hydrolysis reactions of esters, the condensation reaction between an amine and a carboxylic acid, and the esterification reaction between an alcohol and a carboxylic acid
- the pathways used to synthesise primary haloalkanes, primary alcohols, primary amines, carboxylic acids and esters, including calculations of atom economy and percentage yield of single-step or overall pathway reactions.

Key knowledge units

Substitution reactions	4.1.5.1.1
Addition reactions	4.1.5.1.2
Oxidation of alcohols	4.1.5.1.3
Condensation reactions	4.1.5.1.4
Esterification reactions	4.1.5.1.5
Hydrolysis reactions	4.1.5.1.6
Reaction pathways	4.1.6.1
Efficiency of reactions	4.1.6.2

Key terms and definitions

- **Actual yield** amount of product that is actually produced as a result of a chemical reaction
- **Addition reaction** reaction where one molecule combines with another to form a larger molecule with no other products
- **Atom economy** extent to which the reactants are used to make the desired product(s)
- **Condensation reaction** chemical reaction where two molecules combine with the release of a water molecule
- **Esterification** chemical reaction between organic compounds that forms at least one ester as a product
- **Hydrolysis** chemical reaction where water is used to break the bonds of a substance
- **Reaction pathway** one or more reactions designed to convert a reactant to a desired product
- **Substitution reaction** chemical reaction where an atom, or group of atoms in a compound are replaced by another atom, or group of atoms
- **Theoretical yield** expected amount of a product produced in a chemical reaction
- **Percentage yield** efficiency of a chemical reaction that has taken place

Lesson links

This lesson builds on:

- 7A – Structure of organic compounds

Different organic compounds are produced through different reactions.

Substitution reactions 4.1.5.1.1

OVERVIEW

A substitution reaction occurs when an atom, or group, replaces another atom, or group, resulting in the formation of a new substance.

THEORY DETAILS

Saturated hydrocarbons like alkanes can undergo **substitution reactions** with halogens, like chlorine and bromine, to form haloalkanes. These reactions may require heat or ultraviolet light to initiate the reaction, such as the substitution reaction of ethane and bromine as shown in figure 1.

During this reaction, ethane and bromine react to form bromoethane and hydrogen bromide. One of the hydrogen atoms in the ethane molecule is replaced, or 'substituted' by a bromine atom, resulting in the formation of bromoethane. The reaction can continue to proceed with another hydrogen atom being substituted by a bromine atom to form 1,2-dibromoethane.

Figure 1 Substitution reaction involving ethane and bromine to form bromoethane

The haloalkane that is produced can undergo a further substitution reaction with water in the presence of a catalyst or sodium hydroxide to form an alcohol.

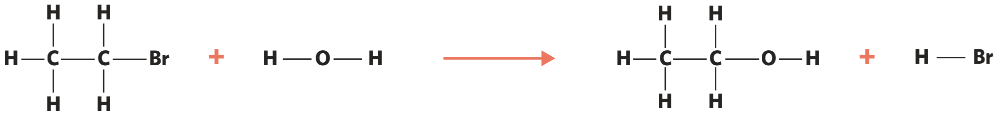


Figure 2 Substitution reaction between bromoethane and water to produce ethanol

As we can see in figure 2, bromine from bromoethane is substituted for an OH group from water to produce ethanol and hydrogen bromide.

Similarly, haloalkanes can react with ammonia to form amines. As shown in figure 3, bromoethane can react with ammonia to form ethanamine and hydrogen bromide. During this reaction, bromine is substituted with NH_2 from ammonia to form the amino functional group.

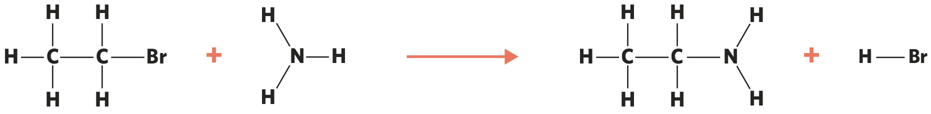


Figure 3 Reaction of bromoethane and ammonia to form ethanamine and hydrogen bromide

As we can see, substituting atoms or groups of atoms in compounds, like alkanes and haloalkanes, creates completely different compounds, many of which can be used in other organic reactions to produce important biomolecules.

Addition reactions 4.1.5.1.2

OVERVIEW

In organic chemistry, an addition reaction is essentially an organic reaction where two or more molecules combine to form a larger molecule.

THEORY DETAILS

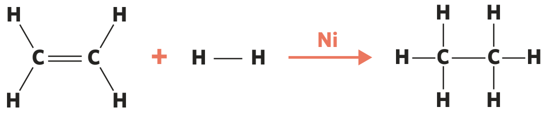
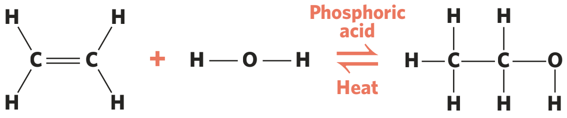
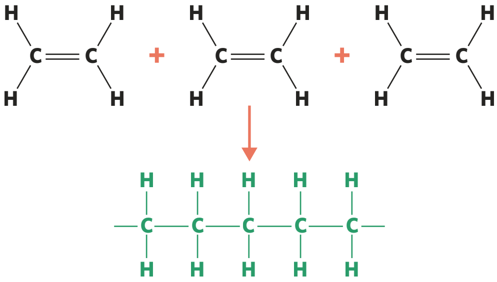
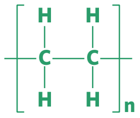
In **addition reactions**, carbon-carbon double and triple bonds, as in alkenes and alkynes respectively, are broken to allow the molecule to bond to other atoms. As a result, the original carbon-carbon double bond becomes a single bond while triple carbon-carbon bonds become a carbon-carbon double bond.

For example, hydrogen chloride can react with ethene to form chloroethane. The double bond in ethene is broken to allow for a chlorine atom to bond to one carbon and a hydrogen atom to bond to the other carbon involved in the double bond. This results in the formation of a single product – chloroethane. This can be seen in figure 4.

Figure 4 Addition reaction between ethene and hydrogen chloride

We can use this concept to produce many other types of organic compounds. Table 1 highlights other addition reactions that relate to the current study design.

Table 1 Examples of addition reactions to produce different organic molecules

Type of addition reaction	Example	Description
Hydrogenation		Alkenes can undergo addition reactions with hydrogen to produce an alkane. This reaction requires the help of a metal catalyst.
Hydration (in particular, production of alcohols)		Alkenes can undergo addition reactions with water to produce an alcohol. This reaction requires liquid phosphoric acid as a catalyst as well as heat due to its high activation energy.
Polymerisation		Alkene and alkyne monomers can undergo addition reactions to form a large polymer molecule. Each monomer is usually represented as the repeated unit as seen in the polymer chain. For the example reaction involving ethene, the monomer would be represented as: 

Chemists can use the concept of addition reactions to identify if organic compounds are unsaturated. Bromine is a yellow/red liquid that can be used to detect the presence of double/triple carbon-carbon bonds. Since we know that unsaturated compounds will undergo an addition reaction with halogens, if a small amount of bromine liquid is added to an organic compound and the reaction changes from a yellow/red colour to being colourless, then we know that it contains at least one carbon-carbon double/triple bond. The amount of bromine that reacts is related to the number of carbon-carbon double/triple bonds present.

Tip When drawing the monomer(s) for a polymerisation reaction, make sure to show the bonds on either side that connect to the next monomer in the chain

Oxidation of alcohols 4.1.5.1.3

OVERVIEW

Building from our knowledge of redox reactions from Unit 3, we will investigate the oxidation reactions involving different types of alcohols.

THEORY DETAILS

The oxidation of alcohols is an important organic reaction as it allows us to produce ketones, aldehydes and carboxylic acids. As mentioned in lesson 7A, there are three different types of alcohols – primary, secondary and tertiary. Primary alcohols are predominantly used to produce aldehydes and carboxylic acids whereas secondary alcohols are often used to produce ketones. Our lesson will focus on the oxidation of primary and secondary alcohols.

In primary alcohols, the hydroxyl (–OH) group is bonded to a carbon that is attached to only one alkyl group. Primary alcohols are first oxidised to aldehydes and then further to carboxylic acids. When the primary alcohol is oxidised, it first loses two of its hydrogen atoms to form water with the oxygen from dichromate ion $Cr_2O_7{}^{2-}{}_{(aq)}$, which acts as an oxidising agent, causing a carbon-oxygen double bond to form, creating an aldehyde. The aldehyde is further oxidised with an oxygen atom forming a hydroxyl functional group (OH) in the aldehyde to create a carboxylic acid. Below is an example of the processes involved in the oxidation of methanol to methanoic acid.

$$CH_3OH_{(l)} \xrightarrow[H_2SO_{4(l)}]{Cr_2O_7{}^{2-}{}_{(aq)}} CH_2O_{(l)}$$

$$CH_2O_{(l)} \xrightarrow[H_2SO_{4(l)}]{Cr_2O_7{}^{2-}{}_{(aq)}} HCOOH_{(l)}$$

Note that there are other oxidising agents such permanganate ions ($MnO_4{}^-$) that can be used to oxidise alcohols however dichromate ions ($Cr_2O_7{}^{2-}$) are most commonly used.

Another method that can be used to oxidise primary alcohols to carboxylic acids involves the vapor form of the alcohol undergoing an oxidation reaction with the oxygen in air in the presence of a silver catalyst at very high temperatures.

There are a few steps that a chemist can take to maximise the production of the aldehyde, instead of allowing the carboxylic acid to form.

- Limit the heat (temperature) of the reaction
- Limit the oxidising agent available in the reaction
- Remove the aldehyde as it is being produced

In secondary alcohols, the hydroxyl group is bonded to a carbon that is attached to two alkyl groups. Secondary alcohols are oxidised to form ketones, as shown in figure 5. However, unlike primary alcohols, the reaction doesn't go further than this.

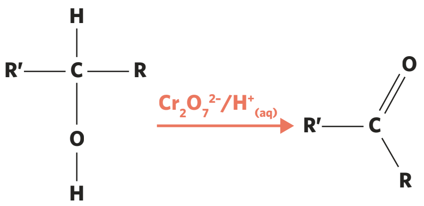


Figure 5 General equation for the oxidation of secondary alcohols to ketones. The R represents different alkyl groups.

For oxidation of alcohols to occur, there must be a hydrogen bonded to the hydroxyl carbon. Therefore, as tertiary alcohols are compounds where the hydroxyl group is attached to a carbon atom bonded to three other carbon atoms, these cannot undergo oxidation. This can be shown in figure 6.

Strong oxidising agents like the dichromate $Cr_2O_7^{2-}$ ion and the permanganate MnO_4^- ion are highly coloured, due to the chromium (Cr) and manganese (Mn) metals, and can therefore be used to indicate the oxidation process. This is known as a qualitative test (or simple test) as the colour change indicates that an organic compound has been oxidised. As shown in figure 7, a solution of potassium dichromate ions dissolved in water is orange.

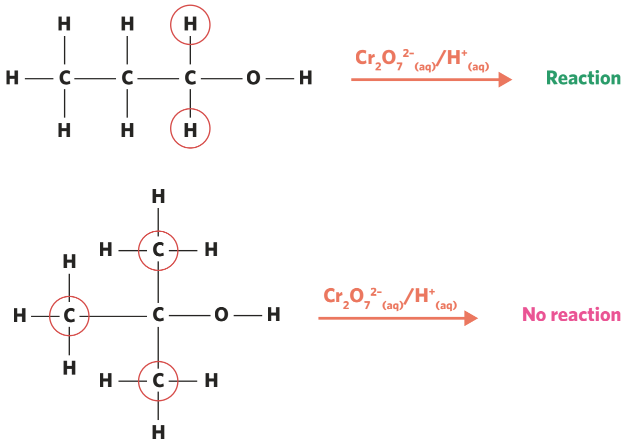


Figure 6 Propan-1-ol, a primary alcohol, showing the hydrogen atoms attached to the hydroxyl carbon making it capable of undergoing oxidation. This is compared with 2-methylpropan-2-ol, a tertiary alcohol, which has no hydrogen atoms attached to the hydroxyl carbon, making it unable to be oxidised.

When used to oxidise butan-1-ol (a primary alcohol), or butan-2-ol (a secondary alcohol), the solution turns green as dichromate is reduced to the green chromium ion (Cr^{3+}). However, in the solution of 2-methylpropan-2-ol (a tertiary alcohol), there is no colour change, showing that the alcohol is not oxidised. This observation matches with the idea that primary and secondary alcohols can be oxidised to however tertiary alcohols cannot.

Fun fact: Police can determine whether a driver has been drinking alcohol or not, using this form of qualitative testing as a colour change indicates the presence of alcohol in the driver's breath.

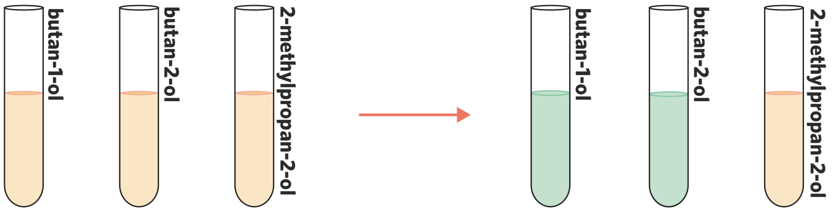


Figure 7 Solutions of the primary alcohol butan-1-ol and secondary alcohol butan-2-ol with potassium dichromate changing the colour of the solutions from orange to green. The tertiary alcohol 2-methylbutan-2-ol will not react with potassium dichromate.

Condensation reactions 4.1.5.1.4

OVERVIEW

In condensation reactions, two molecules are combined, resulting in the release of water.

THEORY DETAILS

In the reaction between a carboxylic acid and ammonia, a primary amide is produced and a water molecule is eliminated during the reaction. As shown in figure 8, the hydroxyl group from the propanoic acid is replaced with the NH_2 from ammonia to produce the amide. The –OH group that is eliminated from propanoic acid then combines with the hydrogen atom from the ammonia to form a water molecule. This is an example of a **condensation reaction**.

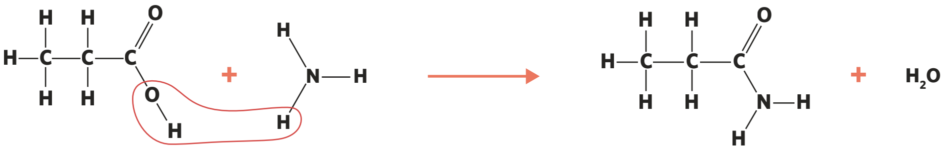


Figure 8 The condensation reaction of propanoic acid and ammonia to form propanamide and a water molecule

We can use the same process to produce secondary amides as seen in the production of N-methylethanamide shown in figure 9 (naming of this organic compound is not required for VCE).

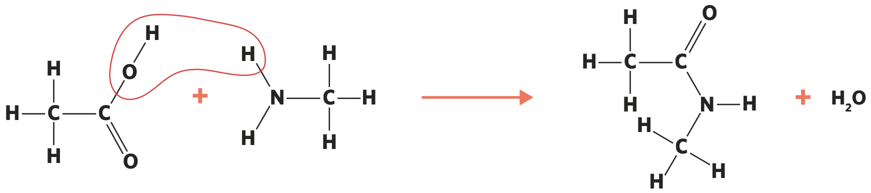


Figure 9 Condensation of ethanoic acid and methanamine to produce N-methylethanamide, a secondary amide

In the reaction above, the –OH group in ethanoic acid is replaced by the NH—CH_3 group from methanamine, producing the secondary amide N-methylethanamide. Like the previous condensation reactions shown above, the –OH group that is removed from the carboxylic acid combines with a hydrogen from the amine to form a water molecule.

Esterification reactions 4.1.5.1.5

OVERVIEW

Esterification is a particular type of condensation reaction where a carboxylic acid and an alcohol react to produce a water molecule and an ester.

THEORY DETAILS

When a carboxylic acid and an alcohol combine, an ester and water molecule is produced in a process known as **esterification**.

Below is an example of an esterification reaction between an alcohol (ethanol) and a carboxylic acid (ethanoic acid). The hydrogen atom of the hydroxyl group in ethanol combines with a hydroxyl group from ethanoic acid to form water, which is eliminated from the reaction. The remaining part of the alcohol and the carboxylic acid are bonded to each other to form the ester ethyl ethanoate. This process also involves the use of concentrated sulphuric acid, which acts as a catalyst for the reaction.

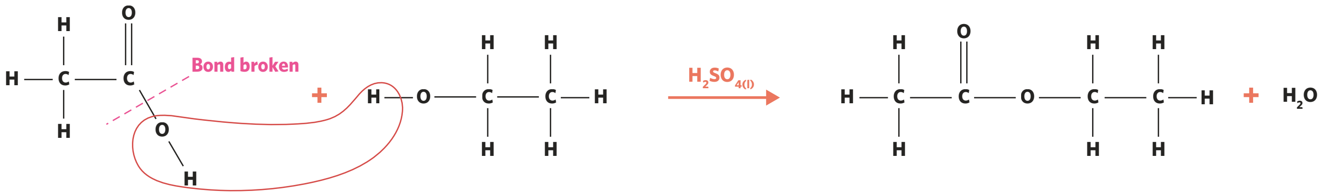


Figure 10 The esterification reaction to produce ethyl ethanoate from ethanoic acid and ethanol.

Esterification is a common reaction in the manufacturing of chemicals like fragrances, medicines and soaps. Acetone, a key ingredient in nail polish remover that accounts for its smell and use as a solvent, is an ester known as ethyl ethanoate, which is produced through the same process as outlined in figure 10.

It is useful to understand this concept as the alcohol and carboxylic acid that have come together to produce an ester form the basis of the name of the ester produced. The name of an ester is composed of two words – the first part relates to the alcohol and the second part relates to the carboxylic acid. Using the suffixes -yl for the alcohol and -oate for the carboxylic acid, we can then name the ester. For example, the reaction between methanol and hexanoic acid will result in the production of methyl hexanoate.

Hydrolysis reactions 4.1.5.1.6

OVERVIEW

In hydrolysis, water is used to break the bonds in a molecule to produce new compounds.

THEORY DETAILS

Hydrolysis reactions can be thought of as addition reaction as the water molecule is added to the molecule it reacts with. In some cases, the compound reacting with water may split into two, with one compound gaining a hydroxyl group and the other gaining a hydrogen ion from the water molecule. These reactions are usually catalysed by an alkaline substance or an acid as the reactions won't occur at standard temperature and pressure.

An example of a hydrolysis reaction that will be important in the context of our study design is the hydrolysis of esters. Through this reaction, esters can be broken down into the original molecules from which they're formed.

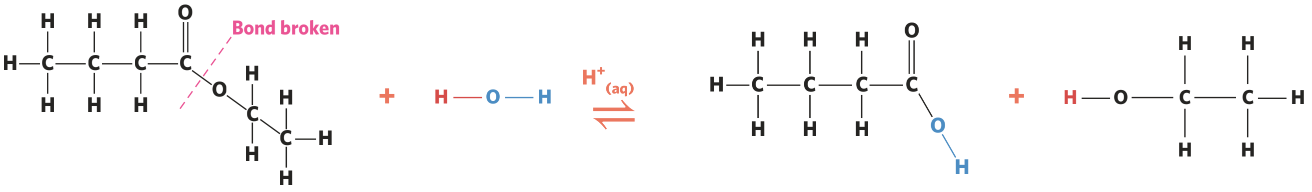


Figure 11 Hydrolysis of ethyl butanoate

As seen in figure 11, the single carbon – oxygen bond in the ester group is broken during the reaction resulting in the formation of butanoic acid and an ethanol – the original reactants used to produce the ethyl butanoate. Understanding this process is incredibly helpful in being able to confidently name esters.

Reaction pathways 4.1.6.1

OVERVIEW

Reaction pathways can be used to create organic compounds in order to get a desired product.

THEORY DETAILS

Chemists often develop compounds that have properties they think will be useful for a particular purpose, like for a new medicine or nano-material. Once they have come up with this compound, they need to design a way to create it from readily available materials. To do this, they compose **reaction pathways** to synthesise a desired organic compound by utilising reactions like the ones described above.

Reaction pathways can be thought of as simple or complex, depending on the number of steps and process required to create the desired product.

In simple reaction pathways, like in the synthesis of propanone from propene, the product can be created from an alkene using only two reactions with simple reactants like water and oxygen. What makes this pathway 'simple' is that the same reaction conditions can be used to develop reaction pathways for other members of the same homologous series, alkane or alkene. This can be seen when we compare the reaction pathways to synthesise propanone from propene and butanone from butene, as seen in figure 12.

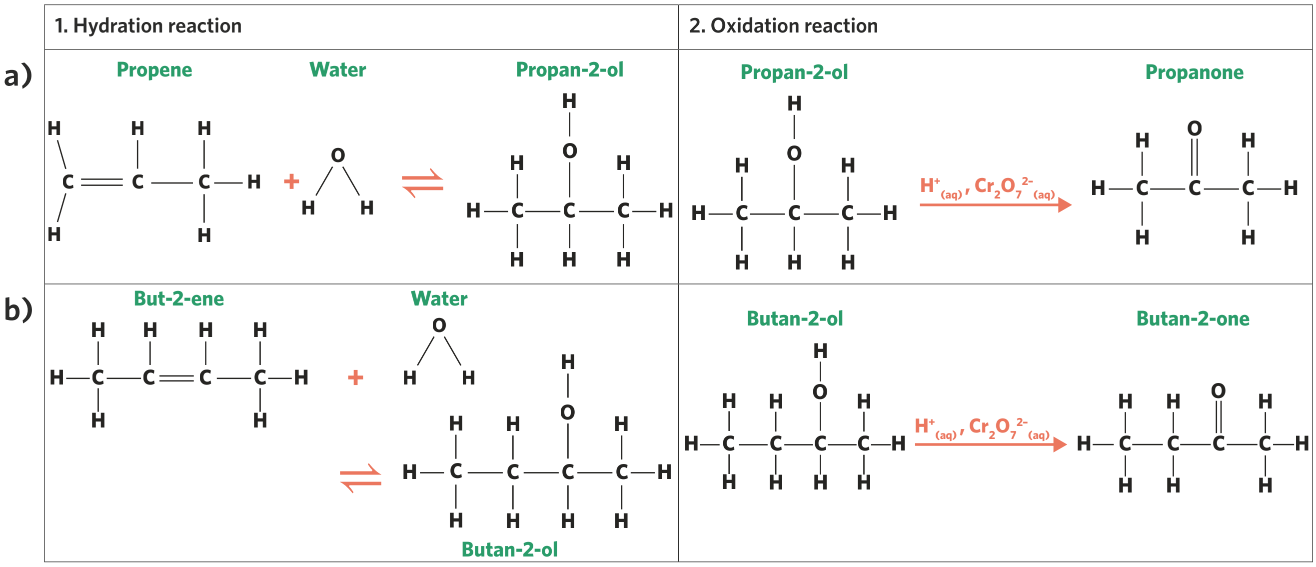


Figure 12 Reaction pathways to synthesise **a)** propanone and **b)** butan-2-one, under the same reaction conditions

Whereas, in a more complex reaction pathway like the synthesis of an ester, the key reactants need to be synthesised first from their most simple form, an alkane or alkene. To create this complex reaction pathway, the synthesis of the required reactants is determined first, followed by the synthesis pathway for the ester.

The process outlined in figure 13 is an example of the steps involved in the production of an ester.

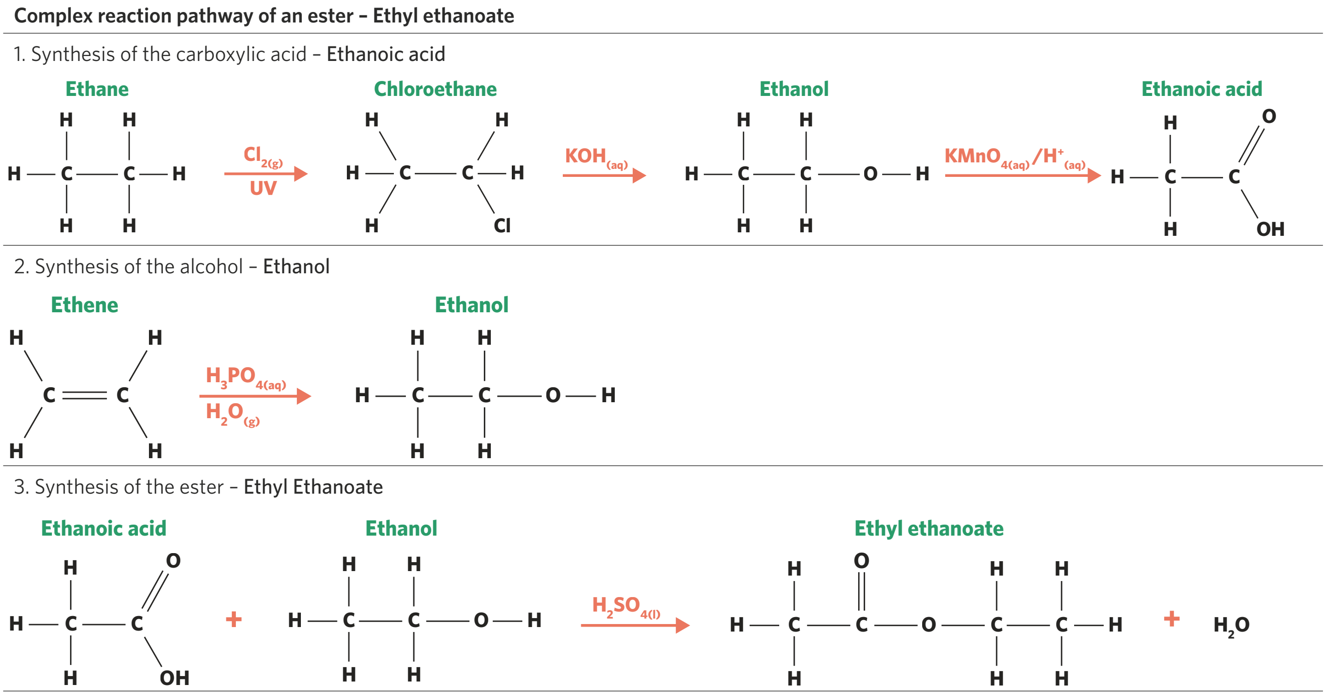


Figure 13 Complex reaction pathway to produce ethyl ethanoate from its most simple compound ethane, broken down into the three key reactions: synthesis of the carboxylic acid, synthesis of the alcohol and synthesis of the ester.

In order to produce the ester we want, we need to be able to work backwards from the desired product, which in the example above is ethyl ethanoate. Knowing that ethyl ethanoate is made from the reaction between ethanol and ethanoic acid, we need to develop reactions that can produce these two reactants. Steps 1 and 2 illustrate a pathway for the synthesis of the two reactants, which are then used in step 3 to produce the final ester.

A summary of this complex reaction pathway is shown in figure 14, reflecting the reactions required to synthesise a product from simple compounds. Remember, this is just one pathway that can be used because depending on what the starting products are, there are many organic pathways.

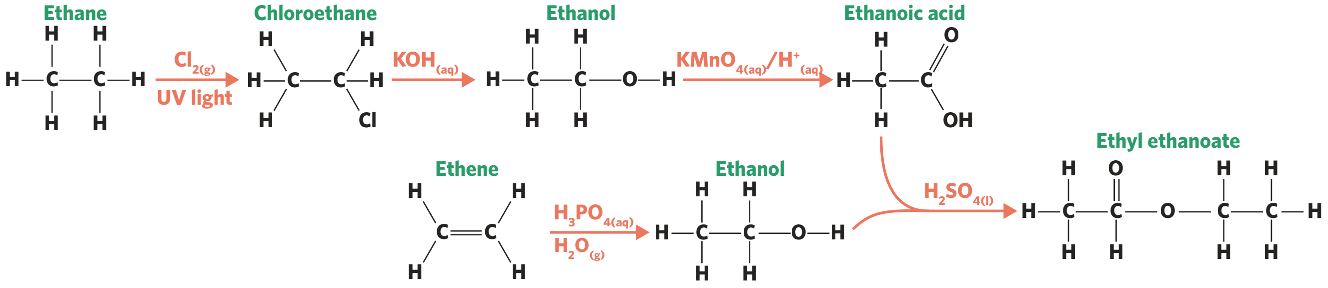


Figure 14 Summary of the complex reaction pathway from ethane and ethene to form ethyl ethanoate

In order to propose a reaction pathway there are a few questions that need to be asked and factors considered.

- What are our starting reactants?
- What are our desired products?
- Are there any reactions where one or more products are formed, therefore needing to be separated? For example, the substitution reaction between bromine gas and ethane can result in bromomethane, 1,2-dibromomethane, 1,1-dibromomethane, and the list goes on.

Reaction pathways can therefore be used to help chemists create products with desired properties by devising a sequence of reactions to convert a reactant to that product. Figure 15 is a flowchart that represents the production of other types of organic compounds.

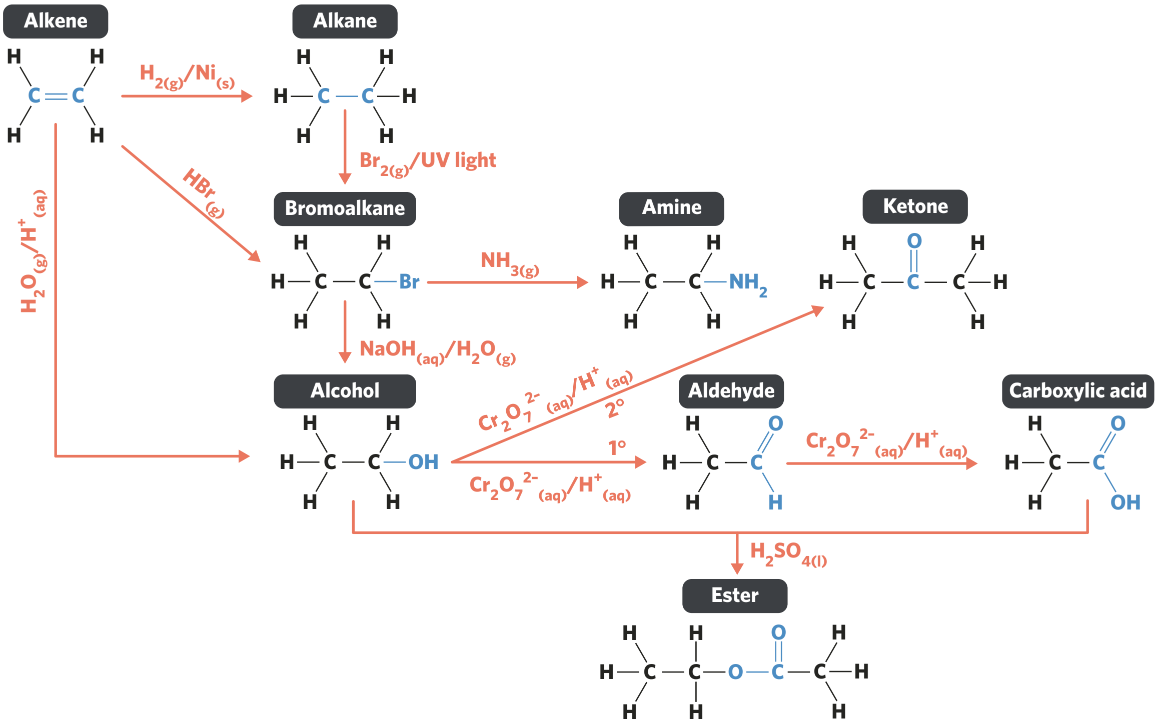


Figure 15 Summary of the possible pathways to produce different types of organic compounds

Efficiency of reactions 4.1.6.2

OVERVIEW

Reactions are rarely 100% efficient but there are tools that can be used to evaluate the efficiency of a chemical reaction.

THEORY DETAILS

An assumption that is often made in the early years of science is that all of the reactants added into a chemical reaction are consumed and result in the products as stated by the chemical equation. Based on what we have learned so far involving the concept of equilibrium, we know that this is not the case. In order to take this into account, we are able to use our understanding of chemical concepts to increase the efficiency of reactions.

There are different methods that can be used to evaluate the efficiency of a chemical reaction.

Atom economy

Since multiple products are sometimes formed in a reaction, not all of the atoms in the reactant species are involved in the production of the desired product.

CH_3CH_2OH	+	CH_3CH_2COOH	→	$CH_3CH_2COOCH_2CH_3$	+	H_2O
ethanol	+	propanoic acid	→	ethyl propanoate	+	water

Consider the esterification reaction above involving ethanol and propanoic acid. The purpose of the reaction is to produce ethyl propanoate, however water is also released as part of the reaction and is considered a by-product. As a result, we can see that not all of the atoms involved in the reaction resulted in the desired product. By comparing the relative atomic mass of the constituent atoms of both the reactants and desired product, we are able to quantitatively determine the **atom economy** of the reaction.

CH_3CH_2OH	+	CH_3CH_2COOH	→	$CH_3CH_2COOCH_2CH_3$	+	H_2O
ethanol	+	propanoic acid	→	ethyl propanoate	+	water

M(Reactants)	M(ethyl propanoate)
$= 46 + 74\ g\ mol^{-1}$	$= 102\ g\ mol^{-1}$
$= 120\ g\ mol^{-1}$	

$$\%\ \text{atom economy} = \frac{\text{Mass of atoms of desired product}}{\text{Mass of atoms of reactants used}} \times 100$$

$$= \left(\frac{102}{120}\right) \times 100$$

$$= 85\%$$

⋆M is a symbol used to represent 'molar mass'.

The concept of atom economy is useful when planning for chemical reactions; we want reactions to minimise 'waste' and maximise the desired product. This is particularly important in making chemical reactions as sustainable and environmentally friendly as possible.

Another method that can be used to evaluate the efficiency of chemical reactions is to determine the yield of a chemical reaction.

Yield of reactions

Unlike atom economy of a reaction, yield is calculated based on what is produced as a result of conducting an experiment. Calculations based on balanced chemical equations using values that aren't derived from an experiment show the ideal outcome of a chemical reaction and are therefore theoretical values; referred to as our theoretical yield. We can compare the **theoretical yield** with the results obtained from conducting the experiment, the **actual yield** or **experimental yield**, to determine the overall percentage yield of a chemical reaction.

$$\%\ \text{yield} = \frac{\text{actual yield}}{\text{theoretical yield}}$$

This formula can be found in the data book.

1 Worked example

During a combustion reaction, 90.2 g of propene reacted to form 210.4 g of carbon dioxide.

$2C_3H_{6(g)} + 9O_{2(g)} \rightarrow 6CO_{2(g)} + 6H_2O_{(g)}$

Calculate the percentage yield of the combustion reaction.

What information is presented in the question?

90.2 g propene used

210.4 g carbon dioxide produced

What is the question asking us to do?

Find the percentage yield of the reaction.

What strategy(ies) do we need in order to answer the question?

1. Determine the theoretical yield of carbon dioxide
2. Compare with the actual yield of carbon dioxide
3. Determine the overall percentage yield

Answer

Theoretical yield of carbon dioxide

$$n(C_3H_6) = \frac{90.2\ g}{42.0\ g\ mol^{-1}}$$

$$= 2.148\ mol$$

$n(C_3H_6) : n(CO_2) = 2 : 6$

$2.148\ mol : x$

$$n(CO_2) = \frac{2.148\ mol}{2} \times 6 = 6.444\ mol$$

$$m(CO_2) = 6.444\ mol \times 44.0\ g\ mol^{-1}$$

$$= 283.54\ g$$

Actual yield of carbon dioxide = 210.4 g

Overall percentage yield:

$$\%\ \text{yield} = \frac{210.4\ g}{283.54\ g} = 74.2\%\ \text{correct to 3 sig figs}$$

As seen in the worked example, often reactions do not give us 100% yield. This can be due to factors such as:

- Reactants/products 'lost' throughout the experimental process
- In the case of equilibrium reactions, they do not proceed to completion
- The rate of the reaction may be too slow for the reaction to go towards completion
- For multi-step processes, inefficiencies during the intermediate phases can have a huge impact on the percentage yield of the overall reaction.

This leads us to the next idea that if we want to calculate the overall percentage yield of a large reaction pathway, requiring many steps, the overall percentage yield is the product of the individual percentage yields for each step in the process.

$$\%\text{ yield} = \frac{\text{actual yield for step 1}}{\text{theoretical yield for step 1}} \times \frac{\text{actual yield for step 2}}{\text{theoretical yield for step 2}} \ \ldots$$

(for all the steps in the reaction pathway)

Due to this, it is important for us to have a deep understanding of chemical reactions and factors affecting the overall reaction in order to make sure waste is minimised and yield is as close to 100% as possible.

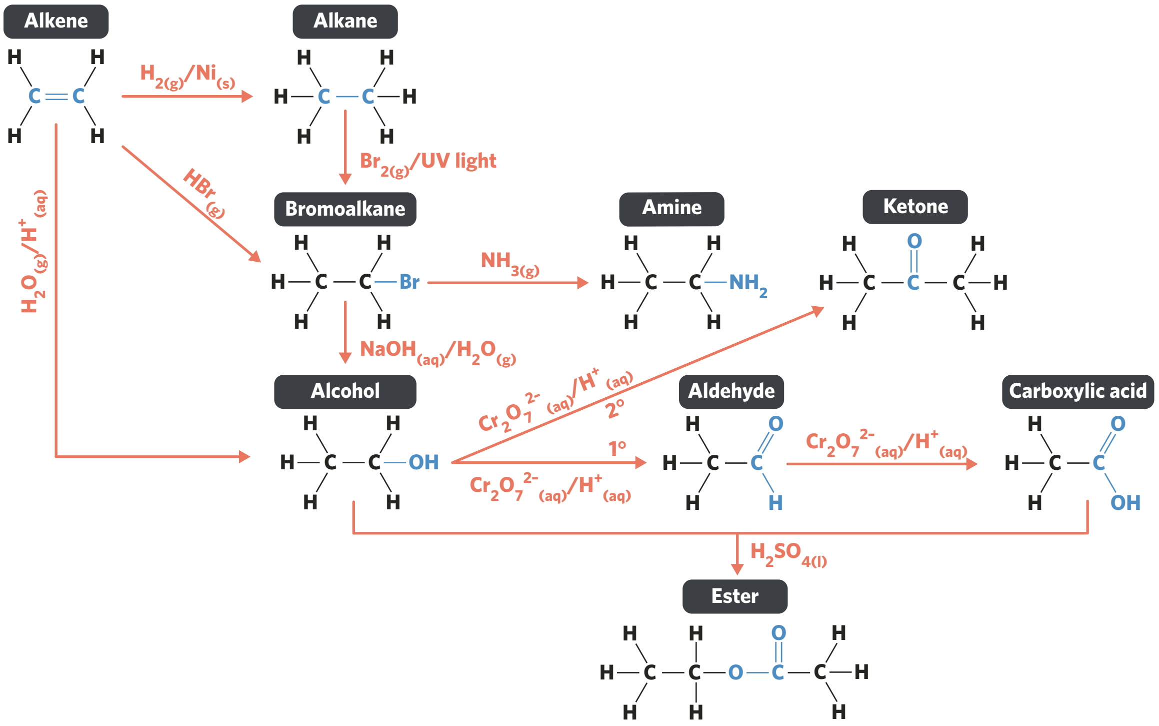
Theory summary

- Alcohols can be oxidised in different ways.
  - Primary alcohols are oxidised to aldehydes first, then further to carboxylic acids.
  - Secondary alcohols are oxidised to ketones.
  - Tertiary alcohols do not undergo oxidation.
- Substitution reactions occur between alkanes and halogens, producing haloalkanes, in the presence of ultraviolet light. Alcohols are produced from a substitution reaction with a haloalkane and the hydroxide ion/water. Amines are produced from a substitution reaction with a haloalkane and ammonia.
- Alkenes undergo addition reactions with H_2 to produce saturated alkanes. Alkenes also undergo addition reactions to produce dihaloalkanes, haloalkanes and alcohols, with different reactants.
- Hydrolysis reactions occur between esters and water to produce alcohols and carboxylic acids.
- Condensation reactions involve the loss of a small molecule like water when two compounds react. When carboxylic acids react with ammonia, primary amides are formed and when they react with primary amines, secondary amides are formed.
- Esterification reactions occur when a carboxylic acid reacts with an alcohol to produce an ester and water, in the presence of an acid catalyst.
- Reaction pathways indicate the sequence of reactions required to convert a reactant, or number of reactants, to a product.
- Efficiency of reactions can be determined by their atom economy and yield.

7F QUESTIONS

Theory review questions

Question 1



Based on the reaction pathway shown above, the reaction involved in producing a haloalkane and/or alcohol from an alkene is an example of what type of reaction?

A Addition **B** Subtraction **C** Substitution **D** Esterification

Question 2

Which of the following statements is true for both atom economy and percentage yield of a reaction?

I Both compare the results from an experiment and theoretical values.

II Both involve calculations based on theoretical reaction conditions.

III Both require experimental data.

A I only

B II only

C I & III only

D II & III only

Question 3

Esterification reactions can be considered to be a subset of which type of reaction?

A Substitution

B Hydrolysis

C Polymerisation

D Condensation

Question 4

The process involved in producing a ketone from an alcohol is referred to as

A substitution.

B oxidation.

C reduction.

D polymerisation.

Exam-style questions

Within lesson

Question 5 (1 MARK)

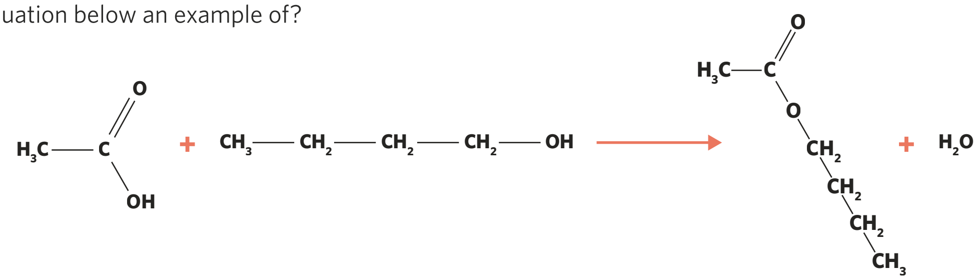
What type of reaction is the equation below an example of?

A Hydrolysis

B Addition

C Condensation

D Hydrolytic reaction



Question 6 (1 MARK)

In which of the following reactions is the atom economy of the production of ethanol 51%?

A $C_2H_{4(aq)} + H_2O_{(l)} \rightarrow C_2H_5OH_{(aq)}$

B $C_6H_{12}O_{6(aq)} \rightarrow 2C_2H_5OH_{(aq)} + 2CO_{2(g)}$

C $C_2H_5Cl_{(aq)} + NaOH_{(aq)} \rightarrow C_2H_5OH_{(aq)} + NaCl_{(aq)}$

D $C_2H_5NH_{2(aq)} + HNO_{2(aq)} \rightarrow C_2H_5OH_{(aq)} + H_2O_{(l)} + N_{2(g)}$

Adapted from VCAA 2018 Northern Hemisphere Chemistry exam MCQ 13

Question 7 (1 MARK)

Glucose undergoes fermentation in the presence of yeast to produce ethanol.

$C_6H_{12}O_{6(aq)} \rightarrow 2C_2H_5OH_{(aq)} + 2CO_{2(g)}$

What is the percentage yield of ethanol for this reaction?

A 26.9%

B 50.0%

C 52.6%

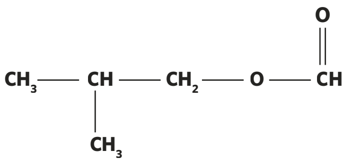
D 100%

Data	
Species	**Mass**
$C_6H_{12}O_6$	6.14 g
C_2H_5OH	1.65 g
CO_2	2.0 g

Question 8 (4 MARKS)

Esters can be used to flavour food. The structure shown is an ester that is used as raspberry flavouring.

Give the **name** and **draw** the structures of the two compounds that reacted to produce this ester.



$CH_3-CH(CH_3)-CH_2-O-CH{=}O$

Question 9 (4 MARKS)

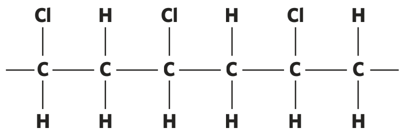
Butene can be used to produce low density plastics.

a Draw the reaction that occurs when but-2-ene is reacted with bromine. (1 MARK)

b Identify the type of reaction that has occurred. (1 MARK)

c Will the products be the same if but-1-ene was reacted with bromine? Explain. (2 MARKS)

Question 10 (2 MARKS)



The structure shown is that of a polymer resulting from an addition reaction.

a Draw the structure of the monomer used to produce this polymer. (1 MARK)

b Give the name of this monomer. (1 MARK)

Question 11 (2 MARKS)

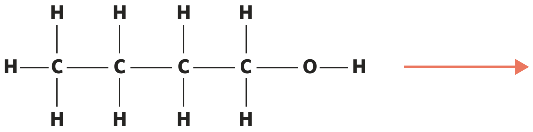
Chloromethane can be produced by a substitution reaction between methane and chlorine gas.

Calculate the atom economy of this reaction.

Question 12 (4 MARKS)

The production of a carboxylic acid from an alcohol requires a 2 step process.

a Draw the structural formula for the aldehyde that is formed as a result of the oxidation of the molecule below. (1 MARK)



b The product from the previous reaction underwent further oxidation. Fill in the blanks with the appropriate molecular formulas to complete the reaction. (2 MARKS)

$$\boxed{} \xrightarrow[H_2SO_4]{\boxed{}} CH_3CH_2CH_2COOH$$

c Name the product formed from this reaction. (1 MARK)

Question 13 (3 MARKS)

Complete the following reaction by

$$C_2H_4 + ? \longrightarrow C_2H_5OH \xrightarrow{\text{Reagent}} CH_3COOH$$

a writing the formula for the reactant . (1 MARK)

b classifying the type of reaction. (1 MARK)

c providing an appropriate reagent. (1 MARK)

Question 14 (6 MARKS)

The reaction pathway below represents the synthesis of an ester.

$$CH_3CH_3 \xrightarrow[Cl_{2(g)},\ \text{UV light}]{\text{Step 1}} \text{Compound A} \xrightarrow[\text{Reagent A}]{\text{Step 2}} CH_3CH_2OH \xrightarrow[Cr_2O_7{}^{2-}{}_{(aq)}/H^+]{\text{Step 3}} \text{Compound B} + CH_3CH_2OH \xrightarrow[\text{Reagent B}]{\text{Step 4}} CH_3COOCH_2CH_3$$

a Identify reagents A and B. (2 MARKS)

b Write the semi-structural formulas for compounds A and B. (2 MARKS)

c What type of reaction is occuring in Step 3? (1 MARK)

d Name the final product of this reaction pathway. (1 MARK)

Multiple lessons

Question 15 (3 MARKS)

A student performs an experiment where the primary alcohol pentan-1-ol is oxidised in the presence of potassium dichromate to form the aldehyde $C_5H_{10}O$.

a If the $Cr_2O_7{}^{2-}$ ion is reduced to Cr^{3+}, write the half equations for the reduction and oxidation reactions occurring. (2 MARKS)

b When the student attempts this experiment, no aldehyde is formed but rather a carboxylic acid. Aside from limiting the amount of heat and removing the aldehyde produced, suggest another possible way that the student could increase the production of the aldehyde rather than the carboxylic acid. (1 MARK)

Question 16 (6 MARKS)

Sulfur trioxide is a useful molecule as it is often used to produce sulfuric acid. The equilibrium reaction to produce sulfur trioxide is shown below.

$2SO_{2(g)} + O_{2(g)} \rightleftharpoons 2SO_{3(g)}$ $\Delta H = -180$ kJ mol^{-1}

a Given that this reaction has a percentage yield of 73%, determine the mass of sulfur trioxide that is actually produced if 2.57 g of sulfur dioxide was used in the reaction. (2 MARKS)

b In an attempt to increase the yield of this reaction, it was suggested that the temperature of the reaction be increased without making any changes to the volume of the vessel. Explain the effect of an increase in temperature on the yield of this reaction ignoring the effects of pressure. (3 MARKS)

c What is the type of reaction occuring in the forward direction? (1 MARK)

EXPERIMENT

OXIDATION OF ALCOHOLS

Alcohols can be oxidised to produce aldehydes and ketones.

The rate of a reaction can give an indication as to the product produced during the reaction in the presence of an acid.

During the reaction, the dichromate ions are reduced to chromium ions.

This results in the solution changing from an orange to a green colour.

Materials

(per group)

- 5 micro test tubes
- 1 micro test tube stand
- 0.1 M potassium dichromate solution
- 1 M sulfuric acid
- Ethanol
- Propan-1-ol
- Propan-2-ol
- 4 × Pasteur pipettes
- 10 mL measuring cylinder

Method

1. Using the measuring cylinder, measuring 2 mL of 0.1 M potassium dichromate into a microtest tube.
2. Measure and add 1.0 mL of sulfuric acid into the test tube containing potassium dichromate. Stir well.
3. Label the remaining micro test tubes A–D.
4. Using a pasteur pipette, add 10 drops of the potassium dichromate/sulfuric acid solution to each micro test tube.
5. Using a new pipette, add 2 drops of ethanol to test tube A.
6. Using a new pipette, add 2 drops of propan-1-ol to test tube B.
7. Using a new pipette, add 2 drops of propan-2-ol to test tube C.
8. Observe the micro test tubes for 10–15 mins and record any changes.

Results

	Test tube A (+ ethanol)	**Test tube B (+ propan-1-ol)**	**Test tube C (+ propan-2-ol)**	**Test tube D (no treatment)**
Observations				

QUESTIONS

Question 1 (1 MARK)

What is the independent variable for this experiment?

Question 2 (3 MARKS)

a What is the purpose of micro test tube D in this experiment? (1 MARK)

b Explain the importance of micro test tube D. (2 MARKS)

Question 3 (3 MARKS)

a Write a balanced half-equation to show the reduction of dichromate ions during this reaction.

b Write a full balanced equation to represent the partial oxidation reaction occurring in test tube A.

c Draw the structural formula for the product of this reaction.

Question 4 (2 MARKS)

Compare the rate of reaction between test tubes B & C.

What does this suggest about the rate of reactions of the oxidation of different alcohols?

ANSWERS

1 The alcohol used in the reaction

2 **a** Micro test tube D acts as a control for the experiment.

✓ ✗ I've identified the role of test tube D.

b [Every experiment requires a control as it acts as a point of comparison for the results obtained for the experiment.[1]][Without a control, we would be unable to relate the results obtained to the variable being tested in the experiment.[2]][The control also minimizes the chance that other variables can affect the experiment.[3]]

✓ ✗ I have identified the role of a control.[1]

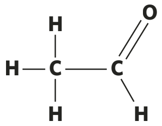
✓ ✗ I have explained the importance of a control on the results.[2]

✓ ✗ I have identified the impact of a control on the reliability of the results.[3]

3 **a** $Cr_2O_7{}^{2-}{}_{(aq)} + 14H^+{}_{(aq)} + 6e^- \rightarrow 2Cr^{3+}{}_{(aq)} + 7H_2O_{(l)}$

b $3CH_3CH_2OH_{(l)} + Cr_2O_7{}^{2-}{}_{(aq)} + 8H^+{}_{(aq)} \rightarrow 3CH_3CHO_{(aq)} + 2Cr^{3+}{}_{(aq)} + 7H_2O_{(l)}$

c



4 [Test tube B turned green before test tube C.[1]][As a result, it can be seen that the oxidation of propan-1-ol occurs at a faster rate than propan-2-ol.[2]]

✓ ✗ I have used the results in the experiment to compare test tubes B and C.[1]

✓ ✗ I have identified the relationship between the rate of reaction and the type of alcohol being oxidised.[2]

NOTE: The exemplar answer above assumes that the reaction of test tube B occurs quicker than test tube C. If your results show the opposite trend, then this should be highlighted in the answer. The checklist would still be valid to check your answer.

CHAPTER 7 QUESTIONS

MULTIPLE CHOICE (10 MARKS)

Question 1 (1 MARK)

Which of the following does **not** contain a chiral carbon?

	Name	Formula
A	2-chlorobutane	$CH_3CHClCH_2CH_3$
B	Lactic acid	$CH_3CH(OH)COOH$
C	Alanine	NH_2CHCH_3COOH
D	Propanoic acid	CH_3CH_2COOH

Question 2 (1 MARK)

Which statement below is correct about the structure of alkanes?

A An alkane is an unsaturated hydrocarbon.

B Alkanes only have single carbon bonds in their structures.

C The general formula for alkanes is C_nH_{2n}.

D Alkanes have single and double carbon bonds in their structures.

Question 3 (1 MARK)

Which one of the following compounds can exist as *cis*- and *trans*- isomers?

A CH_2CH_2

B CH_2CHCH_3

C $CH_3CHCHCH_3$

D $CH_3(CH_2)_{16}COOH$

Question 4 (1 MARK)

The systematic name of $CH_3CH(CH_3)CCl(Cl)CH_2CH_3$ is

A 3,3-dichloro-2-methylpentane

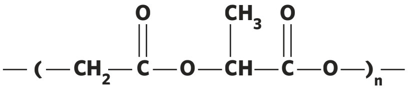
B 2-chloro-2-methylpentane

C 3,3-dichloro-5-methylpentane

D 2,2-dichlorohexane

Question 5 (1 MARK)

The medical field uses stitches that are biodegradable polymers so that patients don't have to come back post-surgery. An example of a biodegradable polymer can be seen below.



$$-(-CH_2-\overset{O}{\overset{\|}{C}}-O-\overset{CH_3}{\overset{|}{CH}}-\overset{O}{\overset{\|}{C}}-O-)_n-$$

The monomers that make up this polymer are:

A $HOCH_2COOH$ and $HOCH(CH_3)COOH$

B CH_2CO and $OCH(CH_3)COO$

C CH_2COO and $CH(CH_3)COO$

D $COOCH(CH_3)$ and COO

Adapted from VCAA 2007 Exam, MCQ10

Question 6 (1 MARK)

Which one of the following reactions has the highest percentage atom economy for the production of ethanol, C_2H_5OH?

A $C_2H_5NH_{2(aq)} + HNO_{2(aq)} \rightarrow C_2H_5OH_{(aq)} + H_2O_{(l)} + N_{2(g)}$

B $C_6H_{12}O_{6(aq)} \rightarrow 2C_2H_5OH_{(aq)} + 2CO_{2(g)}$

C $C_2H_5Cl_{(aq)} + NaOH_{(aq)} \rightarrow C_2H_5OH_{(aq)} + NaCl_{(aq)}$

D $C_2H_{4(aq)} + H_2O_{(l)} \rightarrow C_2H_5OH_{(aq)}$

Adapted from the VCAA 2018 NHT exam, MCQ 13

Question 7 (1 MARK)

Which one of the following molecules does **not** contain a chiral carbon?

A $CH_3CH_2CFClCH_2CH_3$

B $CH_3CH_2CHBrCl$

C $CH_3CHOHCH_2CH_3$

D $CH_3CHFCH_2CH_3$

Question 8 (1 MARK)

What is the name of the product formed when chlorine, Cl_2, reacts with pent-2-ene?

A 1,2-dichloropentane

B 1,4-dichloropentane

C 2,2-dichloropentane

D 2,3-dichloropentane

Question 9 (1 MARK)

The number of structural isomers of C_4H_9Br is

A 3

B 4

C 5

D 6

Question 10 (1 MARK)

Which of these is **not** the correct IUPAC nomenclature for an isomer of 1-chloropent-2-ene?

A 4-chloropent-2-ene

B 3-chloropent-1-ene

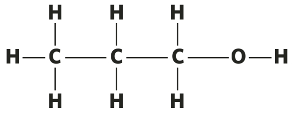
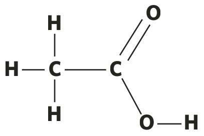
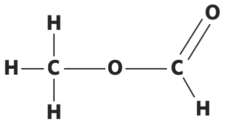
C 5-chloropent-1-ene

D 1-chloropent-3-ene

SHORT ANSWER (32 MARKS)

Question 11 (5 MARKS)

The following table shows a comparison of three different organic compounds.

Compound	Structural formula	Molecular weight	Boiling point
X		60	97°C
Y		60	118°C
Z		60	?

Adapted from the HSC 2010 Chemistry exam, MCQ 14

a Identify the name of compounds X, Y and Z. (1 MARK)

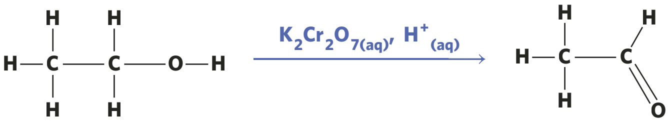
b Using the information in the table, identify whether the boiling point for compound Z would be (1 MARK)

- **A** less than 97 °C.
- **B** between 97 °C and 118 °C.
- **C** more than 118 °C.

c Explain why you chose your answer for b. (3 MARKS)

Question 12 (2 MARKS)

Given the following reaction:



a Give the name for this type of reaction. (1 MARK)

b Identify the functional group of the product in the chemical reaction. (1 MARK)

Question 13 (3 MARKS)

Esters give off an aroma that is specific to their structure. Given that $CH_3CH_2CH_2COOH$ was a reactant in an esterification reaction:

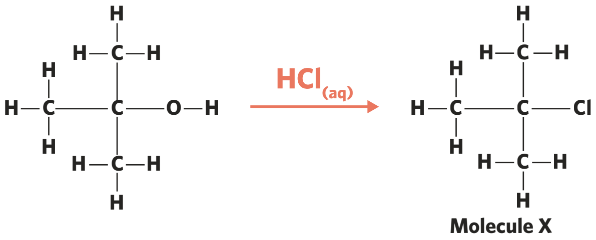
a Write a balanced chemical equation for the reaction of $CH_3CH_2CH_2COOH$ with ethanol using the semi-structural formulas for all organic compounds. (1 MARK)

b Write the IUPAC name for the ester produced. (1 MARK)

c Identify the type of reaction occurring. (1 MARK)

Question 14 (2 MARKS)

2-methylpropene is a colourless flammable gas at room temperature. The diagram below outlines one step in the reaction pathway for the formation of 2-methylpropene.

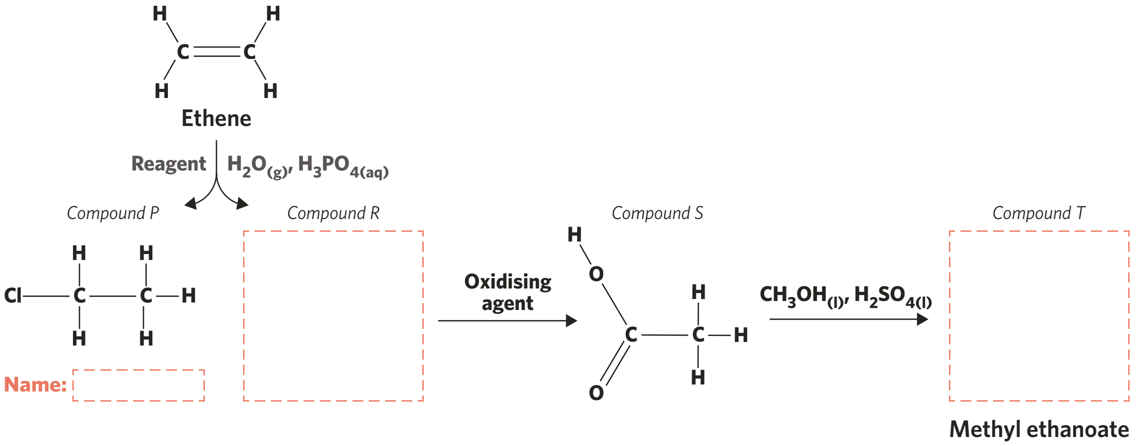


a Identify the type of reaction occurring. (1 MARK)

b State the systematic name for 'Molecule X'. (1 MARK)

Question 15 (3 MARKS)

Alkenes can be used to manufacture a range of products. The reaction pathway diagram below represents one example involving ethene. In this reaction pathway, ethene is used to produce compound P and compound R. compound R can then be used to produce compound S and further to produce compound T. Complete the following in the appropriate boxes in the reaction pathway diagram provided.



a Give the IUPAC systematic name for Compound P. (1 MARK)

b Write the formulas of the reagent required to produce Compound P and the substance used to produce Compound S. (1 MARK)

c Draw the structural formula of Compound R and Compound T. (1 MARK)

Question 16 (4 MARKS)

a Give the systematic names of the alcohol and the carboxylic acid that are required to synthesise ethyl ethanoate. (2 MARKS)

b Write a balanced chemical equation for the synthesis of ethyl ethanoate, using the semi-structural formula for the reactants and products. (1 MARK)

c Identify a method that can be used to confirm that the ester produced is ethyl ethanoate. (1 MARK)

Question 17 (5 MARKS)

Industrially, ethanol (C_2H_5OH) is made by either one of two methods. One method uses a sugar, such as sucrose ($C_{12}H_{22}O_{11}$) and yeast in aqueous solution. The production of ethanol from sucrose and yeast proceeds according to the equation:

$$C_{12}H_{22}O_{11(aq)} + H_2O_{(l)} \rightarrow 4C_2H_5OH_{(aq)} + 4CO_{2(g)}$$

a Determine the mass, in grams, of pure C_2H_5OH that would be produced from 1.5 kg of $C_{12}H_{22}O_{11}$ dissolved in water. $M(C_{12}H_{22}O_{11}) = 342.0 \text{ g mol}^{-1}$ (2 MARKS)

The other method involves the use of ethene (C_2H_4), which is derived from crude oil.

$$C_2H_{4\,(g)} + H_2O_{\,(g)} \xrightarrow{\text{CATALYST}} \mathbf{X} \xrightarrow{MnO_4^-{}_{(aq)}\,/\,H^+{}_{(aq)}} CH_3COOH_{(g)}$$

b Write the semi-structural formula for 'X'. (1 MARK)

c Identify the two types of reactions occurring in the overall reaction. (1 MARK)

d Identify an appropriate catalyst for the first reaction. (1 MARK)

Question 18 (4 MARKS)

A truck driver has just been testing two different trucks running on two different fuel sources: petrodiesel and biodiesel.

When he was driving his biodiesel truck through a cold region, he noticed that the fuel wasn't flowing along the fuel line as well when compared to a warmer region.

a With reference to viscosity and flow along fuel lines, suggest a reason why this was the case. (2 MARKS)

b He also discovered that biodiesel has a higher boiling point and is more viscous than petrodiesel. Using your knowledge of structure and bonding, explain this difference in viscosity and boiling point. (2 MARKS)

Question 19 (4 MARKS)

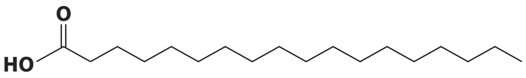
Olive oil contains a mixture of saturated and unsaturated hydrocarbons known as fatty acids. A way in which scientists can determine the structure of these unsaturated fatty acids is to react the compound with iodine (I_2). This results in an addition reaction.

30.30 g of an unsaturated hydrocarbon found in olive oil was reacted with 54.92 g of iodine. The molar mass of this fatty acid is 280.0 g mol^{-1}.

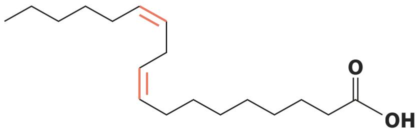
a Calculate the number of double bonds present in the unsaturated fatty acid. (3 MARKS)

b Which of the following compounds could be the skeletal formula for the fatty acid? (1 MARK)

A



B



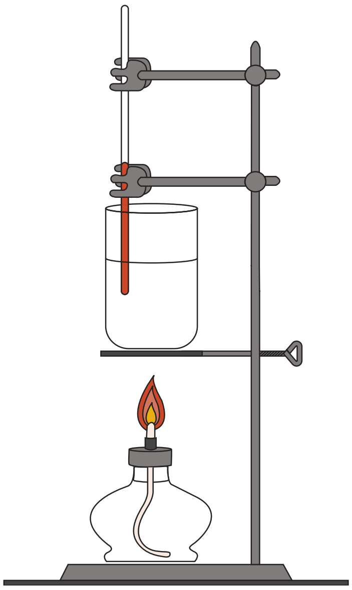
KEY SCIENCE SKILL QUESTION

Question 20 (5 MARKS)

A chemistry class was asked to conduct an experiment to determine the effect of molecular structure on the properties of organic compounds. Each pair of students was given two samples of organic compounds both with the molecular formula of C_5H_{12} but with different structures.

Materials

- Retort stand
- 2 x clamps
- 1 pre calibrated thermometer
- 250 mL beaker
- Bunsen burner
- Sample A
- Sample B
- 2 x test tubes
- Measuring cylinder



The experimental setup can be seen in the figure on the right.

Method

1 Place 2 mL of sample A into a test tube and attach it to the retort stand via a clamp.
2 Fill a beaker with 150 mL of water and place on a stand above the bunsen burner.
3 Slowly lower the test tube into the beaker making sure that it does not touch the bottom of the beaker.
4 Place a thermometer into the test tube and hold it in place via a clamp attached to the retort stand.
5 Turn on the bunsen burner and keep it on until the sample boils.
6 Turn off the bunsen burner and record the temperature.
7 Repeat steps 1–6 for sample B.

Results

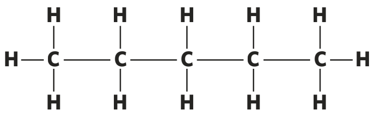
	Sample A	**Sample B**
Boiling point	31.1 °C	10.2 °C

a Identify the dependent variable in this experiment. (1 MARK)

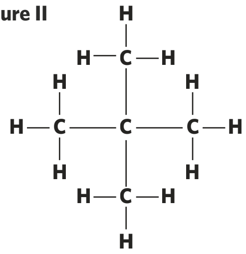
b Identify a systematic error that could occur during this experiment. (1 MARK)

The students were shown these two molecular structures and told that each structure represented one of the samples used.

Structure I

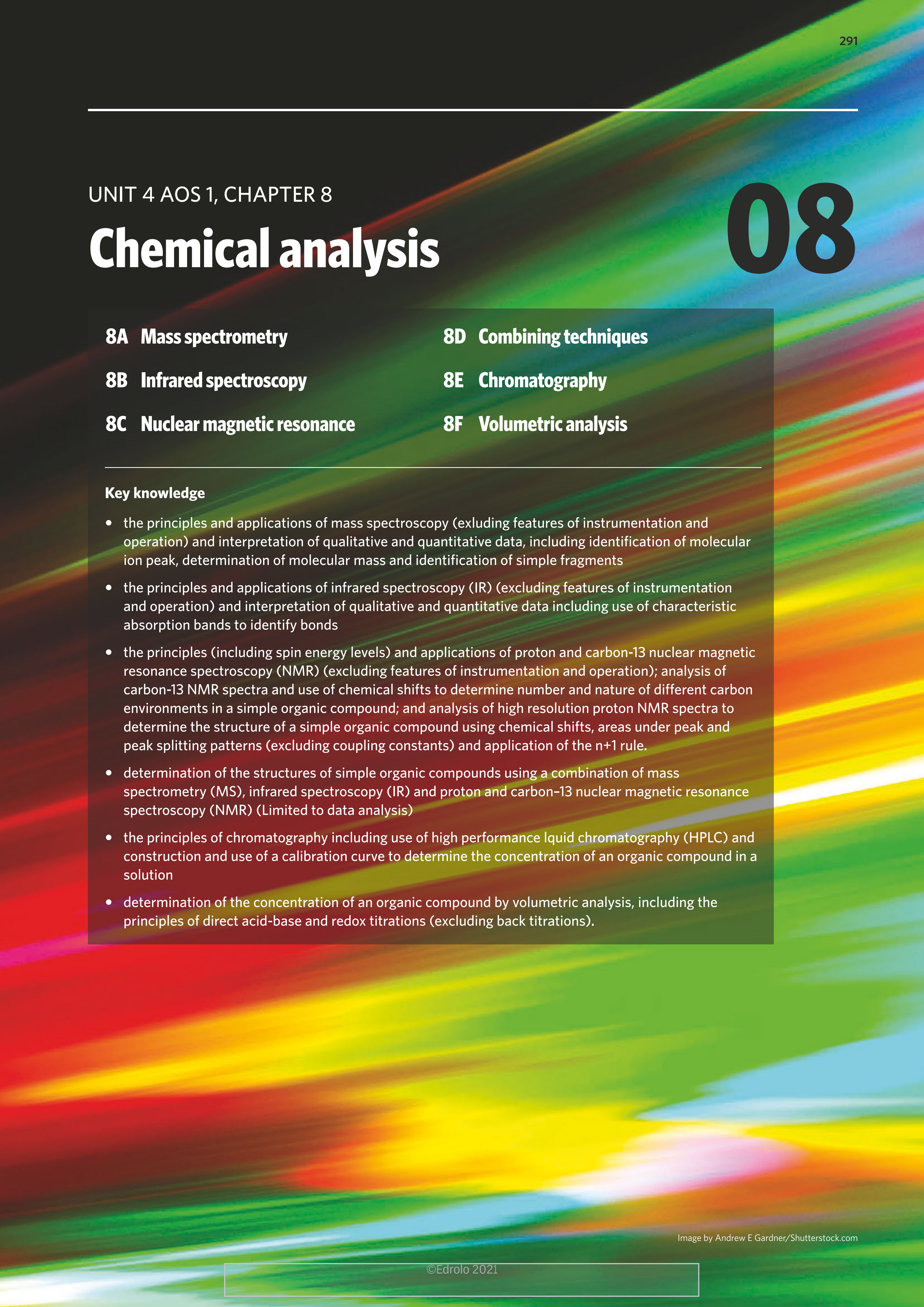


Structure II



c Based on the results, which of the structures would belong to sample A and B? Explain. (2 MARKS)

d Identify the systematic names of both structures. (1 MARK)



UNIT 4 AOS 1, CHAPTER 8

Chemical analysis

08

Key knowledge

- the principles and applications of mass spectroscopy (exluding features of instrumentation and operation) and interpretation of qualitative and quantitative data, including identification of molecular ion peak, determination of molecular mass and identification of simple fragments
- the principles and applications of infrared spectroscopy (IR) (excluding features of instrumentation and operation) and interpretation of qualitative and quantitative data including use of characteristic absorption bands to identify bonds
- the principles (including spin energy levels) and applications of proton and carbon-13 nuclear magnetic resonance spectroscopy (NMR) (excluding features of instrumentation and operation); analysis of carbon-13 NMR spectra and use of chemical shifts to determine number and nature of different carbon environments in a simple organic compound; and analysis of high resolution proton NMR spectra to determine the structure of a simple organic compound using chemical shifts, areas under peak and peak splitting patterns (excluding coupling constants) and application of the n+1 rule.
- determination of the structures of simple organic compounds using a combination of mass spectrometry (MS), infrared spectroscopy (IR) and proton and carbon–13 nuclear magnetic resonance spectroscopy (NMR) (Limited to data analysis)
- the principles of chromatography including use of high performance lquid chromatography (HPLC) and construction and use of a calibration curve to determine the concentration of an organic compound in a solution
- determination of the concentration of an organic compound by volumetric analysis, including the principles of direct acid-base and redox titrations (excluding back titrations).

Image by Andrew E Gardner/Shutterstock.com

8A MASS SPECTROMETRY

In this lesson, we will be learning about the principles of mass spectrometry and how it is used to quantitatively and qualitatively analyse samples.

8A Mass spectrometry	8B Infrared spectroscopy	8C Nuclear magnetic resonance	8D Combining techniques	8E Chromatography	8F Volumetric analysis

Study design dot point

- the principles and applications of mass spectroscopy (exluding features of instrumentation and operation) and interpretation of qualitative and quantitative data, including identification of molecular ion peak, determination of molecular mass and identification of simple fragments

Key knowledge units

Principles of mass spectrometry	4.1.7.1.1
Analysing mass spectra	4.1.7.1.2

Key terms and definitions

- **Mass-to-charge ratio, *m/z*** equal to the mass of a cation divided by its charge
- **Mass spectrometry** an analytical technique used to measure the mass-to-charge ratio of ions
- **Mass spectrometer** an instrument used to measure the mass-to-charge ratio of ions
- **Mass spectrum** a plot of the mass-to-charge ratio of ion fragments
- **Fragmentation** the dissociation of unstable molecular ions
- **Isotopes** two or more forms of the same element that have the same number of protons but different numbers of neutrons
- **Base peak** peak formed from ion fragment with the greatest relative intensity
- **Molecular ion peak** peak formed from the ionised un-fragmented form of a molecule

Lesson links

This lesson builds on:

- 7A – Structure of organic compounds

Mass spectrometry helps determine the structure of organic compounds by identifying simple fragments of the molecules.

Principles of mass spectroscopy 4.1.7.1.1

OVERVIEW

Mass spectrometry is an analysis tool commonly used to identify unknown samples using the unique mass spectrum each molecule produces.

THEORY DETAILS

Mass spectrometry analyses samples by measuring the **mass-to-charge ratio (m/z)** of a molecule in that sample. This information can be used to calculate the molecular weights of a sample's components which can then be used to identify unknown compounds and determine their physical structure. This technique can also be used to distinguish between isomers. Mass spectrometry is therefore used in a wide variety of contexts from environmental science to detecting toxins in contaminated fish and monitoring climate change by detecting the number and nature of airborne particles in the atmosphere. It can also be used with other analytical techniques like chromatography to analyse mixtures of substances, although it will be implemented last as it destroys the sample.

A **mass spectrometer** is the instrument in mass spectrometry that ionises, deflects and detects an atom or molecule so that its mass-to-charge ratio can be measured. The atom or molecule needs to be ionised as only positively charged particles are measured – not electrically neutral or negatively charged ones. It is important to note that these detected ions aren't necessarily a singular ion but could be fragments of the original molecule. This occurs in a four stage process in a mass spectrometer, whereby the compound is ionised, accelerated, deflected and finally detected at the end of the instrument, as shown in figure 1. However, in order for this process to occur the compound first has to be vaporised (converted to a gas state).

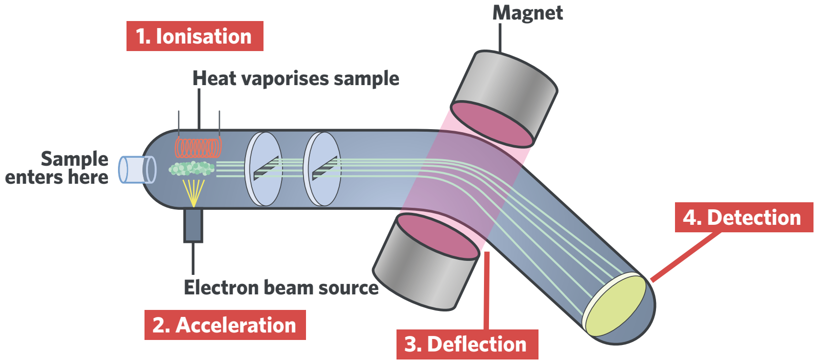


Figure 1 Diagram of a mass spectrometer

In stage 1, the atom or molecule is ionised by removing an electron to make a positive ion. It does this by first vaporising the sample, then bombarding it with a stream of electrons which collide with the sample and cause the molecules to become ionised. In stage 2, the ions are then accelerated so that they all have the same kinetic energy. In stage 3, an electromagnetic field is used to deflect ions, dependent upon their mass and charge. As a result, lighter ions and cations with a 2+ or greater charge are deflected more than heavier ions with lower charges. Combining these two characteristics, we get the mass/charge ratio, which appears on a graph known as a **mass spectrum**. From here, the ions can be detected in stage 4, as an electric current, which can be amplified and recorded. It is important to note that only positively charged ions are picked up by the detector and in turn displayed on the mass spectrum.

An example of the output from a mass spectrometer is shown in figure 2 as a mass spectrum, where the mass-to-charge ratio of ethanal, CH_3COH, is graphed as a function of the relative intensity measured by the mass spectrometer

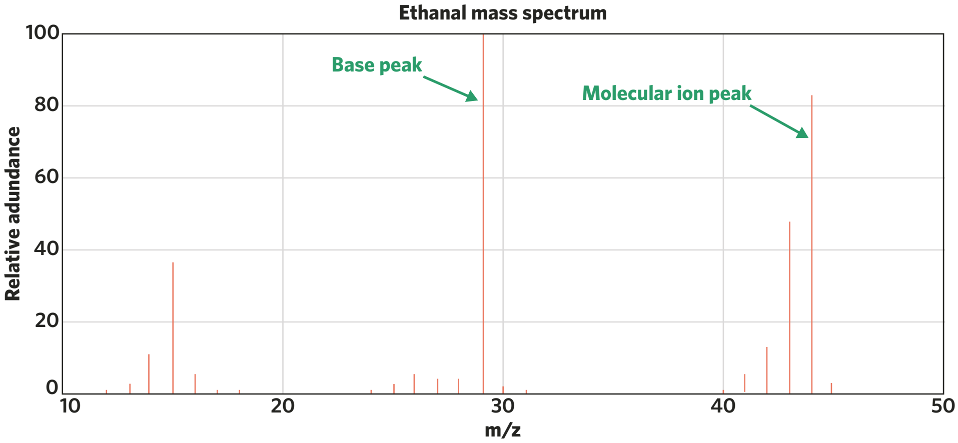


Figure 2 Mass spectrum of the molecule ethanal

The **molecular ion peak** is generated by a singly charged ion, or molecular ion. This occurs when a whole molecule becomes positively charged by losing an electron and produces the peak with the highest m/z. The un-fragmented form of ethanal will still have the molecular formula CH_3COH with a molar mass of 44 g mol^{-1} and so its molecular ion peak will also have a m/z ratio of 44.

Tip The m/z is essentially the same as the molecular/atomic mass of the molecule/atom.

If we look at this mass spectrum of ethanal shown in figure 2 we can identify what is known as the **base peak**, which represents the most intense peak. In this case the base peak is at m/z = 29. The base peak is produced by the most abundant ion, which is often created by a single split in the original compound and in some cases this is also the molecular ion. Since m/z ratios are equal to a fragment's molar mass, the base peak is likely to have been caused by a fragment with molecular formula COH as this has a molar mass of 29 g mol^{-1}. It is assigned a relative intensity of 100%, allowing the other peaks to be measured relative to this one. These relative intensities are dependent upon the energy of the ionising electrons, the stability of the fragmented ions and therefore the ease by which these fragments are formed.

However, molecular ions are energetically unstable so when they are in a mass spectrometer some of them may break up into smaller pieces (i.e. fragment) and this is shown where the m/z value is smaller than the molecular ion. **Fragmentation** can occur by breaking almost any bond in the molecular ion and so they could represent a single atom, a group of atoms or a larger section of the molecule.

$M^+ \rightarrow X^+ + R^{\cdot}$

Where M^+ represents the parent molecular ion, X^+ is a fragment, R is an akyl group and '.' represents an unpaired electron.

The table provided shows the common positively charged fragment ions of organic molecules with their corresponding m/z values.

It's important to always remember to assign a positive charge to each fragment present on the mass spectrum.

Table 1 Formula of common positive fragmented ions and their m/z values

Formula	m/z
CH_3^+	15
OH^+	17
$CH_3CH_2^+$, COH^+	29
CH_3O^+	31
$^{35}Cl^+$, $^{37}Cl^+$	35, 37
$CH_3CH_2CH_2^+$, CH_3CO^+	43
$COOH^+$	45
$^{79}Br^+$, $^{81}Br^+$	79, 81

Analysing mass spectra 4.1.7.1.2

OVERVIEW

Interpreting the mass spectrum of a molecule allows the identification of an unknown molecule based on its mass-to-charge ratio and fragments.

THEORY DETAILS

We can examine the mass spectrum of a molecule to determine the structure of the an unknown compound.

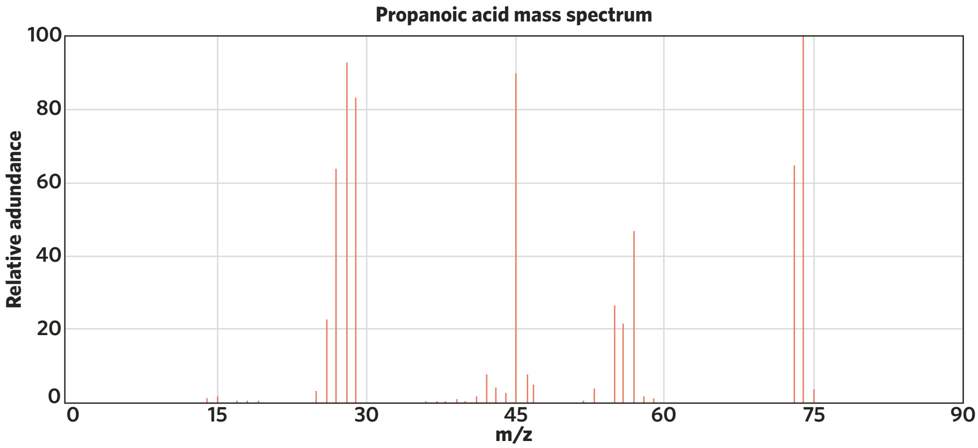


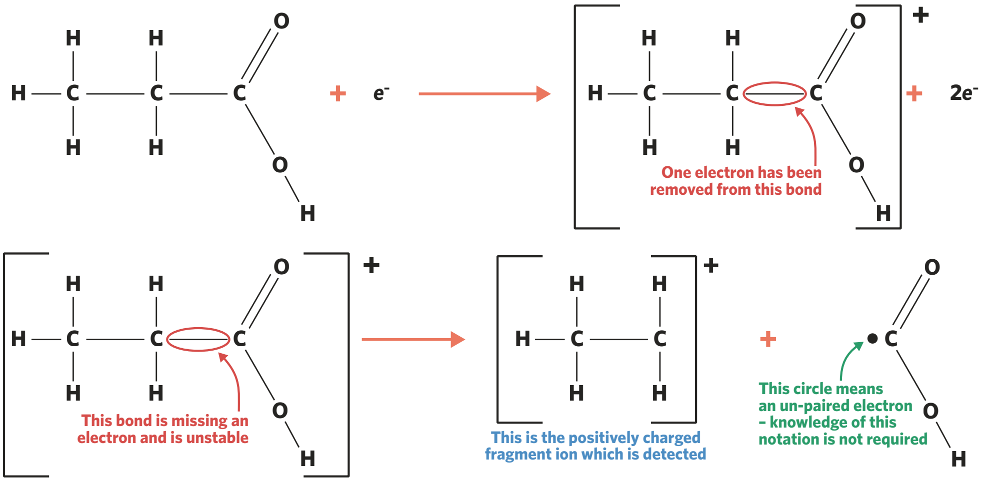
Figure 3 Mass spectrum of propanoic acid

Propanoic acid can be ionised in a mass spectrometer by bombarding it with electrons to remove an electron from the molecule in the following process:

$CH_3CH_2COOH + e^- \rightarrow CH_3CH_2COOH^+ + 2e^-$

Based on the values presented in the periodic table found in the databook, propanoic acid has a molecular mass of 74.0 g mol $^{-1}$. However, if we look at figure 3, we can see that the mass of the ion with the greatest m/z for propanoic acid is 75. Although the peak is relatively small, this may indicate that isotopes are involved and one such isotope is ^{13}C. This means that if a molecule of propanoic acid has a ^{13}C atom in it, it will have a relative atomic mass of 75 instead of 74. However, since the relative abundance of ^{13}C is much smaller than that of ^{12}C, this peak is usually negligible. This explains why we have a small peak at m/z = 75 and a much larger peak at m/z = 74, which is the true molecular ion peak of propanoic acid without a ^{13}C atom present.

The other peaks are the fragment ions which give us an indication of the structure of the propanoic acid molecule. Figure 4 is a structural representation of how other fragment ions can be produced and consequently appear as peaks in the mass spectrum for propanoic acid.



One electron has been removed from this bond

This bond is missing an electron and is unstable

This is the positively charged fragment ion which is detected

This circle means an un-paired electron – knowledge of this notation is not required

Figure 4 Structural equation for the electron bombardment and fragmentation of propanoic acid

As we can see in figure 4, electrons can bombard the bond between C1 and C2 in propanoic acid, resulting in the production of the positively charged fragment ion $CH_3\ CH_2^+$. This explains why we can see a peak at m/z = 29.

The appearance of additional peaks in the mass spectrum is not only due to positively charged fragments of that molecule but they can also be due to the presence of **isotopes** in the molecule. This is because isotopes of the same element differ in atomic mass.

If we look at the molecule 2-chloropropane ($CH_3CHClCH_3$), two peaks are shown for two molecular ions, one with an m/z ratio of 78 and the other with an m/z ratio of 80. This difference in ion peaks is due to the two isotopes of chlorine. The peak with the m/z ratio of 78 is due to the molecular ion that contains ^{35}Cl, whilst the peak with the m/z ratio of 80 contains the isotope ^{37}Cl.

Table 2 Isotopes of common elements and their respective isotopic mass and percentage abundance in nature

Element	Isotopes	Isotopic masses for each isotope	Percentage abundance for each isotope
Hydrogen	^{1}H, ^{2}H	1, 2	99.98, 0.02
Carbon	^{12}C, ^{13}C	12, 13	98.9, 1.1
Oxygen	^{16}O, ^{18}O	16, 18	99.8, 0.2
Chlorine	^{35}Cl, ^{37}Cl	35, 37	75.8, 24.2
Bromine	^{79}Br, ^{81}Br	79, 81	50.8, 49.2

As the number of atoms that have possible isotopes increases, so too does the number of molecular ion peaks, hence increasing the complexity of the mass spectrum.

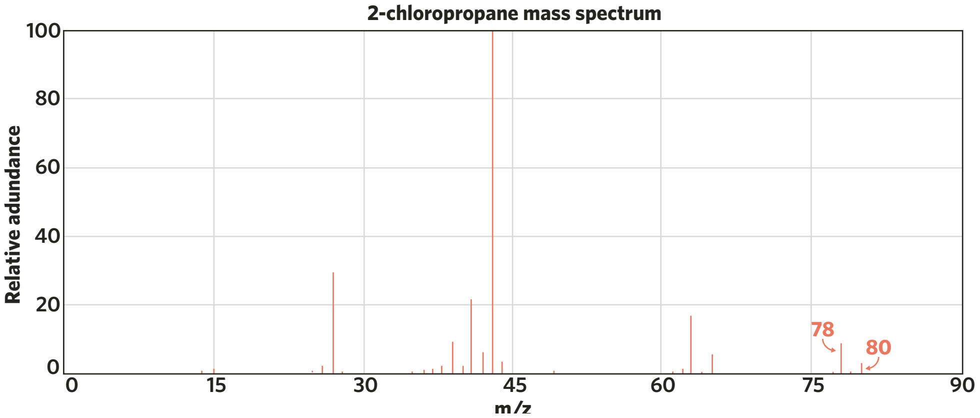


Figure 5 Mass spectrum of 2-chloropropane

As the number of atoms that have possible isotopes increases, so too does the number of molecular ion peaks, hence increasing the complexity of the mass spectrum.

1 Worked example

The mass spectrum of a non-branched alkene has a molecular ion peak of m/z = 56. Determine the molecular formula and name of the alkene.

What information is presented in the question?

Non-branched alkene

m/z = 56

What is the question asking us to do?

Determine the molecular formula and name of the alkene.

What strategy(ies) do we need in order to answer the question?

1. We know that the m/z ratio of the molecular ion peak is equivalent to the relative molecular mass of the molecule and therefore we know that the relative molecular mass of the alkene is 56.
2. Next we need to identify the general formula of alkenes: C_nH_{2n}.
3. Using this general formula we can set up an equation to connect the relative molecular mass with the relative atomic masses of the atoms in the molecule.

Answer

$M(C) = 12 \text{ g mol}^{-1}$

$M(H) = 1 \text{ g mol}^{-1}$

$(12 \times n) + (1 \times (2 \times n)) = 56$

$12n + 2n = 56$

$14n = 56$

$n = 4$

Therefore, the molecular formula is C_4H_8, which is either but-1-ene or but-2-ene

Theory summary

- Mass spectrometry is an analytical tool used to measure the mass-to-charge ratio of molecular ions.
- The output of the mass spectrometer instrument yields a mass spectrum, which can be used to identify a molecule.
- The mass spectrum graph shows the base peak, which has the highest relative intensity, and the molecular ion peak, representative of the relative molecular mass of the compound.
- The molecular ion can break into fragment ions which can tell us of the structure of the molecule and whether there are atoms with isotopes present in the molecule.

8A QUESTIONS

Theory review questions

Question 1

The most intense peak of a mass spectrum is termed

A the highest peak.

B the base peak.

C the molecule peak.

D the most abundant peak.

Question 2

What is the correct order of steps that occur in the mass spectrometer?

A Ionisation → Deflection → Acceleration → Detection

B Acceleration → Ionisation → Deflection → Detection

C Acceleration → Deflection → Ionisation → Detection

D Ionisation → Acceleration → Deflection → Detection

Question 3

The molecular ion peak is generated by

A a positively charged ion.

B an atom.

C a neutral fragment.

D a compound.

Question 4

Why does the process of fragmentation occur?

A The molecular ions are unstable.

B The bonds between molecules are weak.

C The strength of the magnetic field is strong enough to break apart any molecule.

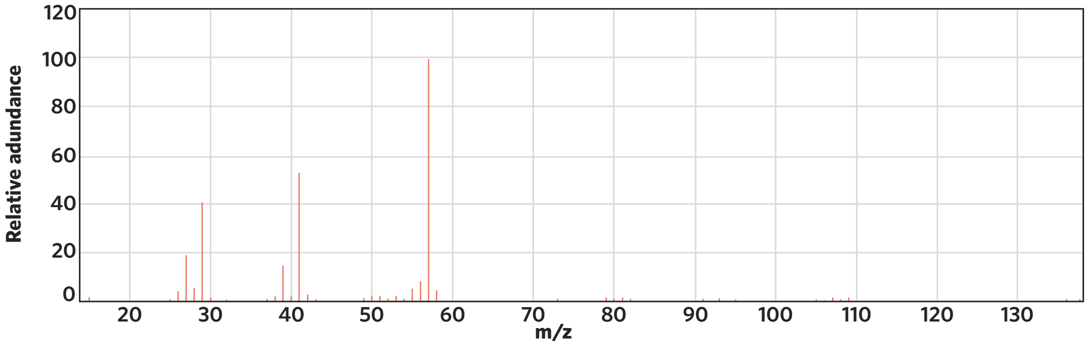
D The molecular ion has to be broken to see its structure.

Exam-style questions

Within lesson

Question 5 (1 MARK)

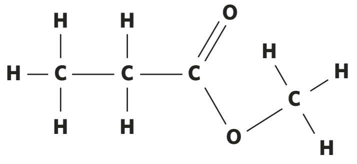
The following mass spectrum is shown for a molecule with the molecular formula C_4H_9Br. Which species is responsible for the base peak?



A $C_4H_9^+$ **B** C_4H_9Br **C** $C_4H_9Br^+$ **D** $C_4H_7Br^+$

Question 6 (1 MARK)

Identify the species that produces the molecular ion peak in the mass spectrum of the provided compound.



A $[CH_3CH_2COOCH_3]^-$

B $[CH_3CH_2COOCH_3]^+$

C $[CH_3CH_2COOCH_3]$

D $[CH_3CH_2COOCH_3]^{2-}$

Question 7 (1 MARK)

The mass spectrum of 2-chlorohexane, $C_6H_{13}Cl$, exhibits ion peaks of 120, 121, 122 and 123. Which of these peaks is due to the most commonly occurring molecular ion? The molecular weight of 2-chlorohexane is 120.620 and the isotope abundances are as follows.

$^1H = 99.99\%$, $^2H = 0.01\%$, $^{12}C = 98.9\%$, $^{13}C = 1.1\%$, $^{35}Cl = 75.8\%$, $^{37}Cl = 24.2\%$.

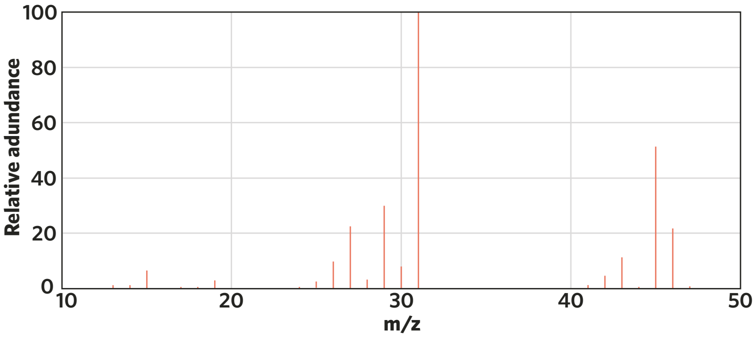
A 120 **B** 121 **C** 122 **D** 123

Question 8 (4 MARKS)

The mass spectrum of an unknown primary alcohol is shown.

a Identify the unknown alcohol. Justify your answer. (2 MARKS)

b The species $[OH]^-$ was not detected. Explain why. (2 MARKS)



Question 9 (2 MARKS)

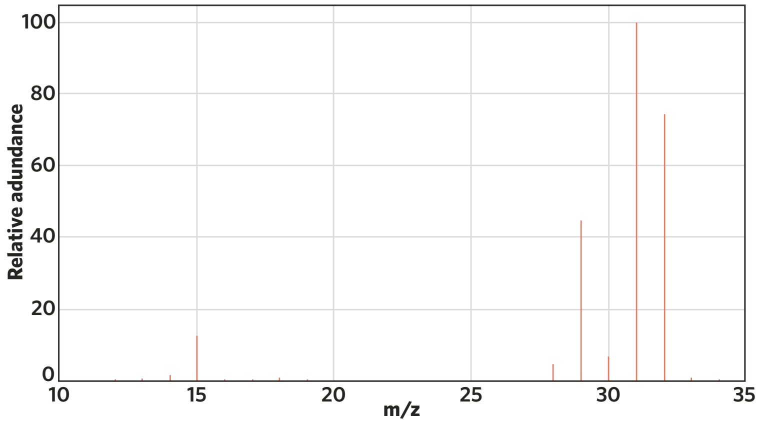
A sample of compound *T* is analysed in a mass spectrometer where it forms the molecular ion T^+ according to $T + e^- \rightarrow T^+ + 2e^-$

Some of the molecular ions fragment as follows: $T^+ \rightarrow A^+ + B^\cdot$ and $T^+ \rightarrow A^\cdot + B^+$

Identify which species would show as peaks in the mass spectrum. Explain.

Question 10 (2 MARKS)

The mass spectrum of methanol is shown below.



What fragment must have been lost from the molecular ion to account for the peak at m/z 31? Justify your answer.

Question 11 (2 MARKS)

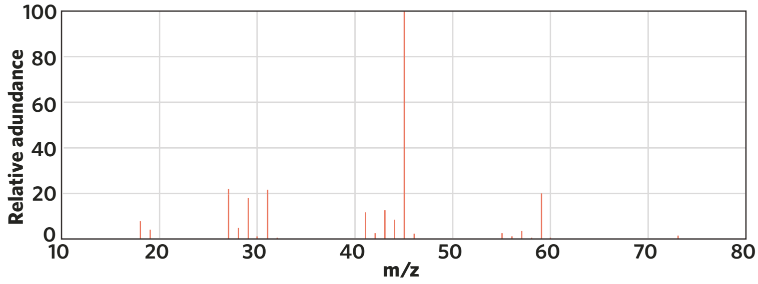
The mass spectrum of an unbranched alkane has a molecular ion peak of m/z = 72.

a Determine the molecular formula of the alkane. (1 MARK)

b State the name of the alkane. (1 MARK)

Question 12 (3 MARKS)

There are a number of structural isomers for the molecular formula $C_4H_{10}O$. Three of these are butan-2-ol, methylpropan-1-ol and methylpropan-2-ol. The mass spectrum given was produced by one of the three named isomers.

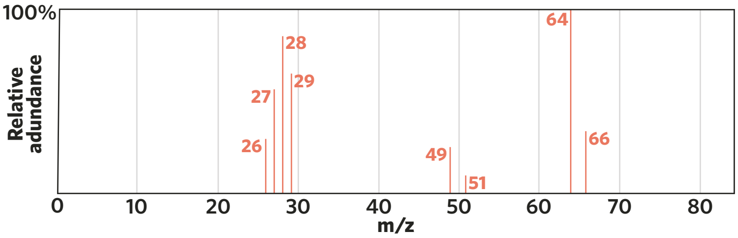


a Identify two possible species that could result in the fragment at 29 m/z. (1 MARK)

b Using the spectrum, name the isomer of $C_4H_{10}O$ that produced this spectrum and justify your answer. (2 MARKS)

Question 13 (4 MARKS)

Chlorine exists as several isotopes including ^{35}Cl and ^{37}Cl. The mass spectrum of chloroethane, C_2H_5Cl with two molecular ion peaks at m/z values of 64 and 66, is shown below.



a Identify the species present at 29 m/z. (1 MARK)

b Identify the fragments that are responsible for the peaks with m/z values of 64 and 66. (1 MARK)

c What do the two molecular ion peaks indicate about the relative abundance of the ^{35}Cl and ^{37}Cl isotopes and how they exist in nature? (2 MARKS)

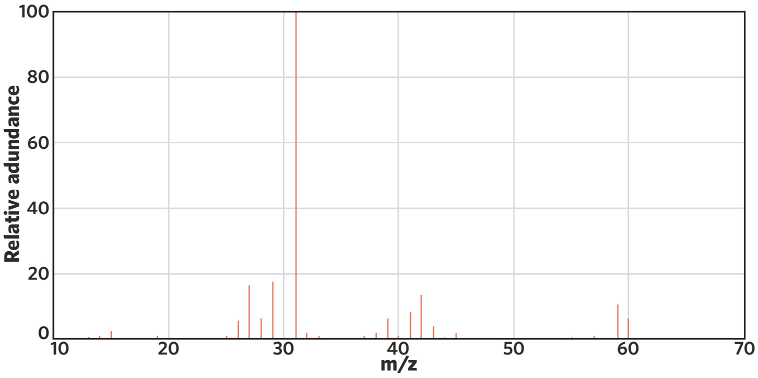
Multiple lessons

Question 14 (2 MARKS)

Explain why mass spectrometry would be the more suitable analytical technique to determine the ratio of ^{235}U to ^{238}U in a sample of uranium metal over a potassium dichromate test.

Question 15 (4 MARKS)

A scientist forgot to label the bottle of a pure alcohol solution he was using but he knew it was either ethanol, propan-1-ol or methanol so he used a mass spectrometer to produce the following mass spectrum.

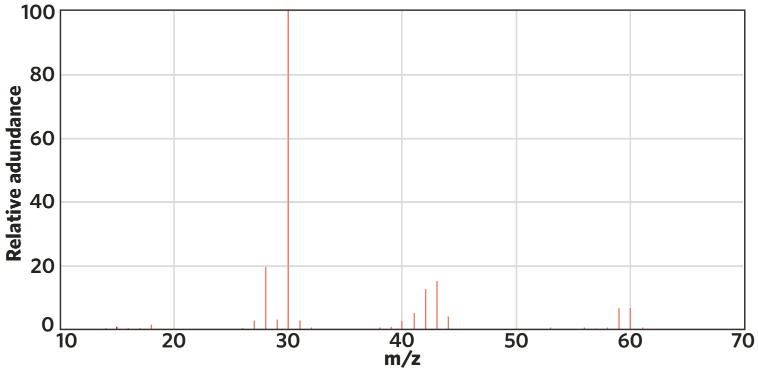


a Identify the name and structural formula for the unknown alcohol. Justify your answer. (2 MARKS)

b This molecule was reacted with propanoic acid and a concentrated sulfuric acid catalyst to produce an unpleasant smelling compound. Name and draw the molecules produced by this reaction. (2 MARKS)

Question 16 (5 MARKS)

A mass spectrum is given for ethylenediamine, which is the non-standard name for the compound with the molecular formula $C_2H_8N_2$ in the following diagram.



a Which peak is the base peak? Explain why. (2 MARKS)

b Identify the species that produces the base peak. (2 MARKS)

c Draw the structure of ethylenediamine. (1 MARK)

8B INFRARED SPECTROSCOPY

In this lesson, we will learn about the principles of infrared spectroscopy and how to apply infrared spectroscopy to identify carbon bonds and functional groups in organic compounds.

8A Mass spectrometry	8B Infrared spectroscopy	8C Nuclear magnetic resonance	8D Combining techniques	8E Chromatography	8F Volumetric analysis

Study design dot point

- The principles and applications of infrared spectroscopy (IR) (excluding features of instrumentation and operation) and interpretation of qualitative and quantitative data including use of characteristic absorption bands to identify bonds

Key knowledge units

Principles of infrared spectroscopy	4.1.8.1.1
Analysing infrared spectra	4.1.8.1.2

Key terms and definitions

- **Bond vibration** bond movement including stretching and bending
- **Infrared light** region of the electromagnetic radiation spectrum where wavelengths range from about 700nm to 1mm
- **Infrared spectroscopy** spectroscopy method that utilises the infrared light absorbance of organic compounds to determine the carbon bonds and functional groups present
- **Infrared spectrum** graph that represents the infrared light absorbance by a molecule at certain wavenumbers
- **Wavenumber** number of complete wave cycles per unit distance with the unit cm^{-1}, also known as light frequency
- **Fingerprint region** unique region of each compound within the range of 500–1400 cm^{-1} in an IR spectrum which can be used to identify the exact molecule

Lesson links

This lesson builds on:

- 7A - Structure of organic compounds

Infrared spectroscopy helps determine the structure of organic compounds.

Principles of infrared spectroscopy 4.1.8.1.1

OVERVIEW

Infrared spectroscopy operates based on the interaction between infrared radiation and organic molecules.

THEORY DETAILS

While mass spectrometry is used to determine the molar mass of a molecule, **infrared spectroscopy** is used to determine the bonds and functional groups present. Infrared spectroscopy is based on the idea of how different bonds in molecules absorb **infrared light** at different wavelengths. There are many forms of light waves or particles which humans can or cannot see. As shown in figure 1, infrared light has a wavelength ranging from 700 to approximately 1 millimeter. The most useful wavelengths for infrared spectroscopy occur between a range of approximately 2500 nm – 20,000 nm. Infrared light absorbed by a molecule causes the bonds within the molecules to vibrate. Infrared radiation does not cause the excitation of electrons, unlike other forms of spectroscopy such as UV-visible spectroscopy. This is due to infrared light having less energy than UV and visible light. There are two main types of **bond vibrations**: stretching and bending, as shown in figure 2.

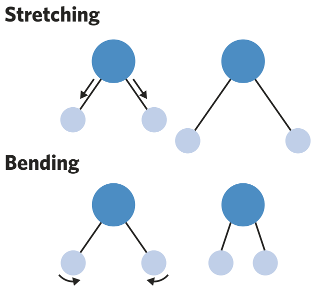


Figure 2 Two types of vibration: stretching and bending

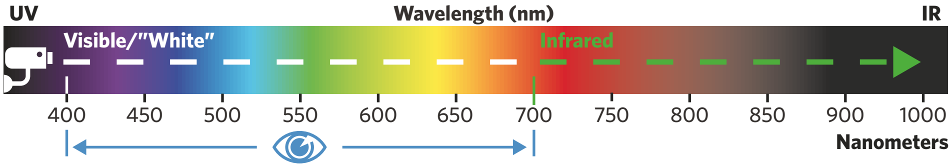


Figure 1 Electromagnetic spectrum

For a molecule to absorb infrared radiation, the dipole of the molecule must change. For this reason, polar bonds are usually only able to absorb infrared radiation.

As we learned in 7A, different compounds have different bonds and functional groups and therefore require a different amount of energy from infrared light for bond vibration to occur. It is important to understand that due to the different frequencies (**wavenumbers**) of infrared light, it has varying levels of energy. Hence, we can say that different bonds or functional groups absorb infrared light with different wavelengths in order to vibrate. Table 1 shows different bonds and functional groups with the corresponding wavenumbers of infrared light that they absorb.

Table 1 Different bonds and functional groups with corresponding infrared light wavenumber

Bond	**Wave number (cm^{-1})**	**Bond**	**Wave number (cm^{-1})**
C—Cl (chloroalkanes)	600–800	C═O (ketones)	1680–1850
C—O (alcohols, esters, ethers)	1050–1410	C═O (esters)	1720–1840
C═C (alkenes)	1620–1680	C—H (alkanes, alkenes, arenes)	2850–3090
C═O (amides)	1630–1680	O—H (acids)	2500–3500
C═O (aldehydes)	1660–1745	O—H (alcohols)	3200–3600
C═O (acids)	1680–1740	N—H (amines and amides)	3300–3500

Source: VCAA Chemistry Data Book

We can use the data above to determine the functional group(s) in an organic compound.

Analysing infrared spectra 4.1.8.1.2

OVERVIEW

The information presented in an infrared spectrum can be used to determine the bonds and functional groups of a molecule.

THEORY DETAILS

The results obtained through infrared spectroscopy are represented as a spectrum. Figure 3 shows an example of a typical **infrared spectrum** of an organic molecule. The horizontal axis represents the wavenumber (cm^{-1}) of infrared light decreasing from left to right (from 4000 to 500 cm^{-1}). The vertical axis shows the transmittance (%) of light through the molecule that we are investigating. The deeper the transmittance peak at a specific wavenumber, the more infrared light that is being absorbed by a particular bond in the molecule.

There are two main regions in the spectrum: the fingerprint region (500–1400 cm^{-1}) and the functional group region (above 1400 cm^{-1}). The **fingerprint region** is unique for each compound, which means different compounds will always have different fingerprint regions. The functional group region is what we mainly use to identify the bonds and functional groups of a compound.

Tip VCAA doesn't expect you to be able to read anything within the fingerprint region. If there is a bond they would like you to focus on within this region, it will be identified for you.

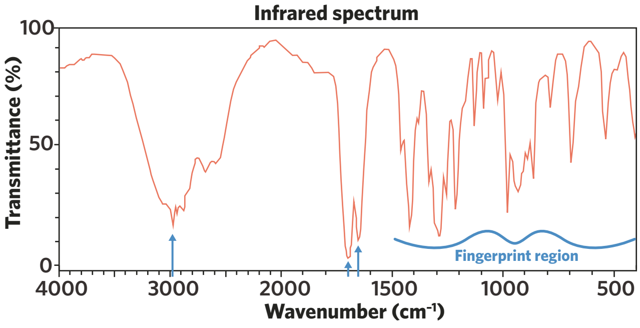


Figure 3 Example of an infrared spectrum. Blue arrows indicate examples of peaks.

We can also see from figure 3 that there are many types of peaks (also known as absorption bands) in an infrared spectrum. It is important to be able to recognize different types of peaks. As can be seen from figure 4, a peak can be strong, medium, weak, broad or narrow. It is sometimes tricky to identify the bond based on the wavenumbers as some bonds have similar wavenumber regions. Hence, it is useful to know the peak shapes of some bonds because different bonds and functional groups may have similar wavenumber ranges but different peak shapes. Table 2 shows how the shape of peaks varies among different bonds.

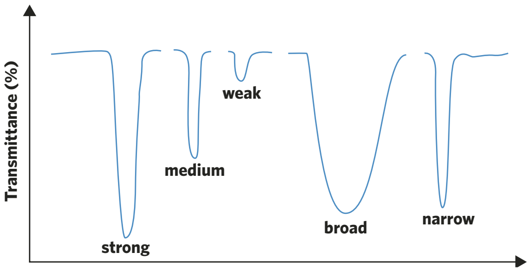


Figure 4 Illustration of different types of peaks in an infrared spectrum

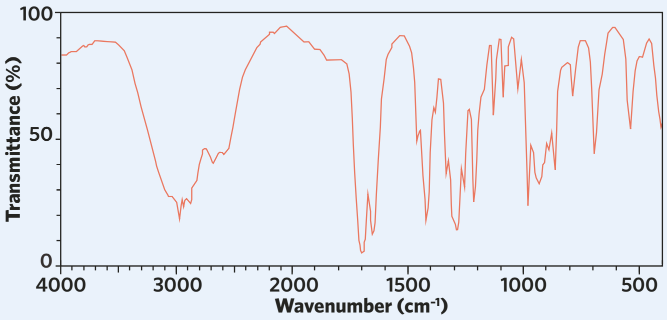
Table 2 Different bonds with their corresponding wavenumbers and types of peaks

Bond	**Wavenumber (cm^{-1})**	**Type of peak**
C—O (alcohols, esters, ethers)	1050–1410	Strong
C═C (alkenes)	1620–1680	Medium
C═O (amides)	1630–1680	Strong
C═O (aldehydes)	1660–1745	Strong
C═O (acids)	1680–1740	Strong
C═O (ketones)	1680–1850	Strong
C—H (alkanes, alkenes, arenes)	2850–3090	Medium
O—H (acids)	2500–3500	Strong, broad
O—H (alcohols)	3200–3600	Strong, broad (NOTE: narrower than O—H (acid) peak)
N—H (amines and amides)	3300–3500	Medium, broad

It is also important to note that IR spectroscopy is most commonly associated with qualitative analysis of a compound, but it can also be used for quantitative analysis. This means that it can be used to determine the concentration of a compound present. In order to do this, a set of samples of known concentration are run through the IR spectroscopy machine to create a calibration curve as a reference point which, in this case, connects the absorbance (closely related to transmittance) of a particular peak in the IR spectrum to the concentration. A more in-depth discussion of creating a calibration curve will occur in 8E.

1 Worked example

A group of chemists performed IR spectroscopy on an organic compound and obtained the IR spectrum below. Determine the bonds and functional groups present in the compound.



What information is presented in the question?

The IR spectrum of the compound.

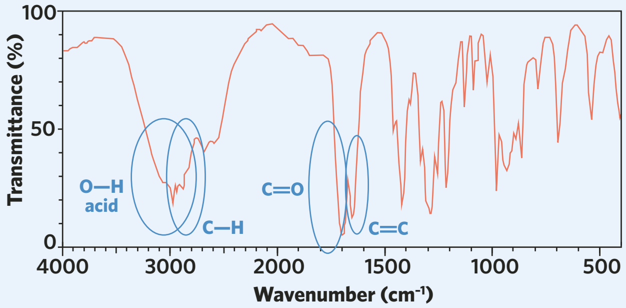
What is the question asking us to do?

Determine the bonds and functional groups present in the compound.

What strategy(ies) do we need in order to answer the question?

1. Identify the peaks and their characteristics in the IR spectrum.
2. Look for corresponding bonds or functional groups from the given table.

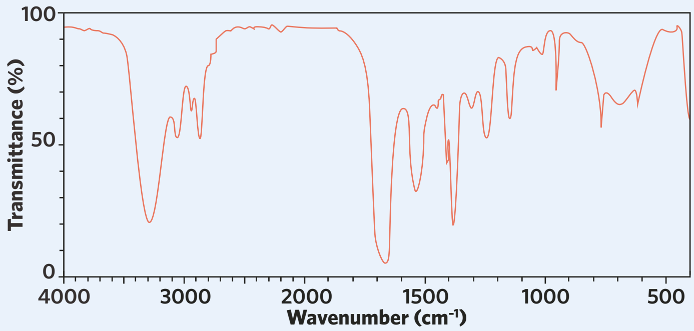
Answer



The strong broad peak from 3000–3400 cm^{-1} represents an acid O—H bond, whereas the medium peak from 2800–3000 cm^{-1} implies the C—H bond. The strong peak at 1700 cm^{-1} shows the C═O bond and the peak between 1600 and 1700 cm^{-1} indicates the presence of a C═C bond.

2 Worked example

Based on the spectrum below, identify the functional group present in the compound.



What information is presented in the question?

The IR spectrum of the compound.

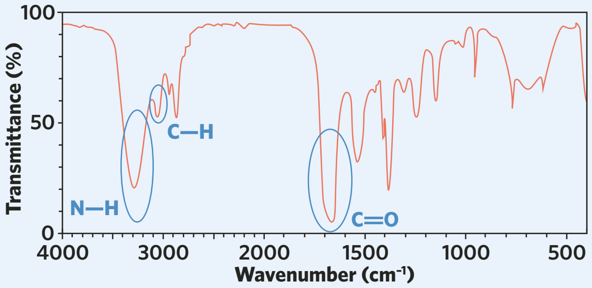
What is the question asking us to do?

Determine the functional group present in the compound.

What strategy(ies) do we need in order to answer the question?

1. Identify the peaks and their characteristics in the IR spectrum.
2. Look for corresponding bonds or functional groups from the given table.

Answer



The peak at 3300 cm^{-1} can be O—H or N—H but it is a medium peak so we can say that it is N—H. The peak at 3000 cm^{-1} is C—H. The peak at 1680 cm^{-1} can be C=C or C=O but it is a strong peak so we can say that it is C=O. As a result, this molecule contains an amide group.

Theory summary

- Infrared spectroscopy is used to determine the bonds and functional groups of organic compounds present and can be used to determine the concentration of a compound given an appropriate calibration curve.
- Different bonds require different amounts of energy from infrared light to vibrate and therefore they absorb infrared light with different wavenumbers.
- Different bonds and functional groups can be determined based on the peaks (or absorption bands) with different wavenumbers and their shapes in an infrared spectrum.

8B QUESTIONS

Theory review questions

Question 1

Which statement below is true about infrared spectroscopy?

A Infrared spectroscopy is used to identify the molar mass of a molecule.

B Infrared spectroscopy is based on the idea of visible light absorption of organic compounds.

C Infrared spectroscopy is used to identify bonds and functional groups in organic compounds.

D A complete molecular formula can sometimes be determined without the use of the fingerprint region of the infrared spectrum.

Question 2

Fill in the blanks to explain the axes in an infrared spectrum.

There are ___________ axes in an infrared spectrum. The ___________ represents the ___________(cm^{-1}) of infrared light decreasing from left to right. The ___________ shows the ___________ (%) of light increasing from bottom to top through the molecule we are investigating.

More than one word may be needed for each blank space.

Question 3

Fill in the blanks to explain why different bonds have different peaks of transmittance at different wavenumbers in an infrared spectrum.

Infrared light with different wavenumbers has different ___________. Each bond requires a specific amount of energy to ___________ and therefore absorbs light with a specific ___________. Hence, this will produce different peaks of transmittance in the IR spectrum.

More than one word may be needed for each blank space

Exam-style questions

Within lesson

Question 4 (1 MARK)

Based on the infrared spectrum given, what are the bonds present in this compound?

I O—H

II C—H

III C=O

IV C=C

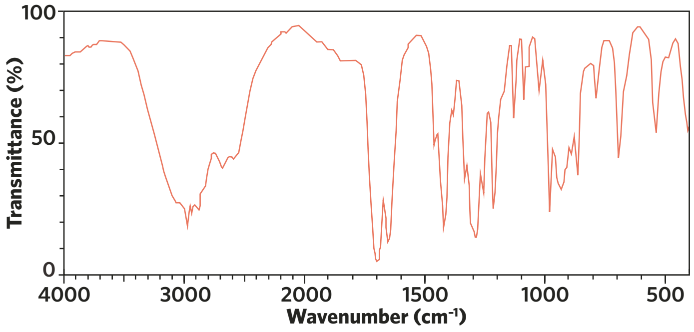
V N—H

A I & III

B I, II, IV & V

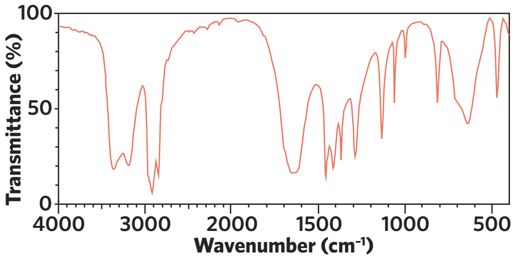
C III only

D I, II, III & IV

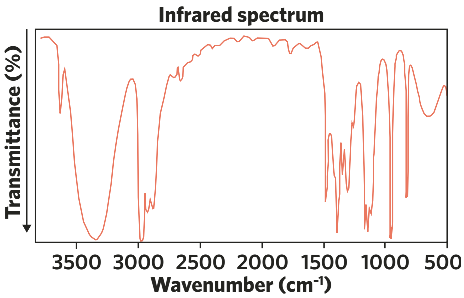


Question 5 (3 MARKS)

Finn was asked to perform IR analysis on an amide, which resulted in the following spectrum. Use the information given to confirm that the molecule being analysed was an amide.



Question 6 (2 MARKS)



Lani was given the following spectrum.

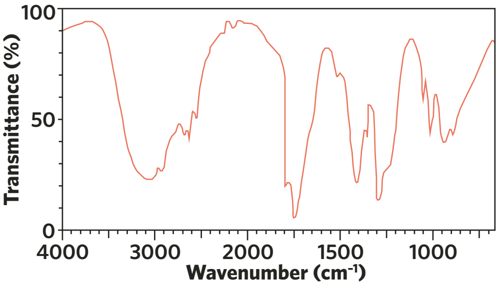
What type of organic compound is represented by this spectrum?

Justify your answer.

Multiple lessons

Question 7 (5 MARKS)

Lucy accidentally mislabelled two solutions with a molecular formula of $C_3H_6O_2$ as an acid and an ester. To differentiate the two, she took a sample of solution A and allowed it to undergo IR spectroscopy. The spectrum from this analysis is provided.

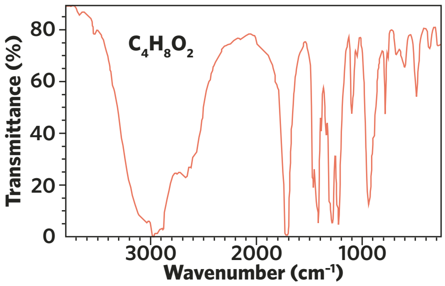


a Identify whether solution A would be the acid or ester. Explain. (2 MARKS)

b Draw the structural formula and give the name for this molecule. (2 MARKS)

c This molecule was created as a result of an oxidation reaction involving excess potassium permanganate in acidic solution. Identify the name of the reactant used in the oxidation reaction. (1 MARK)

Question 8 (4 MARKS)



You are working in a laboratory as a chemical analyst. After performing IR spectroscopy on an unbranched organic compound that has the molecular formula $C_4H_8O_2$, you collected the IR spectrum shown below. Determine the semi-structural formula and the IUPAC name of the compound. Justify your answer.

8C NUCLEAR MAGNETIC RESONANCE

In this lesson, we will learn the principles of NMR spectroscopy and how to apply NMR spectroscopy to determine structures of organic compounds.

8A Mass spectrometry	8B Infrared spectroscopy	8C Nuclear magnetic resonance	8D Combining techniques	8E Chromatography	8F Volumetric analysis

Study design dot point

- the principles (including spin energy levels) and applications of proton and carbon-13 nuclear magnetic resonance spectroscopy (NMR) (excluding features of instrumentation and operation); analysis of carbon-13 NMR spectra and use of chemical shifts to determine number and nature of different carbon environments in a simple organic compound; and analysis of high resolution proton NMR spectra to determine the structure of a simple organic compound using chemical shifts, areas under peak and peak splitting patterns (excluding coupling constants) and application of the *n*+1 rule.

Key knowledge units

Principles of NMR	4.1.9.1.1
Analysing ^{1}H NMR spectra	4.1.9.1.2
Analysing ^{13}C NMR spectra	4.1.9.1.3

Key terms and definitions

- **NMR (nuclear magnetic resonance) spectroscopy** analytical technique that uses electromagnetic radiation and magnetic fields to determine the structure of an organic compound
- **Chemical shift** energy frequency required for the spin flip of a nucleus in comparison to the reference compound TMS (tetramethylsilane)
- **C environment** atoms and bonds surrounding a particular C atom
- **H environment** atoms and bonds surrounding a particular H atom
- **The (*n*+1) rule** principle applied to the splitting patterns in a high resolution ^{1}H NMR spectrum to identify the number of H atoms on the adjacent carbon atom(s)
- **Shielding** effect of electrons surrounding a nucleus on the external magnetic field experienced by the nucleus
- **Spin state** orientation of a nucleus when being placed in an external magnetic field

Lesson links

This lesson builds on:

- 7A – Structure of organic compounds

NMR helps determine the structures of organic compounds.

Principles of NMR 4.1.9.1.1

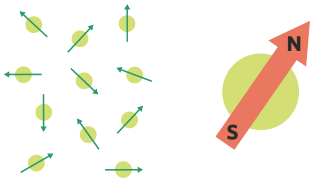
OVERVIEW

Molecules react differently to electromagnetic radiation when placed in a magnetic field. NMR spectroscopy acts upon this property to help determine the structure of organic compounds.

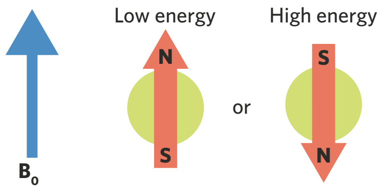
THEORY DETAILS

While IR spectroscopy is used to determine the functional groups and bonds present in an organic compound, **NMR spectroscopy** helps us determine the number of chemical environments and the ratio of atoms in an organic compound. The principles of NMR spectroscopy are based on the concept of the nucleus spin state in the presence of magnetic radiation. NMR spectroscopy is used along with IR spectroscopy and mass spectroscopy to determine the complete structures of organic compounds.

A nucleus has protons and neutrons, which allow it to behave like a magnet. A nucleus can spin around its axis just like the Earth spins around its axis, however, not all nuclei can behave in this way. The spinning action of the nucleus creates a magnetic field. Fortunately, ^{1}H and ^{13}C are two atoms that have nuclear spin and we can utilise the nuclear spins of these two atoms to identify the structures of organic compounds.



Random orientation of nuclei in the absence of an external magnetic field



Directed orientation of nuclei in the presence of an external magnetic field

Figure 1 Illustration of nucleus orientation without external magnetic field B_0 (top) and with the external magnetic field B_0 (bottom)

In the absence of an external magnetic field, the nuclei are randomly oriented. If a nucleus is placed in an external magnetic field its orientation will change, similar to what happens when we place two magnets close to each other. As shown in figure 1, the nucleus can either align with the external magnetic field (B_0) or against it. We call these **spin states**. We say that a nucleus is at its lowest energy level when it aligns with B_0 (alpha spin state) and at its highest energy level if it aligns against B_0 (beta spin state). With the right amount of energy, we are able to change the spin state of a nucleus from low energy to high energy. The nucleus doesn't stay in this high energy state for long and therefore will jump back into its lower energy state. As this happens, the nucleus gives off a certain amount of energy, which corresponds to the radio wave region of the magnetic spectrum. Electrons surrounding the nucleus create an electronic environment around the nucleus, which opposes the external magnetic field. Therefore, electrons around the nucleus reduce the influence of the external magnetic field on the nucleus, an effect referred to as **shielding** and is described in figure 2. This impacts the energy level of the nucleus, which also changes the energy frequency required to cause a nuclei to change spin states.

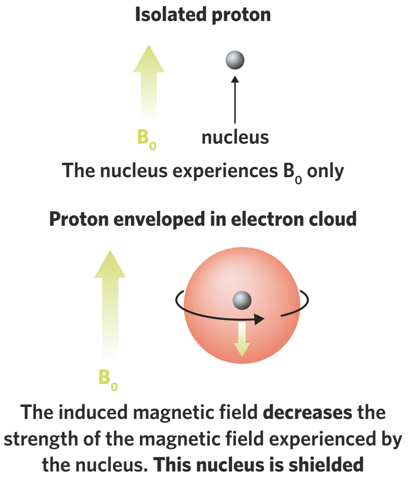


Figure 2 The effect of electrons on the strength of the external magnetic field felt by a nucleus

The processes described above are the foundational principles of NMR spectroscopy and are summarised in figure 3.

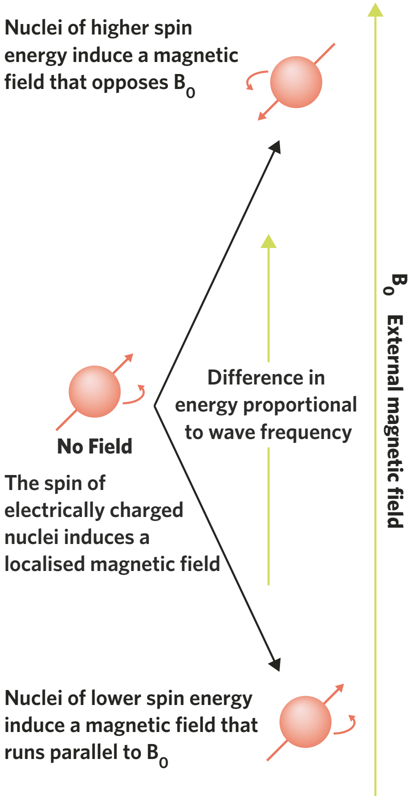


Figure 3 Summary of the changes occurring to a nucleus in the presence of an external magnetic field

In NMR, a compound is placed in an external magnetic field and the energy frequency required to create spin flips (a change in the spin state) in the ^{1}H (also known as proton) and/or ^{13}C nuclei is detected. This information is used to figure out the H and/or C chemical environments in the compound. A **H environment** refers to the atoms and the bonds surrounding a particular H atom, while a **C environment** refers to the atoms and bonds surrounding a particular C atom. In figure 4, carbon number 1 is connected to 3 H atoms and adjacent to the CH_2 group, while carbon number 2 is connected to 2 H atoms and adjacent to the CH_3 group and the OH group. Therefore, we say that ethanol has 2 C environments. H atoms circled in red, blue and green have different surrounding atoms and bonds indicating that ethanol has 3 H environments. Different atoms surrounding a H or C atom will create different electron environments and will therefore require different energy for a change in spin state. To keep the analysis consistent, we compare the energy required by the nuclei of the tested compound to change the spin state to the energy required by the reference compound TMS (tetramethylsilane, $(CH_3)_4Si$) for a change in spin state. TMS is used as it is inert and due to its very predictable splitting pattern (just one peak) on the NMR spectrum. The energy required for a spin flip of a nucleus relative to the reference compound is called the **chemical shift**. Chemical shifts of different H and C environments are detected and presented in ^{1}H NMR spectra and ^{13}C NMR spectra.

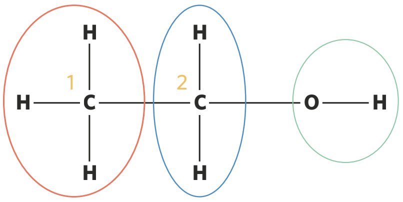


Figure 4 Different H and C environments of ethanol

Analysing ^{1}H NMR spectra 4.1.9.1.2

OVERVIEW

^{1}H NMR spectra can be used to identify the hydrogen environments in a molecule, which can then be used to identify the structure of organic compounds.

THEORY DETAILS

There are two types of ^{1}H NMR spectra: high resolution ^{1}H NMR spectra and low resolution ^{1}H NMR spectra. In this lesson, we only focus on analysing high resolution ^{1}H NMR spectra. As shown in figure 5, a standard high resolution ^{1}H NMR spectrum (also known as high resolution proton NMR spectrum) has two key features: the *x*-axis and the peaks that look like mountain ranges along the *x*-axis. The *x*-axis represents the chemical shifts measured in parts per million (ppm). As mentioned above, each H environment will need a different energy frequency for spin flip to occur, which therefore generates a different peak in a high resolution ^{1}H NMR spectrum. It is important to understand that the peak at 0 ppm is caused by the reference compound TMS (tetramethylsilane). The number of peaks indicates the number of H environments in a compound. There are three peaks in the high resolution ^{1}H NMR of ethyl ethanoate, which means there are three H environments in a molecule of ethyl ethanoate.

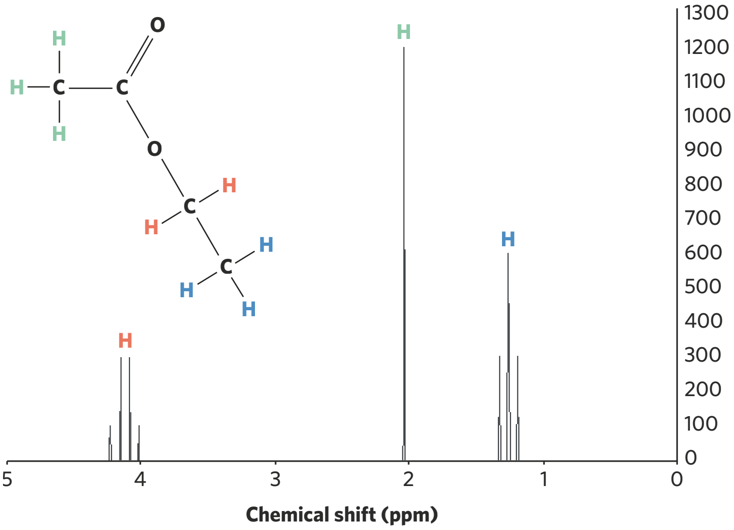


Figure 5 ^1H NMR spectrum of ethyl ethanoate

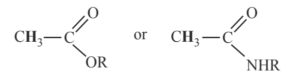
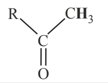
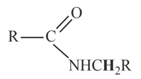
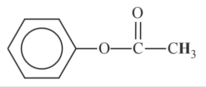
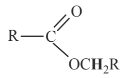
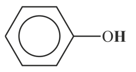
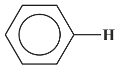
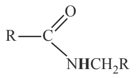
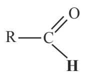
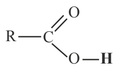
Three different H environments of ethyl ethanoate $CH_3COOCH_2CH_3$ are presented in three different colours: green, red and blue.

As can be observed, there are splitting patterns in each peak in the high resolution ^1H NMR spectrum that are not present in a low resolution spectrum. The **(*n*+1) rule** can be applied to these splitting patterns to identify the number of H atoms on the adjacent carbon atom(s). In this formula, ***n*** represents the number of H atoms on the neighbouring carbon atom while (*n*+1) represents splitting pattern of the peak for the H environment that you are looking at. For example, the peak at **1.3 ppm** shown in figure 5 is split into 3 (also known as a triplet). According to the rule of '*n*+1', for this to occur, the neighbouring carbon needs to be bonded to 2 carbons as:

n (number of H atoms on the neighbouring carbon) + 1 = 3 (splitting pattern of the peak being examined). Therefore, *n* = 2.

The peak at **2 ppm** only has 1 split (also known as a singlet) and therefore the neighbouring carbon atom is connected to 0 H atoms. The peak at **4.2 ppm** is split into 4 (also known as a quartet), meaning that the neighbouring carbon atom is connected to 3 H atoms. A complete structure of the compound can be obtained after combining all the information extracted from the peaks. We can also determine the structure of a compound based on table 1 containing proton environment types with corresponding chemical shifts (ppm). For example, the chemical shift from 9.0–13.0 ppm shows the presence of a COOH group. As mentioned above, because the shielding created by the surrounding electrons reduces the effect of the external magnetic field on a nucleus, it requires less energy for a change in spin state. Therefore, it is important to note that due to nuclear shielding, hydrogens that are in an environment close to a highly electronegative atom (oxygen, nitrogen, fluorine) will be shifted to a much greater extent (higher chemical shift values). As can be seen in figure 5, the orange hydrogens that are in an environment with a nearby oxygen atom have much higher chemical shifts than those that are only near a carbon. Table 2 shows the number of common splitting patterns with the corresponding peak names.

Table 1 Table of types of proton with corresponding chemical shifts (ppm)

Type of proton	Chemical shift (ppm)
$R–CH_3$	0 9–1 0
$R–CH_2–R$	1 3–1 4
$RCH=CH–CH_3$	1 6–1 9
$R_3–CH$	1 5
	2 0
	2 1–2 7
$R–CH_2–X$ (X = F, Cl, Br or I)	3 0–4 5
$R–CH_2–OH$, $R_2–CH–OH$	3 3–4 5
	3 2
$R—O—CH_3$ or $R—O—CH_2R$	3 3–3 7
	2 3
	3 7–4 8
R–O–H	1–6 (varies considerably under different conditions)
$R–NH_2$	1–5
$RHC=CHR$	4 5–7 0
	4 0–12 0
	6 9–9 0
	8 1
	9 4–10 0
	9 0–13 0

Source: VCAA data book

The area under each peak can also be used to determine the relative number of H atoms in the corresponding H environment. In figure 6, the ratio of the areas under the peaks at 4.8 ppm, 3.7 ppm and 1.3 ppm is 1:2:3. This indicates that the ratio of H atoms in the H environment causing the peaks at 4.8 ppm, 3.7 ppm and 1.3 ppm is 1:2:3.

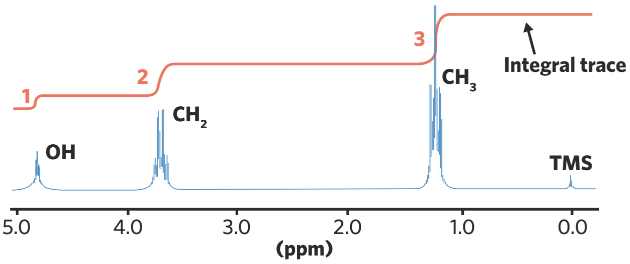


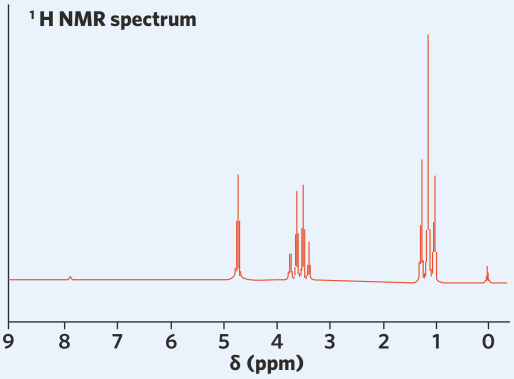
Figure 6 Analysis of area under peaks in the ^1H NMR spectrum of ethanol CH_3CH_2OH

Table 2 Common splitting patterns and their nomenclature

Number of splitting patterns	Peak name
1	singlet
2	doublet
3	triplet
4	quartet
5	pentet
6	sextet
7	heptet

1 Worked example

An organic compound has the molecular formula C_2H_6O and its ^1H NMR spectrum is shown. Determine the structural formula of the compound. Justify your answer.



What information is presented in the question?

Molecular formula C_2H_6O

A ^1H NMR spectrum

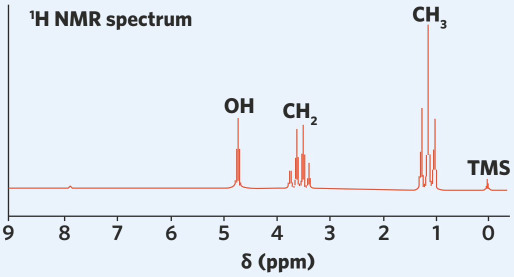
What is the question asking us to do?

Determine the structural formula of the compound.

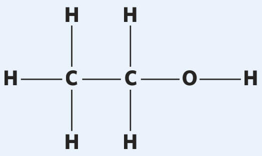
What strategy(ies) do we need in order to answer the question?

1. Determine the number of H environments based on the number of peaks in the ^1H NMR spectrum.
2. Apply *n*+1 rule to the splitting patterns of each peak.
3. Check for the corresponding proton types from the given table based on the chemical shifts.
4. Combine all information collected from the ^1H NMR spectrum to determine the structural formula of the compound.

Answer



There are 3 peaks (excluding TMS) in the ^1H NMR spectrum. The compound therefore has 3 different H environments. The peak at 1 ppm has 3 splitting patterns, thus there are 2 H atoms on the adjacent C atom. According to table 1, 1 ppm shows the presence of a CH_3 bonded to an R group. The peak at 3.7 ppm has 4 splitting patterns, the neighbouring C atom therefore has 3 H atoms. Moreover, 3.7 ppm indicates a CH_2 group in between an R group and an OH group. The compound has 1 O atom and the singlet peak at 4.8 ppm is shifted furthest and therefore there is a hydroxyl group (OH). Hence, the structural formula of the compound is:



Analysing ^{13}C NMR spectra 4.1.9.1.3

OVERVIEW

^{13}C NMR spectra can be used to identify the carbon environments in a molecule which, together with the information provided by a ^{1}H NMR, can then be used to identify the structure of organic compounds.

THEORY DETAILS

Figure 7 shows a standard ^{13}C NMR spectrum. Similar to a ^{1}H NMR spectrum, a ^{13}C NMR spectrum has two key features: the *x*-axis presenting chemical shifts and the peaks along the axis. The peak at 0 ppm is again caused by the reference compound TMS. The number of peaks in a ^{13}C NMR spectrum indicates the number of C environments in an organic compound. As shown in figure 7, the aldehyde CH_3CHO has 2 C environments and therefore creates 2 peaks in the ^{13}C NMR spectrum. Table 3 will help us determine the types of carbon environments based on the chemical shifts. According to table 3, the peak at 200 ppm indicates the presence of a CHO group, whilst the peak at 31 ppm indicates the presence of a CH_3 group.

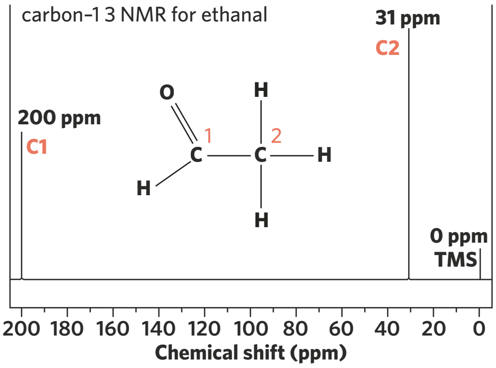
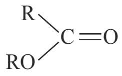
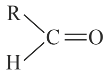


Figure 7 ^{13}C NMR spectrum of CH_3CHO

Table 3 Table of types of carbon with corresponding chemical shifts (ppm)

Type of carbon	Chemical shift (ppm)
$R–CH_3$	8–25
$R–CH_2–R$	20–45
$R_3–CH$	40–60
$R_4–C$	36–45
$R–CH_2–X$	15–80
$R_3C–NH_2$, $R_3C–NR$	35–70
$R–CH_2–OH$	50–90
RC≡CR	75–95

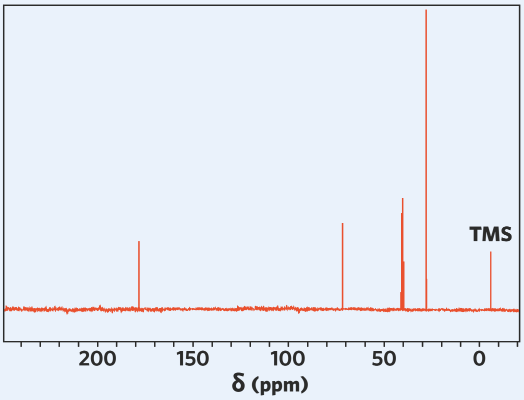
Type of carbon	Chemical shift (ppm)
$R_2C=CR_2$	110–150
RCOOH	160–185
	165–175
	190–200
$R_2C=O$	205–220

Source: VCAA Data Book

However, it is important to note that unlike high resolution ^{1}H NMR, a low resolution ^{13}C NMR spectrum does not produce any splitting patterns and therefore does not reveal the number of carbon atoms in an organic compound.

2 Worked example

An organic compound has the molecular formula $C_4H_8O_3$ and its ^{13}C NMR spectrum is shown below. Determine the structural formula of the compound. Justify your answer.



What information is presented in the question?

Molecular formula $C_4H_8O_3$

The ^{13}C NMR spectrum

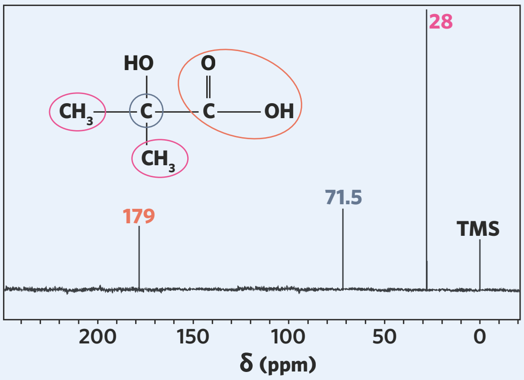
What is the question asking us to do?

Determine the structural formula of the compound.

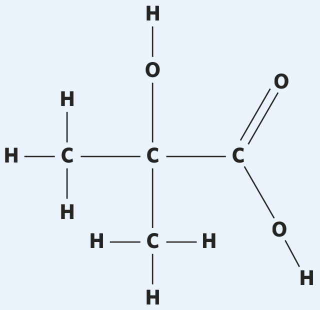
What strategy(ies) do we need in order to answer the question?

1. Determine the number of C environments based on the number of peaks in the ^{13}C NMR spectrum.
2. Look for the corresponding carbon types from the given table based on the chemical shifts.
3. Combine all information collected from the ^{13}C NMR spectrum to determine the structural formula of the compound.

Answer



There are 3 peaks in the ^{13}C NMR spectrum. The compound therefore has 3 different C environments. According to table 1, the peak at 179 ppm indicates the presence of the COOH group. The peak at 71.5 ppm indicates the carbon bonded to OH group, while the peak at 28 ppm indicates either CH_3 or CH_2 group. Because there are 3 peaks in the spectrum, the peak at 28 ppm shows the presence of 2 CH_3 groups. Hence, the structural formula of the compound is:



Theory summary

- NMR spectroscopy is based on the concept of how different nuclei require different energy for spin state flips based on their surrounding environments.
- The ^{1}H NMR spectrum is used to determine the number of different H environments in an organic compound by looking at the number of peaks in the spectrum. The type of proton environment is based on the chemical shift.
- The n+1 rule is used to analyse a ^{1}H NMR spectrum, where n+1 is the number of splits on the ^{1}H NMR spectrum for a given peak and n is the number of hydrogens on the adjacent carbon atom(s) of a particular H environment.
- The ratio of peak areas in a ^{1}H NMR spectrum indicates the ratio of H atoms in the hydrogen environments of an organic compound.
- The ^{13}C NMR spectrum is used to analyse different C environments in an organic compound. The number of C environments is given by the number of peaks in the spectrum and the nature of the carbon environment is based on the respective chemical shifts.

8C QUESTIONS

Theory review questions

Question 1 (1 MARK)

What is the purpose of NMR spectroscopy?

A To determine the molar mass of an organic compound

B To determine the chemical properties of an organic compound

C To determine the number of chemical environments and the ratio of atoms in an organic compound

D To determine the concentration of a compound in a sample

Question 2 (4 MARKS)

Fill in the blanks about the principles of the ^{13}C NMR spectrum. More than one word may be required for each space.

In NMR spectroscopy, the nuclei of ^{13}C atoms can spin and align with or against the external magnetic field. The energy required by a carbon nucleus for a spin flip is called a ___________. Different atoms surrounding ^{13}C atoms will produce different electron environments, which can change the ___________ experienced by the ^{13}C atoms. Therefore, different carbon environments require different ___________ for spin flips. Hence, different carbon environments have different ___________ in a ^{13}C NMR spectrum.

Question 3 (1 MARK)

Which statement is **not** correct about the *n*+1 rule in a ^{1}H NMR spectrum?

A The *n*+1 rule is used to determine the number of H atoms in different H environments in an organic compound.

B *n* represents the number of splitting patterns of a peak.

C (*n*+1) represents the number of splitting patterns of a peak.

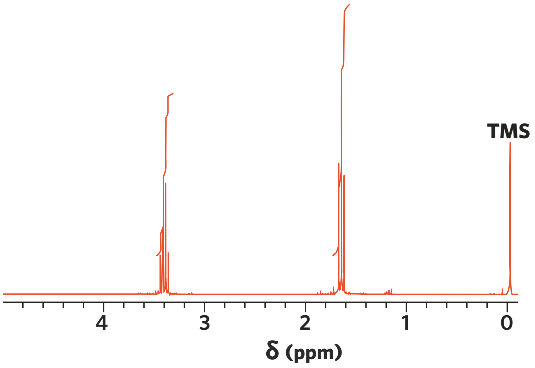
D *n* represents the number of H atoms in the adjacent H environments of a peak.

Exam-style questions

Within lesson

Question 4 (1 MARK)

The proton NMR spectrum of bromoethane has two sets of peaks, both of which are split. Which of the following correctly describes the splitting pattern?



A A singlet and a singlet

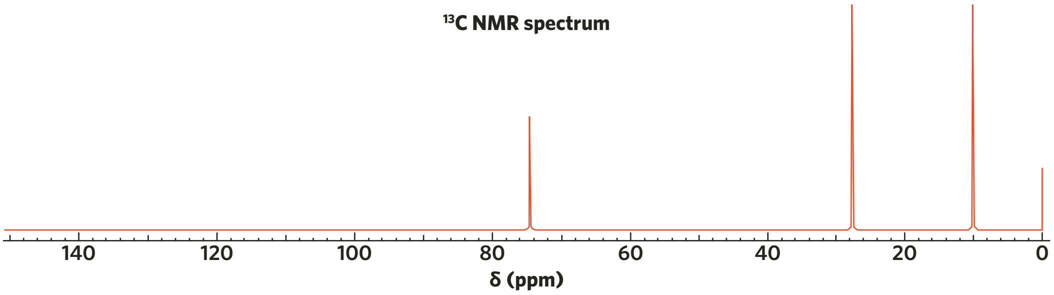
B A doublet and a doublet

C A triplet and a triplet

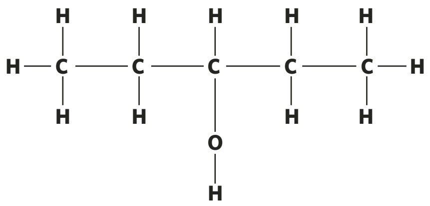
D A triplet and a quartet

Question 5 (1 MARK)

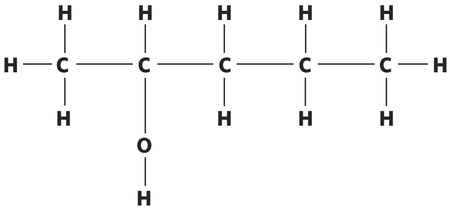
An organic compound has the molecular formula $C_5H_{12}O$ and the ^{13}C NMR spectrum below. Which is the correct structural formula of the compound?



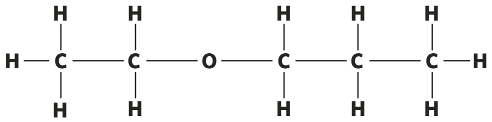
A



B



C



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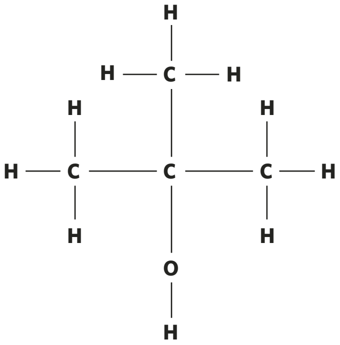
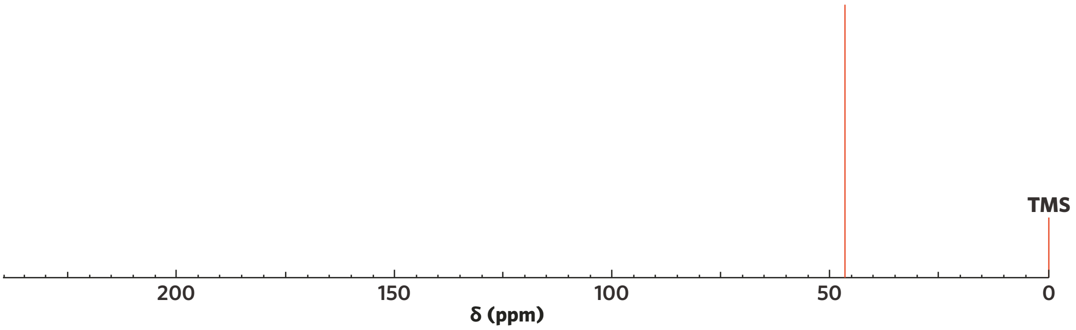


Question 6 (2 MARKS)

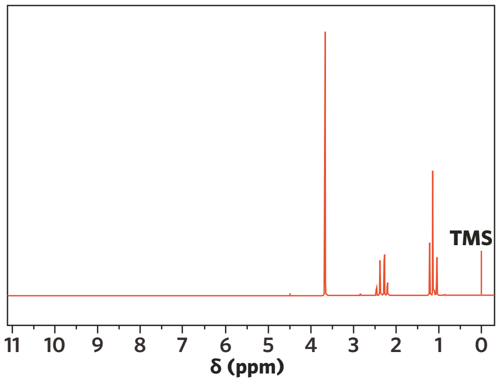
A sample was analysed using ^{13}C NMR. The spectrum is shown below.

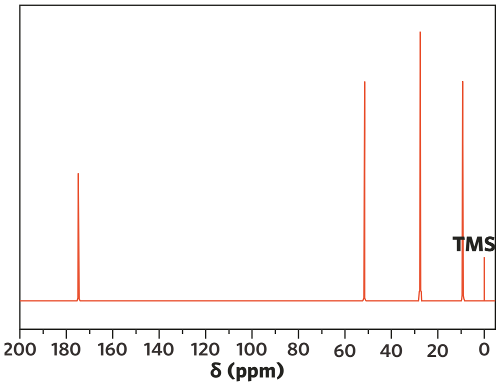


Is this spectrum consistent with the structure of $H_2NCH_2NH_2$? Justify your answer.

Question 7 (5 MARKS)

You are performing NMR spectroscopy on an organic compound with the molecular formula $C_4H_8O_2$. You obtained the ^1H NMR spectrum and the ^{13}C NMR spectrum below.





- **a** Determine the number of H environments in the compound. (1 MARK)
- **b** Determine the number of C environments in the compound. (1 MARK)
- **c** Determine the semi-structural formula of the compound. Justify your answer. (3 MARKS)

Multiple lessons

Question 8 (1 MARK)

Which two isomers of $C_3H_6Cl_2$ have two peaks in their ^{13}C NMR spectrum?

A $CH_3CCl_2CH_3$ and $CHCl_2CH_2CH_3$

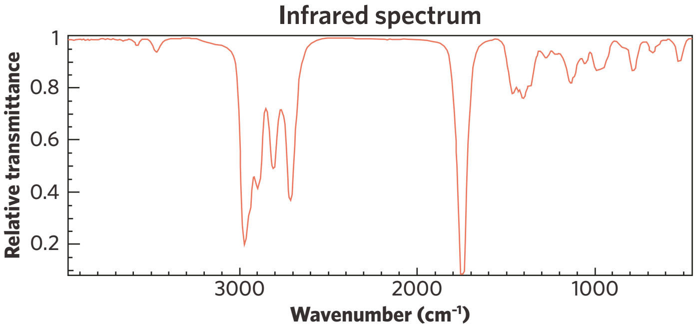
B $CH_2ClCHClCH_3$ and $CH_2ClCH_2CH_2Cl$

C $CHCl_2CH_2CH_3$ and $CH_2ClCHClCH_3$

D $CH_2ClCH_2CH_2Cl$ and $CH_3CCl_2CH_3$

Question 9 (6 MARKS)

A student investigated an organic substance, compound *X*, with the molecular formula C_4H_8O. The infrared spectrum of compound *X* is provided.



It is experimentally determined that compound *X* reacts with potassium dichromate $K_2Cr_2O_7$.

a On the spectrum above circle two peaks that identify bonds or functional groups present in compound *X* and identify the bonds responsible for each peak. (2 MARKS)

b A sample of compound *X* was analysed further using ^1H NMR. The spectral data is represented by the table below. However, the data is missing the peak splitting pattern data for one signal. Fill in the missing information. (1 MARK)

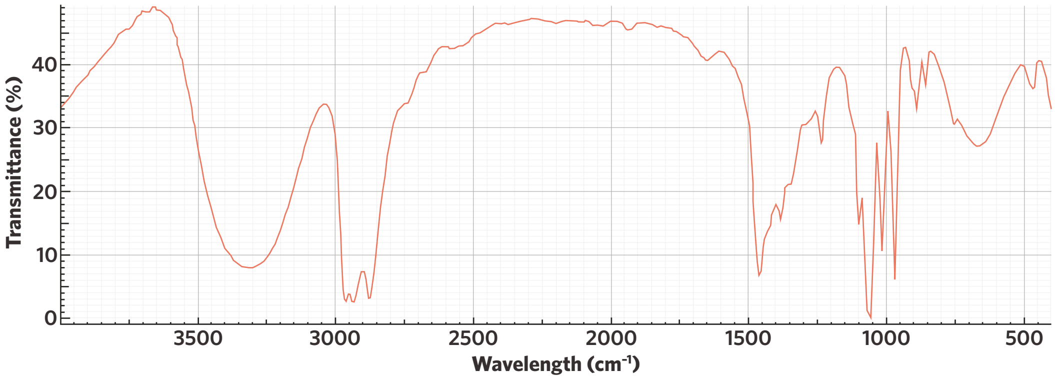
Chemical shift (ppm)	Relative peak area	Peak splitting
1.03	3	triplet
1.66	2	sextet
2.50	2	triplet
9.62	1	?

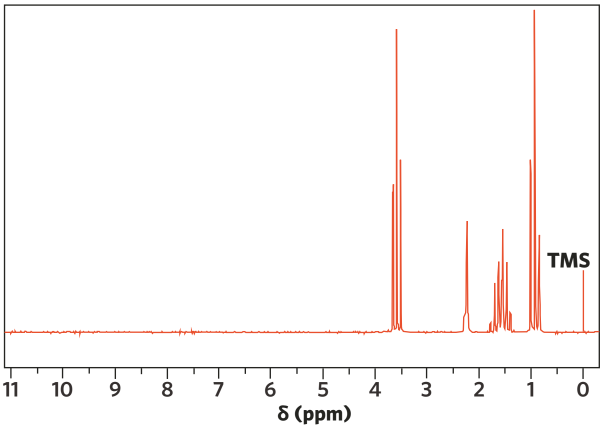
c Based on the spectral data from parts a and b, draw the structural formula of compound *X*. (1 MARK)

d If compound *X* were analysed using ^{13}C NMR, how many signals would we expect to receive? Justify your response. (2 MARKS)

Question 10 (7 MARKS)

An organic compound has the molecular formula C_3H_8O. The IR spectrum and the ^1H NMR spectrum are provided.





Chemical shift	Type of peak
1 ppm	triplet
1.4 ppm	sextet
2.3 ppm	singlet
3.6 ppm	triplet

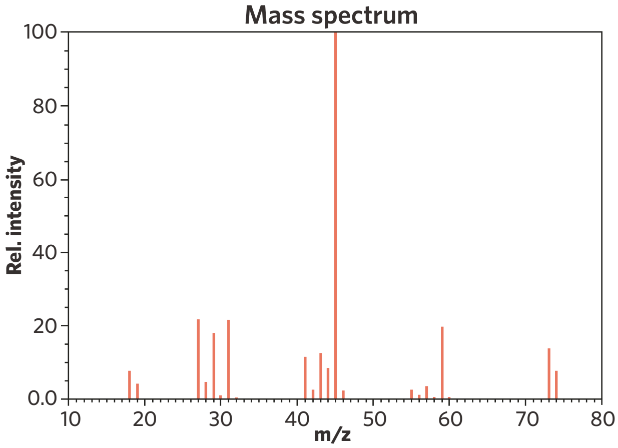
a Determine the class of this organic compound. Justify your answer. (3 MARKS)

b Identify the semi-structural formula of the compound. Justify your answer. (3 MARKS)

c Give the IUPAC name of the compound. (1 MARK)

Question 11 (8 MARKS)

The empirical formula of a compound is known to be $C_4H_{10}O$, but its molecular formula is unknown. The unknown organic compound produced the mass spectrum given below.

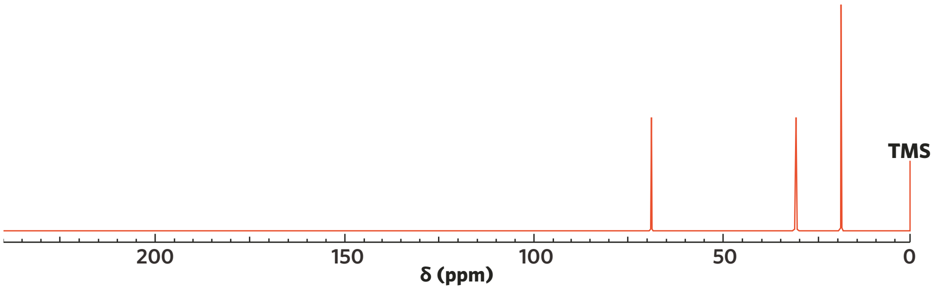


a Use the spectrum to determine the molecular formula for the compound. (1 MARK)

b Draw all possible structural isomers with this molecular formula. (3 MARKS)

c The sample underwent oxidation, resulting in the production of a ketone. Write the IUPAC name of the compound under analysis and justify your answer. (2 MARKS)

d Determine whether the compound you have identified in c is responsible for the ^{13}C NMR spectrum given below. Explain your answer. (2 MARKS)



8D COMBINING TECHNIQUES

In this lesson, we will learn how to identify the structure of unknown compounds by using a variety of analytical techniques.

8A Mass spectrometry	8B Infrared spectroscopy	8C Nuclear magnetic resonance	8D Combining techniques	8E Chromatography	8F Volumetric analysis

Study design dot point

- determination of the structures of simple organic compounds using a combination of mass spectrometry (MS), infrared spectroscopy (IR) and proton and carbon-13 nuclear magnetic resonance spectroscopy (NMR) (Limited to data analysis)

Key knowledge unit

Determining structures of organic compounds	4.1.10.1

Determining structures of organic compounds 4.1.10.1

OVERVIEW

We can use a combination of mass spectrometry, infrared spectroscopy, ^{13}C NMR and ^{1}H NMR, to more accurately identify the structure of an organic compound.

THEORY DETAILS

It's important to understand that all of the techniques explained in the previous lessons can provide very useful information about the identity of a compound. The following checklist is a guide that outlines the information each technique provides with respect to the identity of a compound.

Table 1 Summary of analytical techniques and the type of information provided by each technique

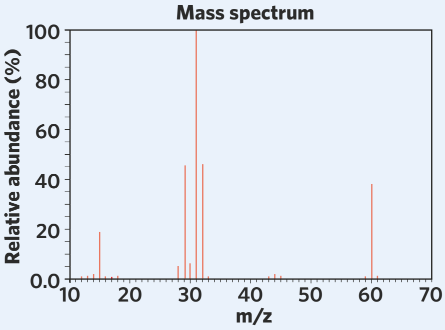
Technique	Information provided with respect to the organic compound
Mass spectrometry	The molar mass of the compound and the branching pattern
IR	The different bonds and functional groups present
^{1}H NMR	The number of hydrogen environments, the ratio of hydrogens in each environment, the type of hydrogen environment, the number of hydrogen atoms on neighbouring carbon atoms
^{13}C NMR	The number of carbon environments, the type of carbon environments

Sometimes, it is only by using a whole range of these techniques that a chemist can accurately determine the identity of an unknown organic compound.

Let's look at two worked examples below.

1 Worked example

a. **Compound A has the empirical formula CH_2O. Using the mass spectrum determine the molecular formula of compound A.**



What information is presented in the question?

Empirical formula: CH_2O

Mass spectrum of the compound

What is the question asking us to do?

Determine the molecular formula of compound A.

What strategy(ies) do we need in order to answer the question?

1. We know that the m/z ratio of the molecular ion peak is equivalent to the relative molecular mass of the molecule and therefore we know that the relative molecular mass of the unknown compound is 60 g/mol.
2. Next we need to use the empirical formula of the compound: CH_2O.
3. Using this empirical formula we can set up an equation to connect the relative molecular mass with the relative atomic masses of the atoms in the molecule's empirical formula.

Answer

$M(C) = 12$ g/mol

$M(H) = 1$ g/mol

$M(O) = 16$ g/mol

$\alpha \times (M(CH_2O)) = 60$ g/mol (molecular ion peak of mass spectrum)

$(12 \times \alpha) + (1 \times (2 \times \alpha)) + (16 \times \alpha) = 60$

$12\alpha + 2\alpha + 16\alpha = 60$

$30\alpha = 60$

$\alpha = 2$

Therefore, the molecular formula is $C_2H_4O_2$.

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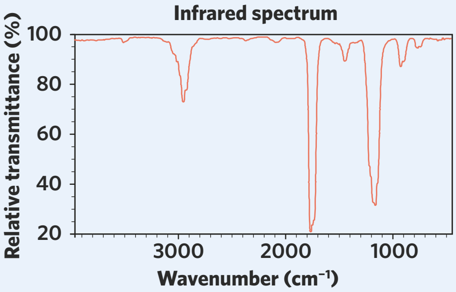
b. **Identify the structural formula of Compound A with the aid of the IR spectrum shown.**



What information is presented in the question?

IR spectrum

Molecular formula: $C_2H_4O_2$

What is the question asking us to do?

Determine the structural formula

What strategy(ies) do we need in order to answer the question?

1. We know that the absorption bands on the IR spectrum relate to the presence of certain funtional groups and bonds.
2. Next we need to identify the possible isomers with the known molecular formula.
3. Using the IR spectrum, we can see which of the isomers will create the above absorption bands.

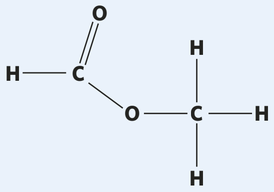
Answer

The IR spectrum is very useful in determining the bonds and functional groups present. With the molecular formula $C_2H_4O_2$, this could potentially be an ester, a carboxylic acid or perhaps even an alkene with two hydroxyl groups. Therefore, let's look at the IR spectrum again and see if we can eliminate any of the options and justify our choice.

If this compound were an acid, then there would be a large and broad O—H (acid) absorption band in the 2500–3500 cm^{-1} region. If it were the compound with two hydroxyl groups, we would also expect a large and broad O—H (alcohol) absorption band in the 3200–3600 cm^{-1} region.

Because neither of these are present, the compound must be an ester. This can be confirmed by the presence of a C═O (ester) peak in the 1720–1840 cm^{-1} region. Therefore, the structure must be methyl methanoate because it is the only ester with the required two carbons.

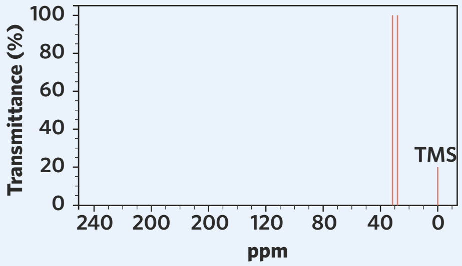
We can also check that methyl methanoate's molar mass is indeed 60 g/mol by drawing its structural and molecular formula: $C_2H_4O_2$.

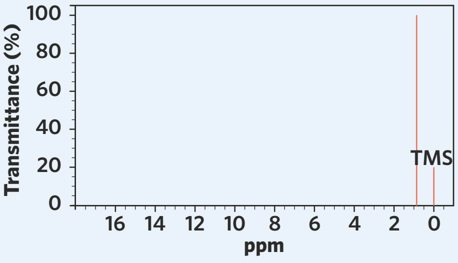


This question highlights that only by using all of these tools of analysis can a compound be accurately identified.

2 Worked example

Previous analysis of compound B has revealed that it has a molecular formula of C_5H_{12}. Its ^{13}C NMR (left) and ^{1}H NMR (right) are shown. Name compound B.





What information is presented in the question?

^{1}H NMR spectrum

^{13}C NMR spectrum

Molecular formula: C_5H_{12}

What is the question asking us to do?

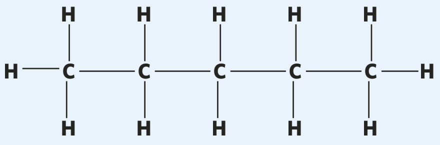
Determine the molecular formula and name of the compound.

What strategy(ies) do we need in order to answer the question?

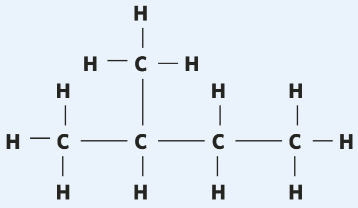
1. Identify and draw all possible structural isomers of C_5H_{12}.
2. Find how many carbon and hydrogen environments exist in each one.
3. Match the given ^{1}H NMR spectrum and ^{13}C NMR spectrum to the appropriate isomer.

Answer

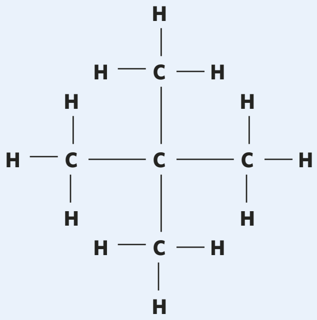
Here are three isomers with the molecular formula C_5H_{12}.



Pentane

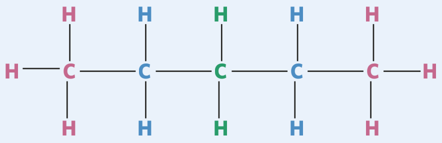


2-methylbutane



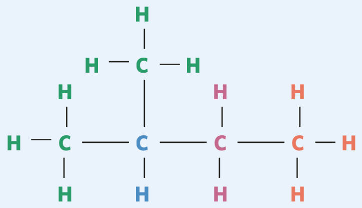
2,2-dimethylpropane

Here are the number of ^{1}H and ^{13}C environments in each isomer.



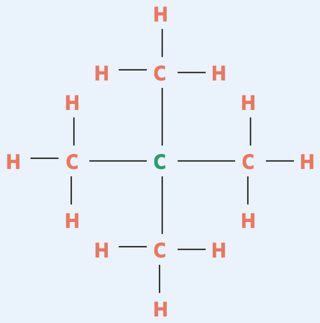
3 ^{13}C environments

3 ^{1}H environments



4 ^{13}C environments

4 ^{1}H environments



2 ^{13}C environments

1 ^{1}H environment

The given ^{13}C NMR spectrum has 2 peaks, which indicates 2 distinct carbon environments, and the ^{1}H NMR has 1 peak indicating 1 proton environment. Since 2,2-dimethylpropane is the only isomer that fits these criteria, it must be compound B.

Theory summary

- Mass spectrometry, infrared spectroscopy, ^{13}C NMR and ^{1}H NMR all reveal important information about a compound.
- By using a combination of these techniques together, an unknown compound can be identified with greater accuracy.

8D QUESTIONS

Theory review questions

Question 1

Mass spectrometry can reveal the

A branching pattern of a compound only.

B molecular mass of a compound only.

C branching pattern of a compound and the molecular mass of a compound.

D number of ^{13}C environments.

Question 2

The ^{13}C NMR spectrum can reveal

A the number of carbon atoms in each environment.

B the types of carbon environments present.

C the number of protons bonded to the adjacent carbon atom.

D None of the above

Question 3

IR spectroscopy is used to

A find the molecular mass of a compound.

B find the number of proton environments.

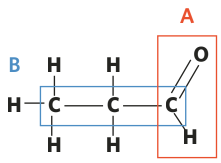
C find the functional groups present.

D None of the above

Question 4

Consider the provided molecule.

The analytical technique that would give the most accurate information about the identity of the parts A and B respectively would be



A ^{1}H NMR and ^{13}C NMR.

B IR and mass spectrometry.

C Mass spectrometry and ^{1}H NMR.

D IR and ^{13}C NMR.

Question 5

Which of the following statements involving ^{13}C NMR, ^{1}H NMR and IR are true?

I All techniques are based on the interaction between the sample molecule and electromagnetic radiation.

II All techniques affect the sample in the same way.

III All techniques measure the wavenumber absorbed by the molecule.

A I only

B I & II only

C III & II only

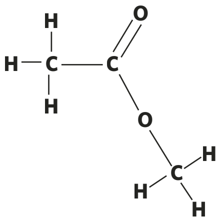
D III & I only

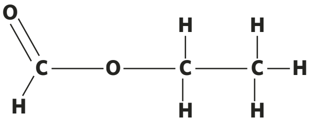
Exam-style questions

Within lesson

Question 6 (1 MARK)

Which of the following points of analysis would be unable to distinguish between these two compounds?





A IR spectroscopy

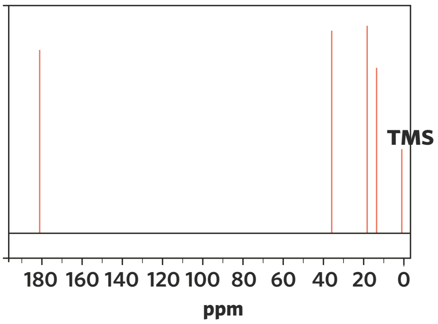
B The number of peaks in ^{13}C NMR spectrum

C The number of peaks in ^{1}H NMR spectrum

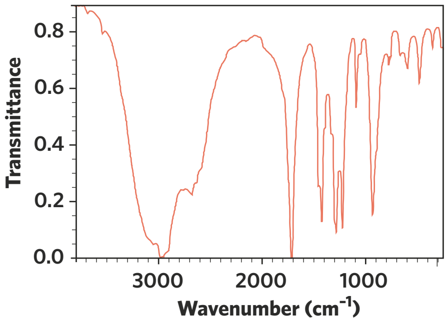
D Mass spectrum

Question 7 (1 MARK)

These two spectra were produced in order to analyse an unknown compound Z.



^{13}C NMR spectrum of compound Z



Infrared spectrum of compound Z

Which of the following compounds would be consistent with these results?

A Butanoic acid

B Propyl ethanoate

C Ethyl propanoate

D Butanal

Question 8 (1 MARK)

Consider the following data and conclude which of the following molecules could produce these results.

A Propan-2-one

B Propan-2-ol

C Propan-1-amine

D Propanal

Technique	**Data**
Mass spectrum	Molecular ion peak at m/z = 58
^{1}H NMR spectrum	3 peaks
^{13}C NMR spectrum	3 peaks

Question 9 (4 MARKS)

There are two alcohols with the molecular formula C_2H_6O; propan-1-ol and propan-2-ol. Using your knowledge of their structures, explain how a chemist could differentiate between the two using

a ^{13}C NMR spectroscopy. (2 MARKS)

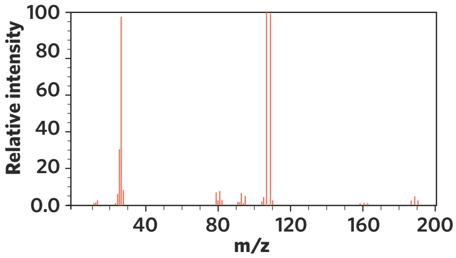
b low resolution ^{1}H NMR spectroscopy. (2 MARKS)

Use a diagram to support your answer.

Question 10 (5 MARKS)

Amelia was asked to determine the structure of a molecule with the formula $C_2H_4Br_2$.

Below is a spectrum showing the results obtained from her analysis.



a The peaks at m/z = 186, 188 and 190 are all considered as the molecular ion peak. Explain why this is the case. (2 MARKS)

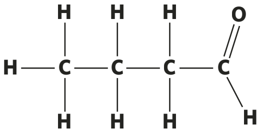
b ^{1}H NMR analysis of one of the isomers resulted in the following:

Chemical shift	Splitting pattern
5.8 ppm	Quartet
2.4 ppm	Doublet

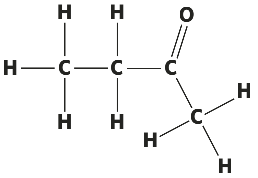
Using the results above, identify the isomer responsible for this data. Justify your answer. (3 MARKS)

Question 11 (6 MARKS)

The molecular structures of two organic compounds with the same molecular formula, butanal and butan-2-one, are shown below.



Butanal



Butan-2-one

a Jasmine wanted to use mass spectrometry to determine the identity of a sample containing one of the above compounds. When she asked her teacher, she was told that it was not the most suitable technique. Explain why mass spectrometry would not be the ideal approach for this investigation. (2 MARKS)

b In another analysis, Jasmine produced one of the two above species however didn't know which of the two molecules was actually produced during the experiment. Using IR spectroscopy, suggest a way that Jasmine could differentiate between the two compounds. (Hint – think about the different regions of an IR spectrum.) (2 MARKS)

c Jasmine wanted to be certain of this result and used ^{1}H NMR spectroscopy. The spectrum that was produced had 4 proton environments. Using the structure of each of the two species, explain which compound she had just analysed. (2 MARKS)

Multiple lessons

Question 12 (6 MARKS)

Katherine, a third year university chemistry student, has decided to analyse an unknown compound which has the empirical formula $C_3H_6O_2$ and produced the following results using a variety of organic chemistry analytical techniques:

Mass spectrum: the largest observable peak occurs at m/z = 74

IR spectrum: there is no broad absorption band in the 2500–3500 cm^{-1} region

^{1}H NMR results were obtained and are displayed in the following table

Chemical shift (ppm)	Peak ratio	Splitting
9.6	1	Singlet
4.0	2	Quartet
1.0	3	Triplet

a What is the molecular formula of this compound? (1 MARK)

b The molecular formula implies that this molecule could be one of three different types of organic compounds. Using the IR spectrum, identify the compound. (1 MARK)

c Using the ^{1}H NMR results, draw and name the compound being tested. (2 MARKS)

d Name the type of reaction that was used to create this compound and write the equation, including all necessary reagents, to represent the reaction involved. (2 MARKS)

8E CHROMATOGRAPHY

In this lesson, we will be learning about the principles of chromatography and how it is used to qualitatively analyse samples.

8A Mass spectrometry	8B Infrared spectroscopy	8C Nuclear magnetic resonance	8D Combining techniques	8E Chromatography	8F Volumetric analysis

Study design dot point

- the principles of chromatography including use of high performance lquid chromatography (HPLC) and construction and use of a calibration curve to determine the concentration of an organic compound in a solution

Key knowledge units

Principles of chromatography	4.1.11.1.1
HPLC	4.1.11.1.2
Analysing chromatograms	4.1.11.1.3

Key terms and definitions

- **Chromatography** analytical technique used to determine the identity of components in a mixture as well as their concentration
- **Chromatogram** visual output of chromatography which can be analysed
- **Stationary phase** solid onto which the components of a sample adsorb
- **Mobile phase** phase that flows through the stationary phase carrying components of a sample with it
- **Adsorption** component adheres to the stationary phase (in the context of chromatography)
- **Desorption** a component is released from the stationary phase and dissolves into the mobile phase (in the context of chromatography)
- **HPLC** (High performance liquid chromatography) type of chromatography technique which pumps the mobile phase through a very tightly packed stationary phase under high pressure
- **Calibration curve** curve that is developed from a set of known standards and is used to identify the concentration of a sample
- **Retention time, R_t** measure of time taken for a component to travel through a chromatography column e.g. HPLC column
- **Eluent** combination of the mobile phase and sample that moves through the HPLC column

Principles of chromatography 4.1.11.1.1

OVERVIEW

Chromatography is a common analytical tool used to identify unknown components of a sample based upon the unique retention time of each component. It can also quantitatively determine how much of a substance is present, but first a reference frame known as a calibration curve must be created using samples of known concentrations.

THEORY DETAILS

Chromatography is a widely used technique for separating and analysing complex mixtures of organic compounds. All methods of chromatography have a **stationary phase** and a **mobile phase**. The mobile phase is what the components of a sample dissolve into and is, for the most part, a liquid. The stationary phase is the surface that the mobile phase (and subsequently sample) flows over. This technique relies on the following two key ideas:

1. How well the stationary phase adsorbs to the sample through a force of attraction (this is known as **adsorption** to the stationary phase).
2. How well the mobile phase can dissolve the sample through an attractive force (this is known as **desorption** into the mobile phase).

Think of it as a tug of war between the stationary phase and the mobile phase as shown in figure 1.

For example, if we have a polar stationary phase, we know that it is capable of permanent dipole-dipole bonding. This means that if a component in the sample is also polar it will be strongly adsorbed to the stationary phase. However, if the mobile phase is polar instead, a polar component will be more strongly desorbed into the mobile phase. Since the components of a mixture have different structures, they will all have different types of intermolecular interactions with varying strength. In turn, the components will be attracted to the stationary phase and the mobile phase differently. As a consequence, each unique substance will have its own specific **retention time** and we can easily recognise each one from the time it takes to elute.

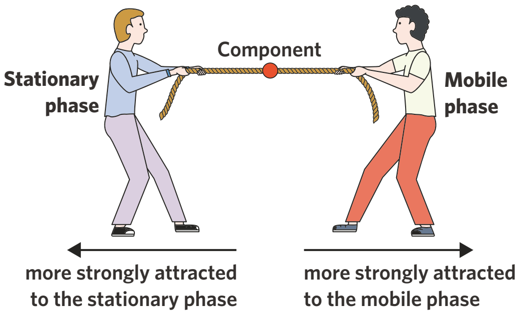


Figure 1 A graphical representation of a component's attraction to the stationary phase and the mobile phase

The reason this technique is commonly used is due to its ability to extract components of a mixture without irreparably damaging the sample. That is, in other types of analysis like mass spectrometry, the sample is destroyed in the process whereas using chromatography means that the sample can be recollected at the end as separate components and then undergo another kind of analysis, giving us a more complete and accurate picture of the compounds in the sample.

HPLC 4.1.11.1.2

OVERVIEW

High performance liquid chromatography (**HPLC**) is a chromatography technique that consists of a solid stationary phase which is tightly packed into a glass column and a solvent acting as the mobile phase.

THEORY DETAILS

High performance liquid chromatography (HPLC) is a highly sensitive analytical technique which is widely used in laboratories across the world. For example, pharmaceutical companies use this technique to determine the quality and purity of their products. In order to achieve the greatest separation possible, a column is set up with a solid stationary phase which consists of tiny particles. Since these particles are very small, they allow for a large number of interactions between the stationary phase and the components in the sample because of the increased total surface area. However, the smaller the particles, the greater the resistance to flow and therefore the mobile phase has to be pumped in at high pressure; hence the name of this technique. A diagram of a column used in HPLC is shown in figure 2.

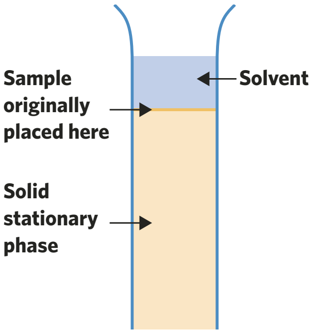


Figure 2 Diagram of a column used in chromatography

A component that is more strongly adsorbed to the stationary phase will spend more time in this phase compared to another component which is less strongly adsorbed to the stationary phase. Likewise, a component that is more soluble in the mobile phase will spend more time in the mobile phase compared to another component which is less soluble in the mobile phase. Therefore, in simpler terms, the components experience different rates of adsorption to the stationary phase and desorption into the mobile phase, leading to different retention times and hence separation on the column. Retention time, in this context, is the time that a component of a sample spends in the HPLC column. The full setup of this technique is illustrated in figure 3.

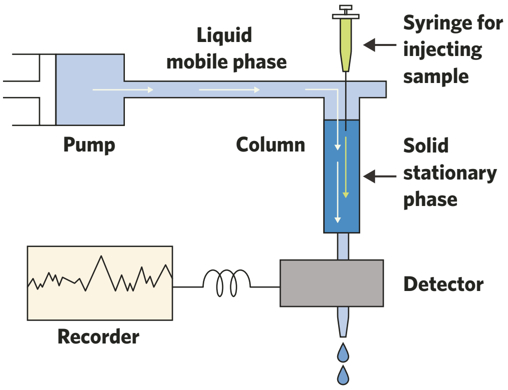


Figure 3 Diagram of the elements of HPLC

Since many organic compounds are clear and cannot be seen with the eye when emerging from the end of the column, a recorder is used to detect the presence of organic compounds based on their absorption of UV light. Therefore, if an organic compound is present in the **eluent** stream, the recorder will detect a decrease in the UV light signal. This is recorded on a chromatogram.

The length of time taken for a component to pass through the column is called the retention time and as mentioned above, depends on the extent to which the components in the sample are attracted to the stationary/mobile phase. This is used to identify the components of a sample because, if carried out under the same conditions, a component will always have the same retention time and therefore, retention time acts as a way to confirm the presence of a specific component in the sample.

Due to the importance of the forces of attraction between each component and the stationary and mobile phase, there are a variety of factors which can influence retention time. These include:

- Identity and composition of the stationary phase
- Identity and composition of the mobile phase
- Length of the column
- Temperature of the column
- Mobile phase flow rate
- Surface area of the stationary phase

The effects of these changes are outlined in table 1.

Table 1 The effect of a change to conditions on retention time

Change to conditions	Effect on retention time
Longer column	Increased
Increased temperature	Decreased
Increased flow rate of mobile phase	Decreased
Increased total surface area of stationary phase	Increased

This is because all of these changes in some way affect the forces of attraction that occur between components of a sample and the stationary and mobile phase. For example, as we learned in Units 1&2, when the temperature increases, so does the solubility of most substances, excluding gases. This means that in HPLC, an increase in temperature (and thereby solubility) will result in components being more strongly desorbed into the mobile phase, leading to shorter retention times.

Analysing chromatograms 4.1.11.1.3

OVERVIEW

Chromatograms produced by HPLC can reveal important information about the composition of a mixture. This information can either be qualitative (i.e. the identities of components in a mixture) or quantitative (i.e. how much of a component there is).

THEORY DETAILS

Without calibration, chromatography is purely qualitative as it allows us to find the identities of different components based on their retention times. For example, a chemist has just analysed the components of a sample using HPLC and the chromatogram shown in figure 4 was produced.

Each peak in the chromatogram represents a component in the sample. The three peaks indicate that there are 3 components in this sample. The chemist also knows that under the exact same conditions the following retention times were recorded.

Table 2 Components and their respective retention times

Identity of component	Retention time (min)
Glucose	10
Benzene	2.9
Methyl methanoate	6.8

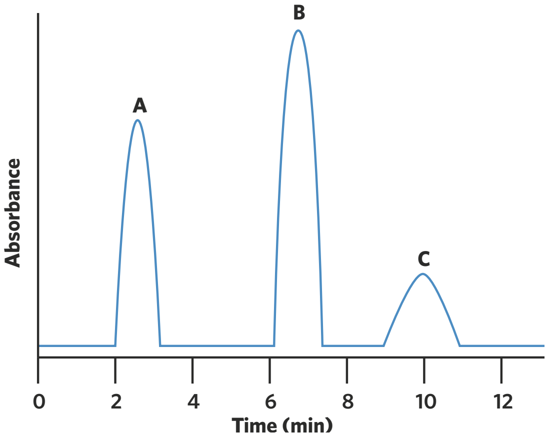


Figure 4 A sample HPLC chromatogram

Therefore, by matching the observed retention times to the retention times of known samples, the chemist can qualitatively determine that the sample consists of glucose (its retention time matches that of peak C), benzene (the retention time that matches that of peak A) and methyl methanoate (the retention time that matches that of peak B). This is one of the very powerful uses of HPLC.

The other powerful piece of information that HPLC can provide relates to quantitative data, which tells us 'how much' of a substance is present. Since the amount of a substance is proportional to the area under its peak, a chromatogram can also reveal the amount of a substance present. This is achieved by running a set of standards of known concentrations in the same HPLC column under the exact same conditions. Having done this, a **calibration curve** like the one shown in figure 5 can be constructed which relates the area under the peak to the concentration or amount of substance present.

In this case, a chemist's unknown sample had a peak area of around 0.36 cm^2. Therefore, by drawing a calibration curve using a 'line of best fit', this value can be matched to an appropriate concentration which is 0.6 M. It is also important to note that a calibration curve is only accurate for concentrations that are contained within the upper and lower bounds of the samples. As a general rule of thumb, we also want to have at least two data points both above and below our unknown concentration to ensure a high level of accuracy. If we created a calibration curve using concentrations that did not include the peak area we wanted to investigate, we would not be able to accurately determine the concentration of the substance.

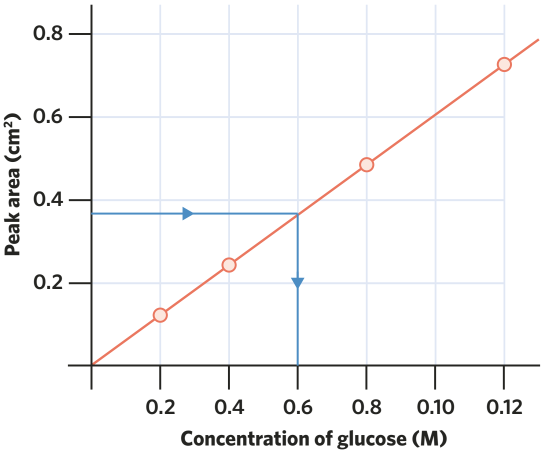


Figure 5 Calibration curve comparing peak area and the concentration of glucose

Theory summary

- Chromatography is an analytical tool used to determine the components of a sample as well as their concentration.
- The output of a chromatography instrument yields a chromatogram, which can be used to identify components of a sample.
- A chromatogram produced by HPLC shows the retention times of the components which can be matched to those of known organic compounds calculated under the same conditions.
- A calibration curve can be constructed by running samples of known concentrations which can relate the area under the peak to the concentration of the component in the sample.

8E QUESTIONS

Theory review questions

Question 1

What can chromatography be used for?

A Separating components only

B Identifying unknown components only

C Determining the concentration of components only

D All of the above

Question 2

Which of the following does **not** influence the retention time of a component?

A Pressure of liquid

B Size of stationary phase particles

C Having a higher concentration of the component

D Temperature of column

Question 3

A calibration curve is generated to

A identify components.

B separate components.

C find retention times.

D determine the concentration of components.

Exam-style questions

Within lesson

Question 4 (1 MARK)

Which of the following components will be most strongly adsorbed to a polar stationary phase?

A Methanol

B Hexane

C 2-methyloctane

D Ethene

Question 5 (1 MARK)

Which of the following components will be most strongly desorbed into a non-polar mobile phase?

A Butan-1-ol

B Octane

C Methane

D Methanoic acid

Question 6 (1 MARK)

Consider the following statements about a high performance liquid chromatography (HPLC) column that uses a non-polar mobile phase and a polar stationary phase to analyse a solution:

I Polar molecules in the solution will be attracted to the solvent particles by dipole-dipole attraction.

II Non-polar molecules in the solution will be attracted to the stationary phase by dispersion forces.

III Non-polar molecules in the solution will travel through the HPLC column more rapidly than polar molecules.

Which of these statements are true?

A I and II only

B I and III only

C II and III only

D I, II and III

Question 7 (1 MARK)

The following calibration curve was generated by using samples of an Iron solution with concentrations of 1.0, 2.0, 3.0, 4.0 ppm.

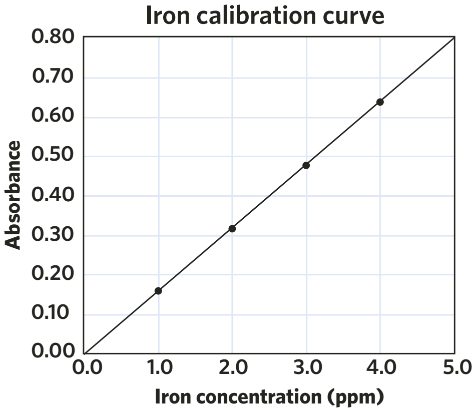
By measuring the absorbance of the solution, the concentration of iron in a test tube is most accurately able to be determined if it is between

A 6.0–7.0 ppm

B 0.0–0.5 ppm

C 1.0–1.2 ppm

D 2.4–2.6 ppm



Question 8 (3 MARKS)

Anna was trying to separate the compounds in a soft drink. Using your knowledge of chromatography, explain how components of a sample are separated by HPLC.

Question 9 (4 MARKS)

A doctor had just purchased a new HPLC device and wanted to start using it to determine the concentration of acetylsalicylic acid in a patient's blood.

In order to analyse patients results, the doctor developed a calibration curve.

a Outline the steps required to produce a calibration curve for this experiment. (2 MARK)

b During the analysis, the air conditioning in her practice suddenly stopped working, resulting in a dramatic increase in the temperature of the room where the HPLC device was set up.

Using your knowledge of chromatography, explain and justify what will happen to the retention times of components of a sample at this new elevated temperature. (2 MARKS)

Question 10 (2 MARKS)

There are two main types of HPLC – one is called normal phase HPLC which uses a polar stationary phase and a non-polar mobile phase, and the other is called reverse phase HPLC which uses a polar mobile phase and a non-polar stationary phase. Suggest which type would cause methanol to have a longer retention time than the other. Explain.

Question 11 (8 MARKS)

Katherine recently created her own brand of coffee and claims that each cup of 100 mL contains 40 mg of caffeine. In order to test this claim, a worker at the department of food safety decided to use HPLC by putting a sample from the cup of coffee into the HPLC column which produced a number of different peaks. The worker then ran samples of known concentrations of caffeine through the machine and recorded the area under the peaks.

a Explain how the worker could use the chromatograms with the standard solutions to confirm the presence of caffeine. (2 MARKS)

b Explain how the worker could use the area under the peak of known concentrations to determine whether Katherine's claim is correct. (2 MARKS)

c Using the following table, construct a calibration curve. (2 MARKS)

Concentration (mg/100 mL)	Area under peak (arbitrary units)
20	103
30	148
40	200
50	247
60	295
Katherine's coffee	180

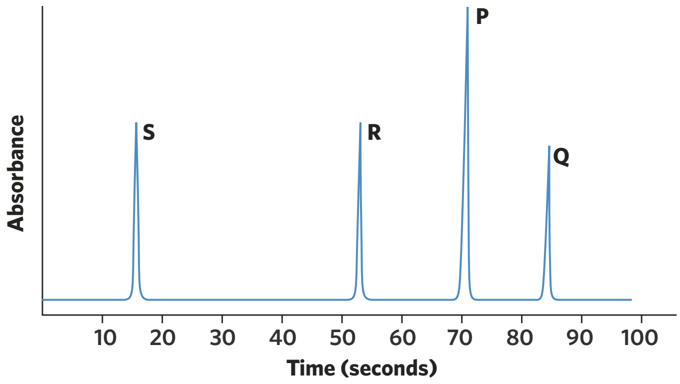
d Comment on the accuracy of Katherine's claim. (2 MARKS)

Multiple lessons

Question 12 (5 MARKS)

A small sample was taken from a crime scene and sent off to the laboratory for forensic analysis. The analyst decided to use HPLC with a polar stationary phase to analyse the sample. The results are shown in the graph.

Adapted from VCAA 2016 Short Answer Q1



a It was identified that there were 4 different components present in the sample – propanoic acid, propane, ethanol and methane. Identify the peaks corresponding to each of the molecules. (1 MARK)

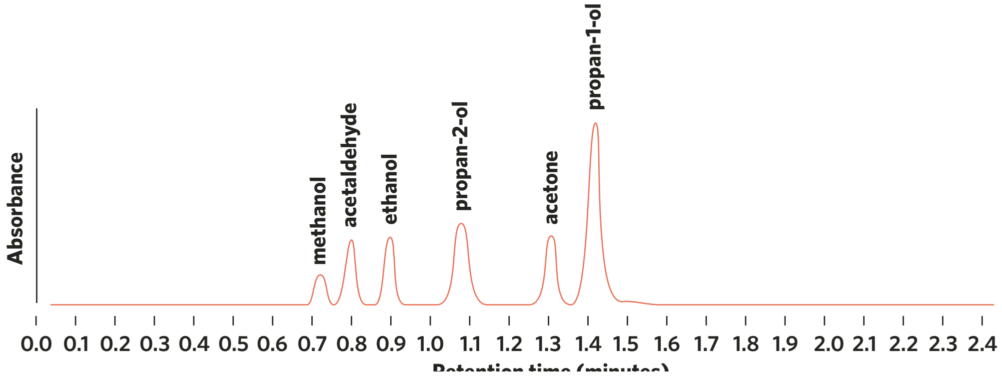
b Unfortunately, due to improper laboratory practices, two of the molecules in the sample underwent a condensation reaction which resulted in a funny smelling vapor. Write a full balanced equation using molecular formula to represent this reaction and identify the name of the main product formed. (2 MARKS)

c Draw the structural formula for the product identified in part b. (1 MARK)

d The analyst wanted to use mass spectrometry to confirm the molecules present. Identify the disadvantage of using this technique in this situation. (1 MARK)

Question 13 (5 MARKS)

Sergeant Harris pulled over a driver who was driving erratically on the freeway. Following protocol, Sergeant Harris took a sample from the driver and sent it off for analysis. The results from HPLC analysis are shown below.



Adapted from VCAA 2010 Exam 1 Short Answer Q5

a Identify the type of stationary phase used in this analysis. (1 MARK)

b Propan-2-ol and propan-1-ol both have the same molecular formula, but show different retention times. Further analysis of both molecules show that the boiling points of both molecules are also different. Explain this difference in boiling point of the two molecules. (2 MARKS)

c Both propan-2-ol and propan-1-ol were extracted from the sample and allowed to undergo oxidation. Give the names of the types of organic molecules formed when each of the two alcohols underwent oxidation. (2 MARKS)

8F VOLUMETRIC ANALYSIS

In this lesson, we will learn how titration is used as an analytic technique in the context of acid-base and redox reactions to determine the unknown concentration of different solutions.

8A Mass spectrometry	8B Infrared spectroscopy	8C Nuclear magnetic resonance	8D Combining techniques	8E Chromatography	8F Volumetric analysis

Study design dot point

- determination of the concentration of an organic compound by volumetric analysis, including the principles of direct acid-base and redox titrations (excluding back titrations)

Key knowledge units

Principles of titration	4.1.12.1
Acid-base titration	4.1.12.2.1
Redox titration	4.1.12.2.2

Key terms and definitions

- **Standard solution** solution of accurately known concentration
- **Primary standard** substance used to make a primary standard solution
- **Primary standard solution** solution whose concentration can be precisely calculated
- **Titration** quantitative technique used to find the unknown concentration and/or amount of solutions
- **Titrant** solution of known concentration used in a titration reaction
- **Analyte** substance being analysed in a titration reaction
- **Titre** volume of the solution delivered from the burette to reach the end point of titration
- **Aliquot** portion of sample solution that is to be analysed during titration
- **Concordant titres** volume of three or more titres that fall within approximately 0.1 mL of each other
- **Endpoint** point at which a colour change occurs during a titration
- **Equivalence point** point at which the reaction has occurred as per the stoichiometric ratio of the balanced equation
- **Indicator** substance that will experience a colour change under a specific condition

Lesson links

This lesson builds on:

▶ 4A – Redox reactions

Some titration reactions can involve redox reactions.

Principles of titration 4.1.12.1

OVERVIEW

Titration reactions are used to determine the unknown concentration of a solution or amount of a substance in a solution.

THEORY DETAILS

As you may recall from unit 2, titration is a quantitative analysis technique that is often used to determine the concentration of unknown solutions. As part of this process, a solution of accurately known concentration, also known as the **titrant**, is used to measure the amount or concentration of a substance in a sample solution, also referred to as the **analyte**. The basic setup of this reaction can be seen in figure 1. The titrant is dispensed incrementally from the burette and reacts gradually with the analyte in the conical flask.

During titration, the titrant and analyte undergo a chemical reaction which eventually causes a colour change in the solution found in the flask. This colour change represents the **endpoint** and is able to be detected because of the presence of an **indicator** that was initially added into the sample solution.

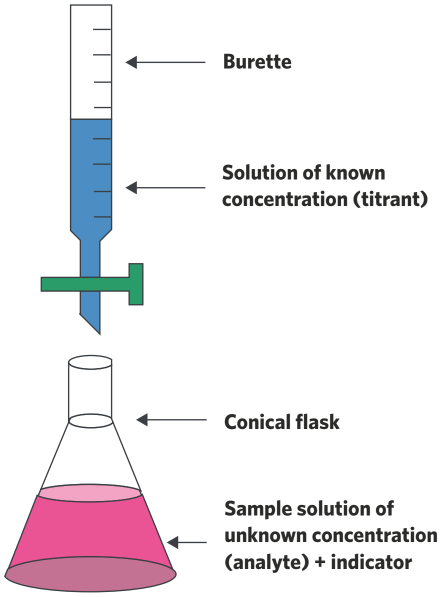
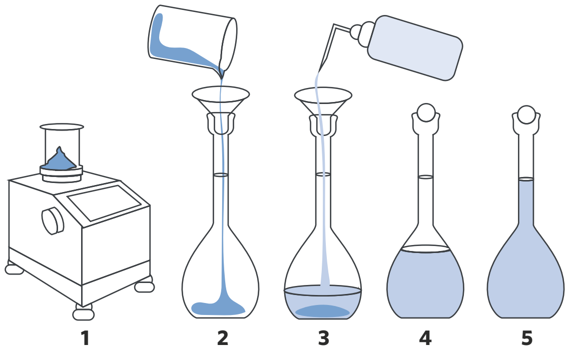


Figure 1 The basic setup for a titration reaction

Not only does this indicate the end of the titration, but also that the titrant and analyte have reacted to the stoichiometric ratio as indicated in the balanced chemical equation, referred to as the **equivalence point**. Due to this, it is very important that we choose an appropriate indicator in which the colour change occurs within the range of the equivalence point. It is important to note that the endpoint generally occurs just before the equivalence point. However, for calculation purposes, we assume that the equivalence point is approximately the same as the endpoint. The volume of titrant, known as the **titre**, used to reach the endpoint is measured and used to calculate the amount or concentration of the analyte solution. This process is repeated multiple times until **concordant titres** (usually all titres within ±0.1 mL) are obtained to increase the reliability and precision of the results by minimising the effects of random errors.

The solution of accurately known concentration used in titration is known as a **standard solution**. The titrant used is often standardised by a solution known as the **primary standard solution.**

To prepare the primary standard solution, a **primary standard** is accurately weighed and dissolved in deionised water in a volumetric flask according to the steps outlined in figure 2. The amount of primary standard used depends on the concentration of the solution we want to prepare.



1 Mass of primary standard is weighed
2 Primary standard is transferred to volumetric flask
3 Deionised water is added to the volumetric flask until primary standard is dissolved
4 Solution is left at rest to allow any volume expansion from newly-formed intermolecular bonds
5 Deionised water is added until the meniscus lies on the required volume

Figure 2 Preparation of a primary standard solution

The steps required to prepare the primary standard, as illustrated in figure 2, are quite straightforward. Due to the fact that the primary standard solution is used to confirm the concentration of other secondary standard solutions (those used during titration), there are some criteria that need to be met before substances can be considered to be used as a primary standard, such as:

- The substance must be pure and found in a stable form.
- The substance must not react with the atmosphere (e.g. moisture, carbon dioxide etc.).
- The substance must be soluble in solution.
- The substance must be readily available (+ inexpensive).
- The substance must be able to be weighed accurately (high, known molar mass to reduce error).

An example of a primary standard would be sodium carbonate Na_2CO_3 (anhydrous or 'without water'), which fits all of the above criteria. Common reagents such as NaOH and HCl cannot be used as primary standards as they both will react with the atmosphere. Sodium hydroxide reacts with CO_2 from the atmosphere according to the following equation:

$$NaOH_{(s)} + CO_{2(g)} \rightarrow Na_2CO_{3(s)} + H_2O_{(l)}$$

This leads to a significant mass increase that will affect any calculations made using the initial concentration of sodium hydroxide. Any concentration of HCl will also change over time, as it has a tendency to vaporise in small amounts when exposed to standard laboratory conditions, again affecting any calculations made using its initial concentration.

Any factor that may compromise the concentration of the solution will affect the results obtained during the titration reaction, therefore we must be careful when choosing a primary standard. Furthermore, we need to be just as careful during the preparation of the standard solution to minimize the chances of errors occurring. For example:

- Incorrect weighing of substances
- Contamination of instruments used or substances
- Rinsing of apparatus with an inappropriate substance

All of these errors can impact on the accuracy of the standard solution produced, which will then affect the results obtained.

Acid-base titrations 4.1.12.2.1

OVERVIEW

Acid-base titrations are used to determine the concentration of acids or bases via a neutralisation reaction between the two substances.

THEORY DETAILS

As a recap of unit 2, acid-base reactions are neutralisation reactions in which the hydroxide ions (OH^-) from the base react with hydrogen ions (H^+) from the acid to produce an ionic 'salt' and water. In an acid-base reaction, this hydrogen ion is transferred from the acid to the base. Using the same setup as other titration reactions, acid-base titration reactions are used to determine the concentration of an unknown base or acid. The average value of concordant titres, or mean titre, obtained during the reaction is used in calculations to determine the unknown value.

A list of indicators and their associated pH ranges can be found in the databook

1 Worked example

Chris and Tom were asked to determine the concentration of a sample of the basic calcium hydroxide solution, $Ca(OH)_2$. After conducting multiple titrations with a 20.00 mL aliquot of calcium hydroxide, they found that it took an average of 21.40 mL of 1.50 M nitric acid, HNO_3, solution for a colour change to occur. Calculate the concentration of the calcium hydroxide solution.

What information is presented in the question?

20.00 mL aliquot of calcium hydroxide

21.40 mL of 1.50 M nitric acid used

What is the question asking us to do?

Find the concentration of calcium hydroxide.

What strategy(ies) do we need in order to answer the question?

1. Determine the amount of nitric acid used in the reaction.
2. Use stoichiometry to determine the amount of calcium hydroxide present in the aliquot.
3. Find the concentration of the calcium hydroxide.

Answer

The balanced equation for this reaction is

$$2HNO_{3(aq)} + Ca(OH)_{2(aq)} \rightarrow Ca(NO_3)_{2(aq)} + 2H_2O_{(l)}$$

$$n(HNO_3) = 1.50\text{ M} \times \left(\frac{21.40\text{ mL}}{1000\text{ mL}}\right)\text{L}$$

$$= 0.0321\text{ mol}$$

$$n(HNO_3) : Ca(OH)_2$$

$$2 : 1$$

$$n(Ca(OH)_2) = 0.0321\text{ mol} \times \frac{1}{2}$$

$$= 0.0161\text{ mol}$$

$$c(Ca(OH)_2 = \frac{0.0161\text{ mol}}{0.02000\text{ L}}$$

$$= 0.8025\text{ M}$$

$$= 0.803\text{ M correct to 3 sig figs}$$

Acid-base reactions can be represented through a titration curve which shows the change in pH of the analyte solution during titration. The change in pH throughout the reaction depends on the concentration of hydroxide and hydrogen (or hydronium H_3O^+) ions found in the analyte solution.

As highlighted in figure 3, the equivalence point can be located at the point during which the curvature of the curve starts to change. This can sometimes be referred to as the point of inflection. Based on the shape of the titration curves in figure 3, we can see that the analyte began as a basic solution and progressively became more acidic. From this, we can imply that the analyte solution is basic and the titrant is acidic.

When choosing an appropriate acid-base indicator, we need to make sure that the equivalence point falls within the pH range for the colour change of the indicator. For example, when a strong acid reacts with a weak base, we would expect that the pH of the solution at the equivalence point would be lower than 7 (i.e. more acidic) and therefore need to pick an acid-base indicator that will change colour within this range.

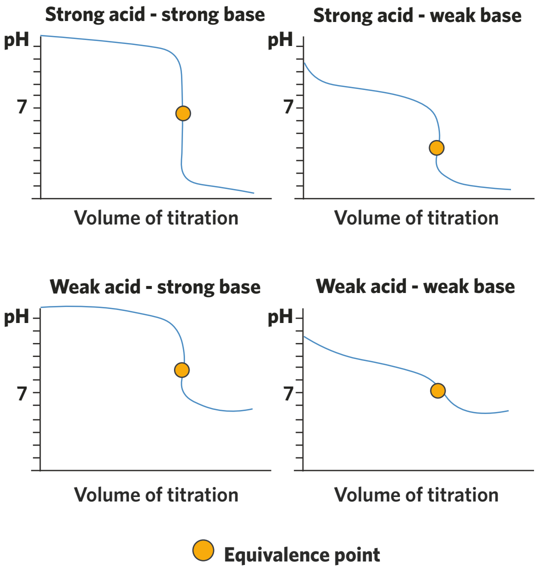


Figure 3 Example of a titration curve involving the titration of different strengths of acids and bases.

Redox titrations 4.1.12.2.2

OVERVIEW

Redox titration reactions involve the redox reaction between an oxidising and reducing agent.

THEORY DETAILS

As we learned previously in unit 3, redox reactions involve the exchange of electrons through the combination of both reduction and oxidation reactions. Redox titrations use the concept of these redox reactions to determine the unknown concentration and or amount of solutions.

2 Worked example

Without sulfur dioxide, wines can undergo a fermentation reaction that causes an unpleasant taste. The concentration of sulfur dioxide can be determined through a redox titration with an iodine solution as follows:

$SO_{2(aq)} + I_{2(aq)} + 2H_2O_{(l)} \rightarrow 4H^+_{(aq)} + SO_4{}^{2-}{}_{(aq)} + 2I^-{}_{(aq)}$

Starch was added to the wine sample as an indicator for this reaction.

a A mean titre of 14.88 mL of a 0.100 M iodine solution was used to react with a 20.00 mL aliquot of wine. Determine the concentration of sulfur dioxide in the wine sample.

b In order to prepare the wine sample for titration, 25.00 mL of wine was transferred to a volumetric flask and was filled to the 100.00 mL mark with deionised water. Determine the concentration of sulfur dioxide in the original wine.

---

a A mean titre of 14.88 mL of a 0.100 M iodine solution was used to react with a 20.00 mL aliquot of wine. Determine the concentration of sulfur dioxide in the wine sample.

What information is presented in the question?

14.88 mL of 0.100 M iodine solution was used.

20.00 mL aliquot of wine containing sulfur dioxide.

What is the question asking us to do?

Find the concentration of sulphur dioxide in the aliquot.

What strategy(ies) do we need in order to answer the question?

1. Determine the amount of iodine used.
2. Calculate the concentration of sulfur dioxide.

Answers

$n(I_2) = 0.100\text{M} \times (\frac{14.88 \text{ mL}}{1000 \text{ mL}})\text{L}$

$= 0.001488 \text{ mol}$

$n(I_2) : n(SO_2)$

$1 : 1$

$n(SO_2) = 0.001488 \text{ mol}$

$C(SO_2) = \frac{0.001488 \text{ mol}}{0.02000\text{L}}$

$=0.0744$ M correct to 3 sig figs

---

b In order to prepare the wine sample for titration, 25.00 mL of wine was transferred to a volumetric flask and was filled to the 100.00 mL mark with deionised water. Determine the concentration of sulfur dioxide in the original wine.

What information is presented in the question?

25.00 mL of of wine was diluted to 100.00 mL.

Aliquot was taken from this diluted solution.

What is the question asking us to do?

Calculate the concentration of sulfur dioxide in the original wine sample.

What strategy(ies) do we need in order to answer the question?

1. Determine the dilution factor.
2. Calculate the concentration of sulfur dioxide in original wine.

Answers

25.00 mL : 100.00 mL

1 : 4

Wine was diluted to the ratio of 1 : 4 – dilution factor is 4

$C(SO_2)_{\text{original}} = 0.0744 \text{ M} \times 4$

$= 0.298 \text{ M}$

As we can see from the worked example, the calculations involved in redox titration are similar to those of acid-base titration. The main differences between acid-base and redox titrations are the indicators used and the details of the titration curves.

Often redox titrations involve substances that change colour as a result of the redox reaction, which means they sometimes do not require the use of an indicator. Other times, substances such as starch can be used for reactions involving iodine (as shown in the worked example).

As seen in figure 4, redox titration curves show the changes in E^0 V (measured by a voltmeter) throughout the reaction as opposed to changes in pH as in acid-base reactions.

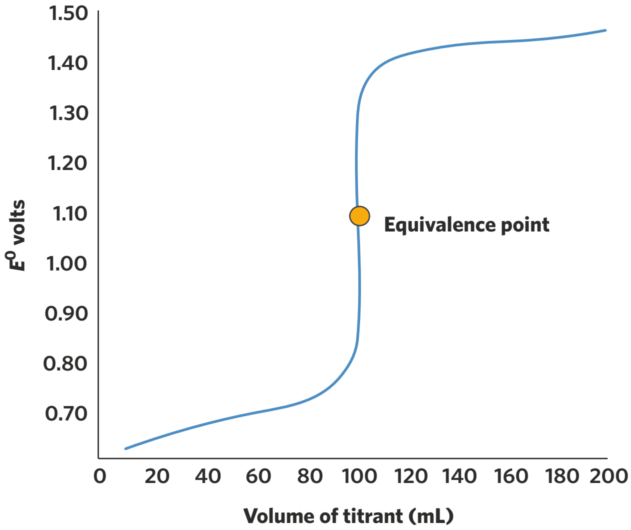


Figure 4 Example of a redox titration curve

Theory summary

- Titration is a quantitative technique to determine the unknown concentration of a solution and/or the amount of a compound in a solution.
- Titrations use standard solutions of known concentration to determine unknown concentrations.
- Primary standards need to be readily available, pure and not react with components in the air as it may compromise the concentration of the standard solution.
- Titration curves of acid-base reactions show pH changes whereas titration curves of redox reactions show changes in E^0 V.

8F QUESTIONS

Theory review questions

Question 1

Which one of the following does **not** describe a primary standard?

A Lightweight **B** Pure **C** Easily available **D** Can be dissolved in solution

Question 2

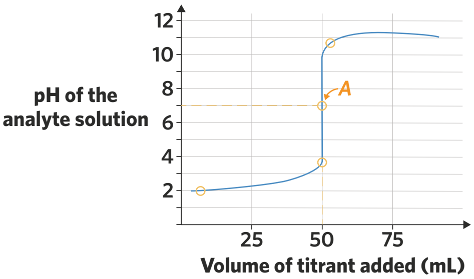
The point *A* that is referred to in the graph is known as the

A indicator point.

B equivalence point.

C endpoint.

D equal point.



Question 3

Fill in the missing words.

During titration, the ____________ found in the ____________ is added to the ____________ solution found in the conical flask. Due to the presence of the ____________, the analyte solution will eventually change colour, signifying the ____________ of the reaction.

A Primary standard; burette; titrant; indicator; equivalence point

B Titrant; burette; analyte; indicator; endpoint

C Primary standard; analyte; titrant; equivalence point

D Analyte; flask; titrant; detector; endpoint

Exam-style questions

Within lesson

Question 4 (1 MARK)

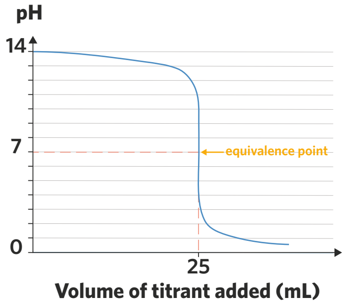
Based on the titration curve provided, what type of substance was present in the conical flask?

A Fuel

B Acid

C Base

D Solid metal



Question 5 (1 MARK)

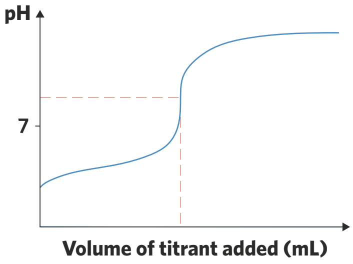
A student was asked to titrate an unknown acid with NaOH. The following titration curve illustrates the titration reaction that occurred. Based on the results, which of the following indicators is most suitable for this reaction?

A Methyl orange

B Methyl red

C Bromophenol blue

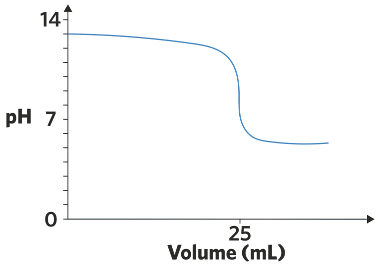
D Phenolphthalein



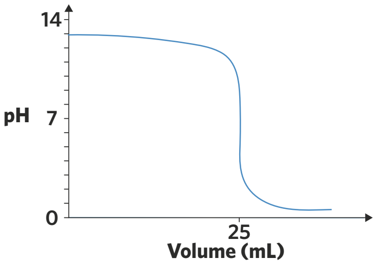
Question 6 (1 MARK)

Which of the following graphs represents a reaction in which the equivalence point occurs when the solution is at a pH of above 7?

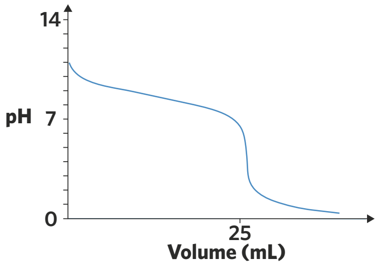
A



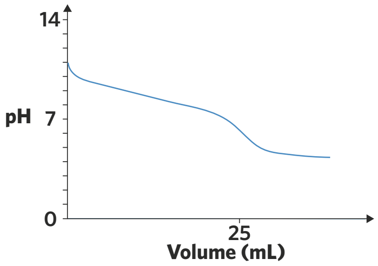
B



C



D



Adapted from VCAA 2015 Exam 2 MCQ 1

Question 7 (5 MARKS)

Carboxylic acids are weak acids that can be used in titration reactions involving bases. A 20.00 mL aliquot of NaOH was titrated against 0.20 M benzoic acid, C_6H_5COOH. The results can be found in the table.

Experiment number	Titre (mL)
1	12.01
2	12.10
3	11.98

a Write a balanced equation for this reaction. (1 MARK)

b Calculate the concentration of the NaOH solution. (3 MARKS)

c Benzoic acid is sometimes used as a primary standard for these types of reactions. What is meant by the term 'standard solution'? (1 MARK)

Question 8 (5 MARKS)

Oxalic acid, $H_2C_2O_4$, can be used as a protective layer on marble sculptures to preserve the integrity of the structure. Oxalic acid can take part in titration reactions with an acidified solution of potassium permanganate, $KMnO_4$, resulting in an exothermic reaction according to the equation:

$$2MnO_4^-{}_{(aq)} + 16H^+{}_{(aq)} + 5C_2O_4^{2-}{}_{(aq)} \rightarrow 2Mn^{2+}{}_{(aq)} + 8H_2O_{(l)} + 10CO_{2\,(g)}$$

In a titration between these two substances, it was found that an average of 18.91 mL of a 0.500 M solution of potassium permanganate was required to reach the endpoint.

a Given that an aliquot of 25.00 mL was used, determine the concentration of the oxalic acid solution. (3 MARKS)

b The oxalic acid aliquot was taken from a solution that was prepared by taking a 25.00 mL sample of concentrated oxalic acid solution and using deionised water to make it to 200.00 mL . Determine the mass of oxalic acid used to produce this solution. (2 MARKS)

Question 9 (6 MARKS)

A group of students were asked to perform a titration to find the concentration of an ammonia-based household cleaner. The students were given the following instructions:

1. Add 25.00 mL of household cleaner into a 250 mL volumetric flask.
2. Add deionised water to the flask until the solution reaches 250 mL.
3. Add a 20.00 mL aliquot of dilute household cleaner solution to a conical flask.
4. Add a few drops of indicator.
5. Fill the burette with 0.10 M HCl and titrate against the cleaner solution.
6. Repeat steps 3–5 until concordant titres are obtained.

a Write a balanced equation for the titration reaction between the cleaner solution and HCl. (1 MARK)

b Given that the mean titre of HCl used was 14.56 mL, calculate the concentration of ammonia in the aliquot. (2 MARKS)

c Determine the concentration of ammonia in the household cleaner. (1 MARK)

d The students were given the following indicators to use in their experiment: Bromophenol blue, phenolphthalein, phenol red. Given that ammonia is a relatively weak base, what would be the most suitable indicator to use in this titration reaction? Justify your answer. (2 MARKS)

Question 10 (7 MARKS)

Citrus fruits are acidic due to the presence of citric acid, $C_6H_8O_7$. A 0.50 M solution of sodium hydroxide was used to determine the concentration of citric acid in the following reaction:

$$3NaOH_{(aq)} + C_6H_8O_{7\,(aq)} \rightarrow Na_3C_6H_5O_{7(aq)} + 3H_2O_{(l)}$$

For a 20.00 mL sample of orange juice, the following titres (in mL) of sodium hydroxide were recorded:
13.51, 9.45, 14.01, 13.67, 13.55.

a Determine the concentration of citric acid found in the orange juice. (3 MARKS)

b Sodium hydroxide has a tendency to absorb moisture from the air. Based on this property, explain why sodium hydroxide cannot be used as a primary standard (2 MARKS)

c Potassium hydrogen phthalate ($M = 204.2\ g\ mol^{-1}$) is commonly used as a primary standard to standardise sodium hydroxide solutions. If 250.00 mL of a 1.0 M potassium hydrogen phthalate solution is required, outline the steps involved in the preparation of this standard solution. (2 MARKS)

Multiple lessons

Question 11 (6 MARKS)

Permanganate ions can be used to detect the presence of hydrogen peroxide. In order to do this, hydrogen peroxide, H_2O_2 is titrated with potassium permanganate, $KMnO_4$ during which hydrogen peroxide is oxidised to $O_{2(g)}$ by permanganate ions MnO_4^- and the permanganate ion is reduced to the Mn^{2+} ion. Due to the changes in oxidation state of the manganese ion, a colour change can be observed as a result of the reaction.

a Write a balanced overall redox equation for this reaction. (1 MARK)

b How could the experimenter tell that the permanganate ions underwent a redox reaction and not an acid-base reaction? (1 MARK)

c In an experiment, a student used 12.01 mL of a 1.50 g L^{-1} solution of potassium permanganate to titrate against a 20.00 mL aliquot of hydrogen peroxide. Determine the concentration of the hydrogen peroxide solution. (3 MARKS)

d Hydrogen peroxide can cause severe burns and eye damage. Identify 2 safety considerations when handling hydrogen peroxide. (1 MARK)

Question 12 (5 MARKS)

It was found that 14.55 mL of a 0.500 M solution of $KMnO_4$ was required to oxidise a 20.0 mL sample of $FeSO_4$ to Fe (III) ions in an acidic solution.

a Write a balanced redox half-equation for the reduction of permanganate ions to manganese ions, Mn^{2+}. (1 MARK)

b Determine the concentration of the $FeSO_4$ solution. (3 MARKS)

c The $FeSO_4$ aliquot used in the reaction was transferred from a 250.00 mL flask that was originally made from a 25 mL solution of concentrated $FeSO_4$. Determine the concentration of the original sample of $FeSO_4$. (1 MARK)

EXPERIMENT

VOLUMETRIC ANALYSIS OF HOUSEHOLD CLEANERS

Many household cleaning products contain ammonia (NH_3). Prolonged exposure to a concentrated ammonia can be harmful to the body. As chemists, we can determine the concentration of this ammonia through volumetric analysis.

Materials

(per group)

- Window cleaner (e.g. Windex)
- Methyl orange indicator
- Distilled water
- Hydrochloric acid (1.0 M)
- Burette
- Volumetric flask
- Conical flask
- Retort stand
- Clamp
- 10mL pipette
- Funnel
- 50 mL measuring cylinder
- 250 mL beaker

Method

1. Clamp the burette onto the retort stand.
2. Use a 10 mL pipette to add 10.0 mL of the window cleaner to a conical flask.
3. Using a measuring cylinder, measure and add 10.0 mL of distilled water to the conical flask.
4. Add three drops of methyl orange to the conical flask.
5. Place the conical flask underneath the burette that is clamped to the retort stand.
6. Loosen the clamp and slowly lower the position off the burette so that the tip is almost inside the opening of the conical flask.
7. Using a funnel, fill the burette with hydrochloric acid and record the starting volume.
8. Slowly release the hydrochloric acid from the burette whilst gently swirling the conical flask.
9. Allow the burette to deliver the hydrochloric acid until the solution in the conical flask turns from yellow to peach/light orange.
10. Record the final volume acid in the burette.
11. Discard the solution in conical flask and repeat steps 2–10 until concordant titres are reached.

Results

	Trial 1	**Trial 2**	**Trial 3**
Initial reading on the burette (mL)			
Final reading on the burette (mL)			
Titre (mL)			

QUESTIONS

Question 1 (2 MARKS)

List the dependent and independent variables in this experiment, and explain the difference between the two.

Question 2 (6 MARKS)

a A group of students conducting the same experiment got the following results:

Substance	**Result**
Household cleaner solution	20.0 mL
Hydrochloric acid	11.42 mL, 16.10 mL, 11.33 mL, 11.25 mL

Determine the concentration of ammonia in the original bottle of household cleaner. (3 MARKS)

b Using the experimental values obtained from your experiment, calculate the concentration of ammonia in the original bottle of household cleaner. (3 MARKS)

Question 3 (3 MARKS)

A chemistry student conducting this experiment rinsed the burette before the titration with distilled water. Another student rinsed the burette with hydrochloric acid. Which method will produce the most accurate results? Explain.

ANSWERS

1 [Dependent variable: Concentration of ammonia in the household cleaner[1]]
[Independent variable: The brand/type of household cleaner[2]]
[The independent variable is the variable we are manipulating to observe an effect. The dependent variable is the variable we are measuring.[3]]

✓ ✗ I have identified the dependent variable.[1]

✓ ✗ I have identified the independent variable.[2]

✓ ✗ I have compared both variable types.[3]

2 **a** $NH_{3(aq)} + HCl_{(aq)} \rightarrow NH_4Cl_{(aq)}$

$$\text{Avg titre for HCl} = \frac{11.42 + 11.33 + 11.25}{3}$$

$$= 11.33\text{ mL}$$

$$n(\text{HCl}) = 1.0\text{ M} \times (\tfrac{11.33}{1000})\text{L}$$

$$= 0.01133\text{ mol}$$

$n(\text{HCl}) : n(\text{NH}_3)$

1 : 1

$n(\text{NH}_3) = 0.01133\text{ mol}$

$$c(\text{NH}_3) = \frac{0.0133}{(20.0 \div 1000)\text{L}}$$

$$= 0.567\text{ M}$$

NH_3 was diluted 1:2, therefore:

$$c(\text{NH}_3)_{\text{household cleaner}} = 0.567 \times 2$$

$$= 1.13\text{ M}$$

b Please have your answer checked by your teacher.

3 [The burette is filled with hydrochloric acid of concentration 1.0 M.[1]][Rinsing the burette with water dilutes the HCl concentration, and thus more HCl would be required to neutralise the ammonia in the flask. So, the volume of HCl used in the reaction would be higher than the actual value. As a result, the concentration of ammonia calculated would be higher than the actual value.[2]][Rinsing the burette with HCl does not affect the concentration of HCl, and so does not affect the volume required to titrate. The concentration of ammonia calculated would be closer to the true value.[3]][Therefore, rinsing with HCl provides the most accurate results.[4]]

✓ ✗ I have identified the solution in the burette.[1]

✓ ✗ I have explained how washing the burette with water affects the results.[2]

✓ ✗ I have explained how washing the burette with hydrochloric acid affects the results.[3]

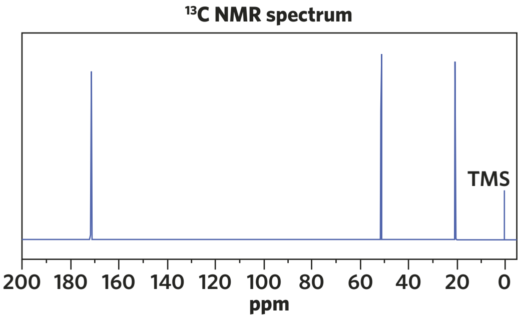
✓ ✗ I have linked the answer to the question.[4]

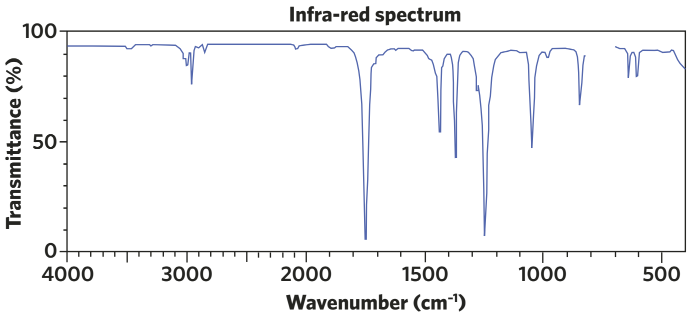
CHAPTER 8 QUESTIONS

MULTIPLE CHOICE (10 MARKS)

Question 1 (1 MARK)

An organic compound Q is under investigation. The two spectra given below were obtained via ^{13}C NMR and infrared spectroscopy.





Which of the following is consistent with the above spectra for compound Q?

A $CH_3CH(OH)CH_3$

B CH_3COCH_3

C $CH_3CH(OH)COONH_2$

D CH_3COOCH_3

Question 2 (1 MARK)

Compound D has the same molecular formula as the compound $CH_3COOCH_2CH_3$. If the ^{13}C NMR spectrum outputs three signals, which semi-structural formula best matches compound D?

A $CH_3CH_2COOCH_3$

B $CH_3CH_2CH_2COOH$

C $CH_3CH(CH_3)COOH$

D $HCOOCH_2CH_2CH_3$

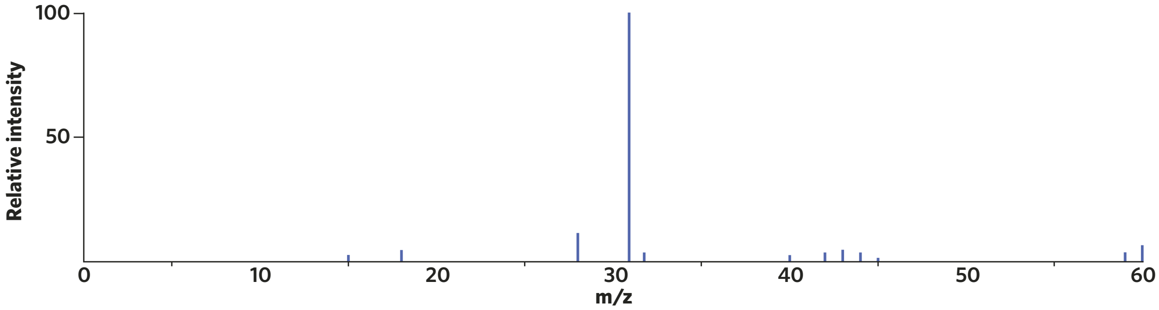
Question 3 (1 MARK)

A HPLC column has a non-polar stationary phase. Which of the following would be the most suitable mobile phase to distinguish between a mix of unknown carboxylic acids?

A	Decane	$C_{10}H_{22}$
B	Cyclohexane	C_6H_{12}
C	Carbon tetrachloride	CCl_4
D	Methyl ethanoate	CH_3COOCH_3

Use the following information to answer questions 4 and 5.

The mass spectrum for an unknown straight chain alkanol is shown below.



Question 4 (1 MARK)

Which of the following is the compound that produced this mass spectrum?

A CH_3COOH

B Butan-2-ol

C C_3H_8O

D Methyl methanoate

Question 5 (1 MARK)

The fragment that produces the base peak on the mass spectrum is

A $[CH_2OH]$

B $[C_3H_8O]^+$

C $[COOH]^-$

D $[CH_2OH]^+$

Question 6 (1 MARK)

The high resolution proton NMR of 2-chloropropane produces two distinct sets of peaks, both of which are split. Which of the following correctly describes the splitting pattern?

A A triplet and a singlet

B A triplet and a septet

C A singlet and a septet

D A doublet and a septet

Question 7 (1 MARK)

Researchers analysing groundwater from an ecological reserve take numerous samples from the surrounding area and manage to separate them into their respective pure compounds. The infrared spectrum of one such unknown organic compound is observed to have a broad peak at approximately 3200 cm^{-1}. It is also observed to react exothermically with an ammonia solution and produces 3 distinct peaks on a high resolution proton NMR. A potential name for the compound would be

A propanoic acid.

B propan-1-ol.

C ethanamine.

D ethanoic acid.

Question 8 (1 MARK)

A sample of a hydrocarbon undergoing chemical analysis is placed in a strong magnetic field and then irradiated with electromagnetic radiation at the radio frequency. This will most likely result in

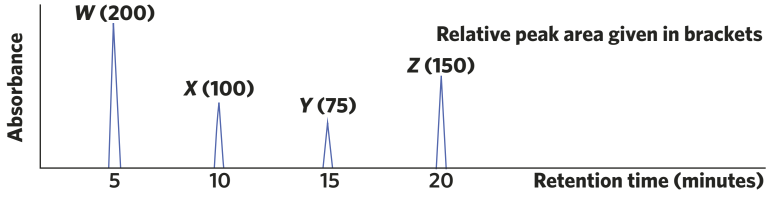
A a change in the energy, or 'spin' of the hydrogen atoms.

B stretching and vibrations in the bonds between the molecules.

C ionisation and fragmentation of the molecule.

D promotion of the electrons to higher energy levels.

Question 9 (1 MARK)



The diagram shows the recorder response of an organic sample containing four distinct straight chain alkanes that have undergone High Performance Liquid Chromatography using a non-polar stationary phase. The following statements refer to this chromatogram:

I The boiling point of the compounds arranged from highest to lowest is $Z \rightarrow Y \rightarrow X \rightarrow W$

II If the experiment were completed under identical conditions but the temperature of the HPLC column was increased, all of the retention times would also increase.

III Using an identical sample with double the concentration will also double all of the retention times.

IV If compound *W* were discovered to be ethane, then if ethanoic acid were also present in the sample, it would have a retention time between 5 and 10 minutes.

V Using an identical stationary phase with a greater surface area would greatly increase the retention times.

Which of the above statements are true?

A I, III and V only

B I and V only

C I, II, IV and V only

D II, III and V only

Question 10 (1 MARK)

A redox titration is performed between an aqueous solution of Antimony (III) (Sb^{3+}) of unknown concentration and a 0.43 M solution of the oxidising agent potassium bromate under acidic conditions. The balanced ionic equation for this reaction is given below.

$6H^+_{(aq)} + BrO_3^-{}_{(aq)} + 3Sb^{3+}_{(aq)} \rightarrow Br^-_{(aq)} + 3Sb^{5+}_{(aq)} + 3H_2O_{(l)}$

Titres of 12.05 mL, 12.70 mL, 12.10 mL and 12.05 mL of potassium bromate solution were required to reach the endpoint of the titration.

If the analytes were composed of 20.00 mL aliquots of Sb^{3+}, what would be the concentration of the Sb^{3+} solution and the mass of potassium bromate to produce the concordant titre?

A 0.79 M, 0.66 g

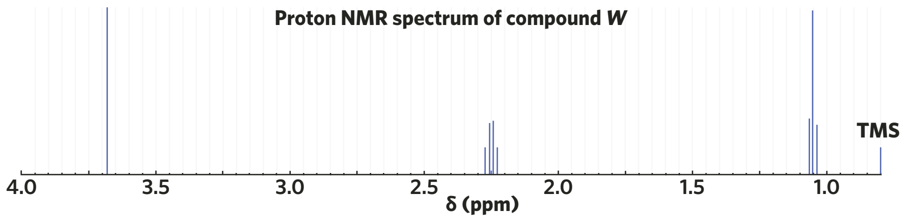
B 0.78 M, 0.87 g

C 0.78 M, 0.66 g

D 0.79 M, 0.87 g

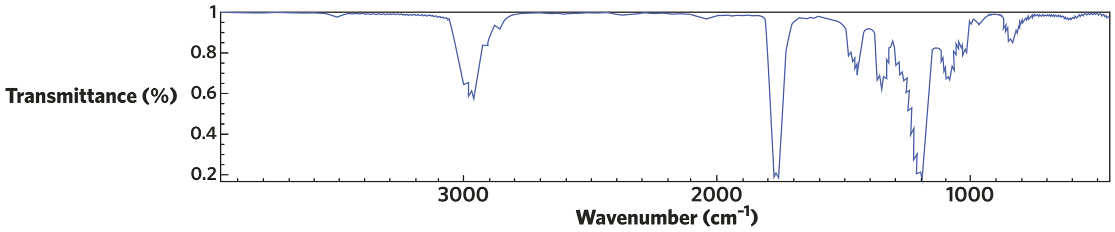
SHORT ANSWER (30 MARKS)

Question 11 (6 MARKS)



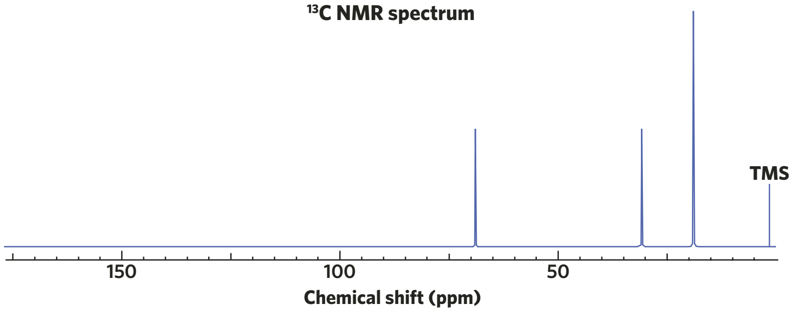
a Using the proton NMR spectrum given above, identify the number of hydrogen environments present in compound *W*. Give a reason for your answer. (2 MARKS)

b The chemist analysing compound *W* determined the molecular formula to be $C_4H_8O_2$. Use this information and the IR spectrum given below, determine the functional group present in compound *W*. Justify your answer. (2 MARKS)



c Draw and give the IUPAC name for compound *W*. (2 MARKS)

Question 12 (4 MARKS)



The ^{13}C NMR spectrum for an unidentified molecule is given above.

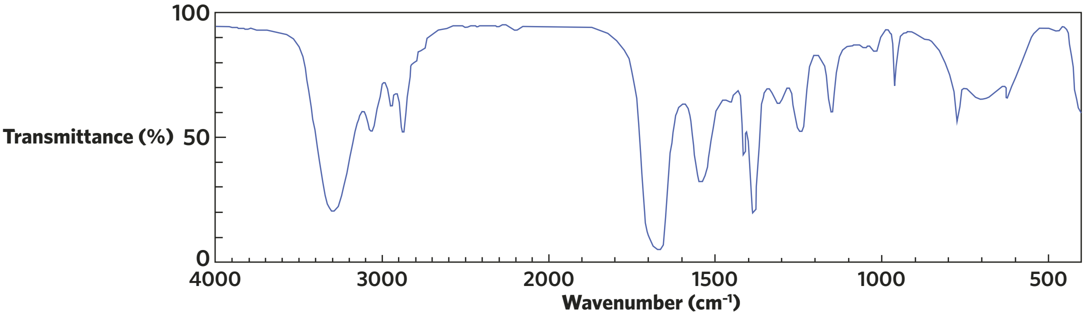
a What is the purpose of the peak labelled TMS in the process of ^{13}C NMR? (1 MARK)

b James proposes that the unidentified molecule is 2-methylpropan-2-ol. Explain whether this response is consistent with the ^{13}C NMR spectrum given (include a diagram in your answer). (3 MARKS)

Question 13 (4 MARKS)

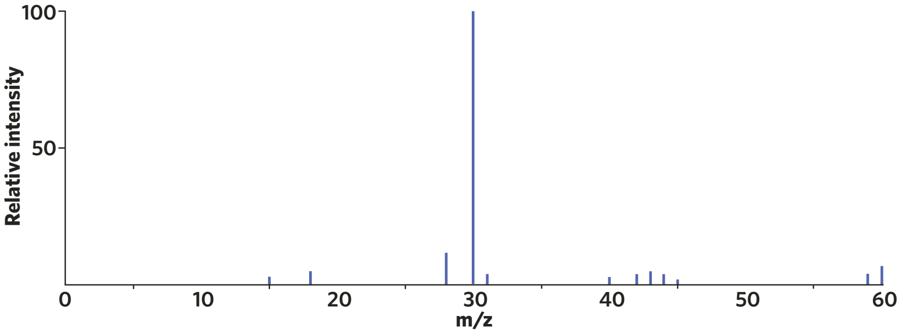
An organic compound under analysis is identified as an amide.

Identify and explain **two** pieces of evidence that support this classification from the IR spectrum given below. (4 MARKS)



Question 14 (10 MARKS)

A sample containing an unknown organic compound was examined by Mr Meek. The sample was known to have the empirical formula CH_4N, and produced the mass spectrum given below.



a On the diagram above, circle the molecular ion peak. (1 MARK)

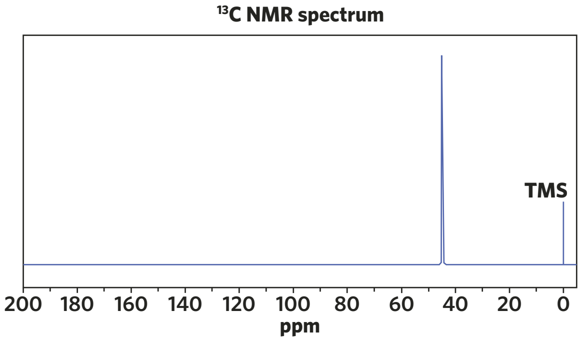
b Use your answer from part a to determine the molecular formula of the unknown sample. (2 MARKS)

c The molecule is known to have a straight chain structure, and only consists of single bonds. Using your answer to part b, draw the structural formula for the molecule. (1 MARK)

d Write the semi-structural formula for the ion produced at 30 m/z, and the charge on this ion. (1 MARK)

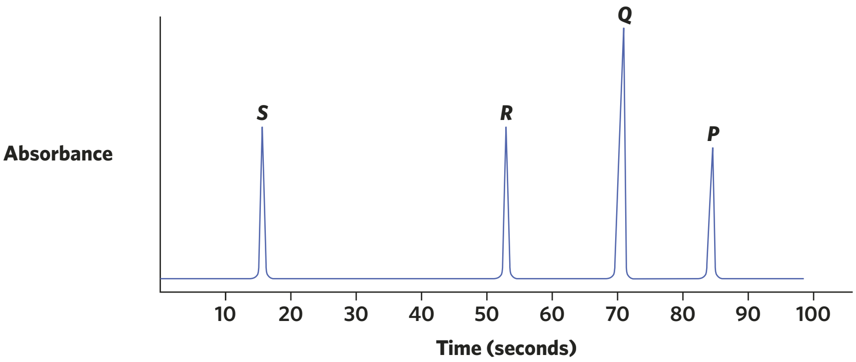
e Georgie explains that mass spectrometry can be used to determine the functional groups present in an organic compound. Comment on the accuracy of this statement. (3 MARKS)

f The following spectrum was obtained for the organic compound. Is this data consistent with the structure determined in part c? Justify your response. (2 MARKS)



Question 15 (7 MARKS)

The following chromatogram was produced by running a new perfume product through HPLC.



a Based on the data shown, what is the retention time of compound *R*? (1 MARK)

b What information does the area under the peaks provide in analysing the perfume? (1 MARK)

c This HPLC uses ethanol as the stationary phase. List the compounds *S*, *R*, *Q* and *P* in order of increasing polarity. Justify your choice. (3 MARKS)

d The experiment was conducted again under the same conditions, however the column was cooled. What effect will this have on the retention times of each component? (1 MARK)

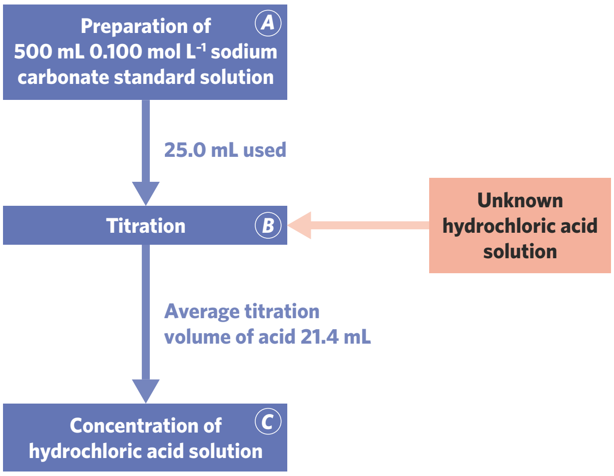
e A chemistry student Giao decided to triple the rate at which the mobile phase flows through the HPLC column. List the four substances *S*, *R*, *Q* and *P* in order of ascending retention time. (1 MARK)

KEY SCIENCE SKILL QUESTION

Question 16 (6 MARKS)

Matt accidentally spilled a bottle of hydrochloric acid on the laboratory floor. To determine the severity of the spill, he wanted to determine the concentration of hydrochloric acid in the sample. He was given the following flow chart to help him through the process.

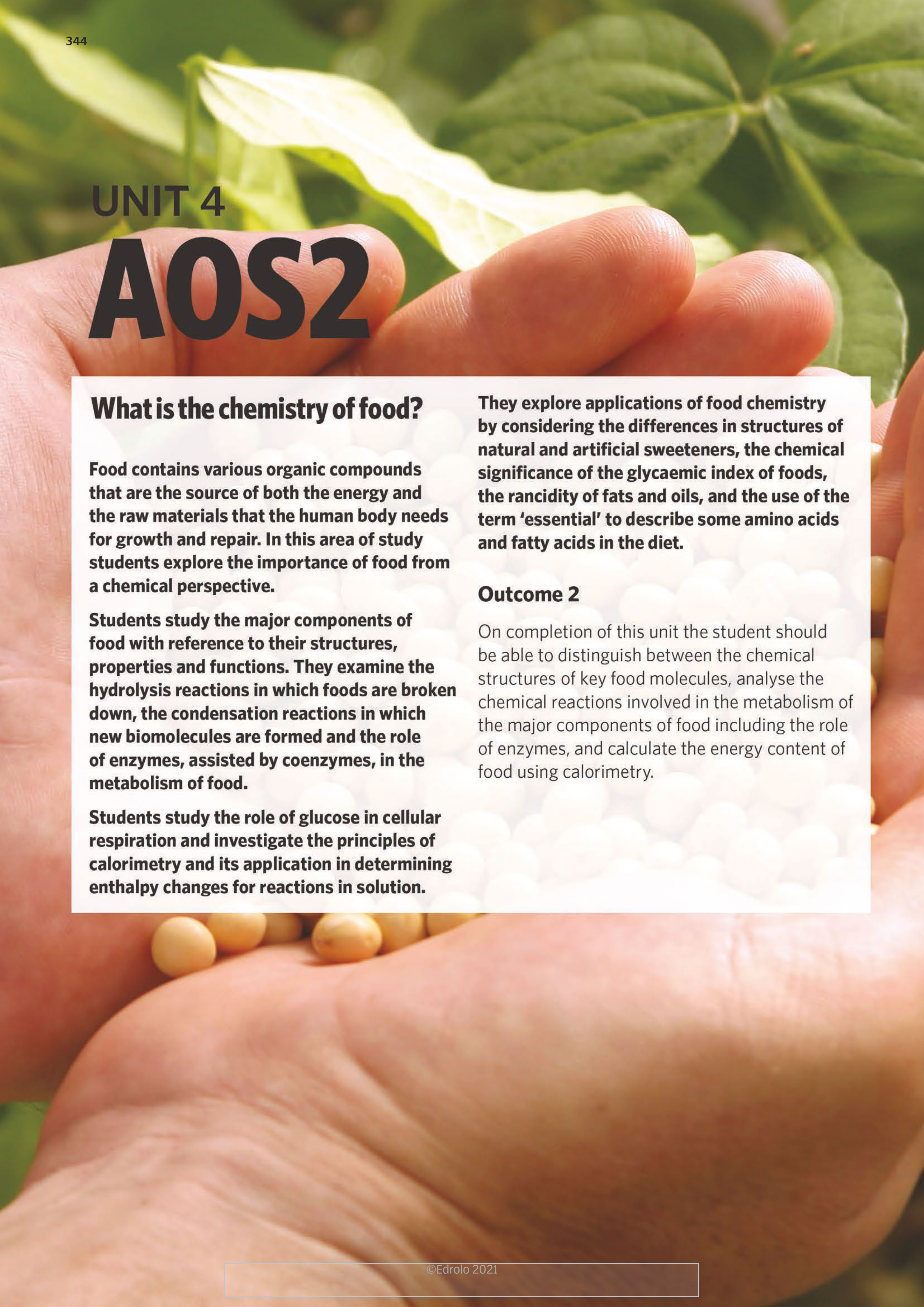
Adapted from NESA 2010 Section I Part B Q28



a Outline the steps required to produce the sodium carbonate standard. (2 MARKS)

b Identify the dependent variable. (1 MARK)

c In a rush, Matt took a 20.0 mL pipette without realising and used this to obtain the aliquot of sodium carbonate used in step B. Describe how this would affect the accuracy of his results. (3 MARKS)



UNIT 4

AOS2

What is the chemistry of food?

Food contains various organic compounds that are the source of both the energy and the raw materials that the human body needs for growth and repair. In this area of study students explore the importance of food from a chemical perspective.

Students study the major components of food with reference to their structures, properties and functions. They examine the hydrolysis reactions in which foods are broken down, the condensation reactions in which new biomolecules are formed and the role of enzymes, assisted by coenzymes, in the metabolism of food.

Students study the role of glucose in cellular respiration and investigate the principles of calorimetry and its application in determining enthalpy changes for reactions in solution.

They explore applications of food chemistry by considering the differences in structures of natural and artificial sweeteners, the chemical significance of the glycaemic index of foods, the rancidity of fats and oils, and the use of the term 'essential' to describe some amino acids and fatty acids in the diet.

Outcome 2

On completion of this unit the student should be able to distinguish between the chemical structures of key food molecules, analyse the chemical reactions involved in the metabolism of the major components of food including the role of enzymes, and calculate the energy content of food using calorimetry.

UNIT 4 AOS 2, CHAPTER 9

09

Food chemistry (part 1): proteins and vitamins

Key knowledge

- proteins: formation of dipeptides and polypeptides as condensation polymers of 2-amino acids; primary (including peptide links), secondary, tertiary and quaternary structure and bonding; distinction between essential and non-essential amino acids as dietary components
- the distinction between denaturation of a protein and hydrolysis of its primary structure
- enzymes as protein catalysts: active site; modelling of process by which enzymes control specific biochemical reactions (lock-and-key and induced fit models); consequences of variation in enzyme-substrate interaction (lock-and-key mechanism) due to the behaviour of a particular optical isomer; explanation of effects of changes in pH (formation of zwitterions and denaturation), increased temperature (denaturation) and decreased temperature (reduction in activity) on enzyme activity with reference to structure and bonding; action of enzymes in narrow pH ranges; and use of reaction rates to measure enzyme activity
- the principles of the action of coenzymes (often derived from vitamins) as organic molecules that bind to the active site of an enzyme during catalysis, thereby changing the surface shape and hence the binding properties of the active site to enable function as intermediate carriers of electrons and/or groups of atoms (no specific cases required).
- vitamins: inability of humans to synthesise most vitamins (except Vitamin D) making them essential dietary requirements; comparison of structural features of Vitamin C (illustrative of a water-soluble vitamin) and Vitamin D (illustrative of a fat-soluble vitamin) that determine their solubility in water or oil.

9A STRUCTURE OF PROTEINS

In this lesson, we will learn how proteins, an important type of biomolecule, are formed from smaller 'building blocks' and look at the different structural levels of proteins.

9A Structure of proteins	9B Breakdown of proteins	9C Enzymes	9D Structure and properties of vitamins

Study design dot point

- proteins: formation of dipeptides and polypeptides as condensation polymers of 2-amino acids; primary (including peptide links), secondary, tertiary and quaternary structure and bonding; distinction between essential and non-essential amino acids as dietary components

Key knowledge units

Building blocks of proteins	4.2.1.1
Formation of dipeptides and polypeptides	4.2.1.2
The different protein structures	4.2.1.3

Key terms and definitions

- **2-amino acid (α-amino acid)** amino acid whose carboxyl and amino group are bonded to the same central carbon atom
- **Essential amino acid** amino acid that cannot be synthesised by the human body
- **Non-essential amino acid** amino acid that can be synthesised by the human body
- **Primary structure** linear sequence of amino acids in a polypeptide
- **Secondary structure** arrangement of a primary protein structure in a way that results in a α-helix or β-pleated sheet
- **Tertiary structure** overall three-dimensional structure of a protein
- **Quaternary structure** combination of multiple polypeptide chains known as subunits
- **Dipeptide** product of a condensation reaction between two 2-amino acids
- **Polypeptide** product of a condensation reaction between multiple 2-amino acids

Lesson links

This lesson builds on:

- 7A – Structure of organic compounds

Amide functional groups (CONH) are present in the structure of proteins.

- 7F – Types of organic reactions

The idea of condensation reactions is important in the formation of proteins.

Building blocks of proteins 4.2.1.1

OVERVIEW

Proteins are made up of building units called amino acids.

THEORY DETAILS

Structure of amino acids

Proteins are biopolymers made up of monomers called amino acids. We can imagine amino acids as the small blocks used to build a big three-dimensional structure which is a protein. In this lesson, we will only concentrate on the **2-amino acid** (also known as α-amino acids). There are currently 20 naturally occurring types of 2-amino acids discovered by scientists which have slightly different structures. However, they all have the general structure shown in figure 1.

A 2-amino acid has one amino group (NH_2), one carboxyl group (COOH), one side chain R and one H atom bonded to a central carbon. The amino group and the carboxyl group are separated by the central carbon. The only difference in structure between different amino acids is the R side chain.

As shown in figure 2, alanine, arginine and asparagine have three different R side chains highlighted in three different colours. A full table that indicates the structures and symbols of all 20 different amino acids can be found in the VCAA data book.

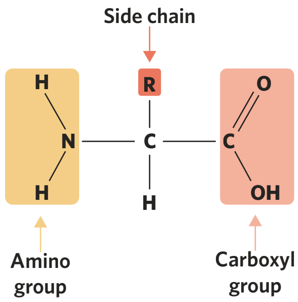


Figure 1 General structure of an amino acid

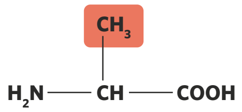
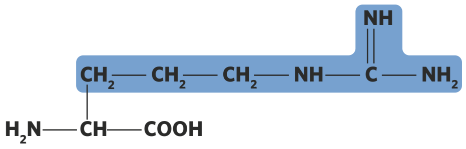
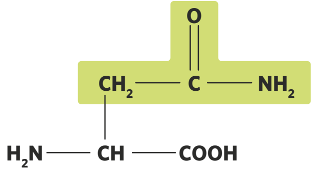
Name	Symbol	Structure
alanine	Ala	 $H_2N-CH(CH_3)-COOH$
arginine	Arg	 $H_2N-CH(CH_2-CH_2-CH_2-NH-C(=NH)-NH_2)-COOH$
asparagine	Asn	 $H_2N-CH(CH_2-C(=O)-NH_2)-COOH$

Figure 2 Symbols and structures of alanine, arginine and asparagine

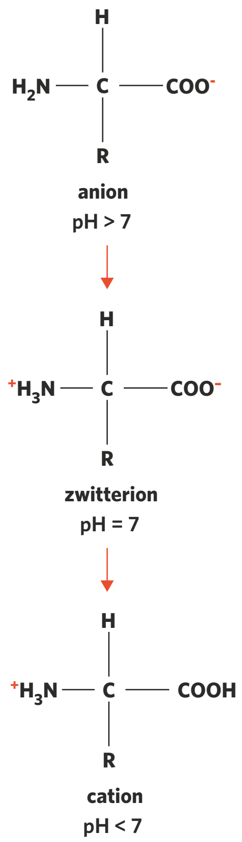


Figure 3 Structure of an amino acid depends on the pH of the solution

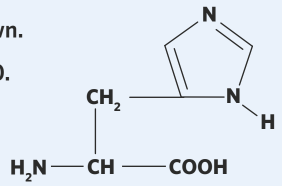
Acid-base properties of amino acids

In a solution, amino acids usually do not appear as a charge-free molecule shown in figure 1. The structure of amino acids can change depending on the pH of the solution. In an acidic solution with a high concentration of protons (H^+), the NH_2 group can accept H^+ from the solution (NH_2 group acting as a base) to form NH_3^+. Therefore, the amino acid appears as a cation. In a basic solution with a high concentration of OH^-, the H atom of the COOH group is donated to the OH^- in the solution (COOH group acting as an acid) to form COO^-. In this case, the amino acid appears as an anion. In a neutral solution, an amino acid appears as a special form called a **zwitterion** with the presence of both negative and positive charges. This is due to the fact the concentration of H^+ and OH^- in a neutral solution are equal, the NH_2 group can accept H^+ forming NH_3^+ and the H atom of the COOH group is therefore donated, forming COO^-. This idea is summarised in figure 3. It is important to note that different amino acids change their structures at different pH levels.

1 Worked example

The structure of amino acid histidine is shown.

Draw the structure of histidine at a pH of 2.0.



What information is presented in the question?

Structure of the amino acid

pH is 2.0 (acidic solution)

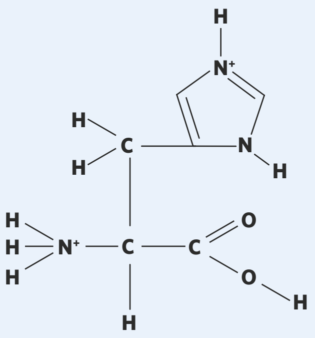
What is the question asking us to do?

Draw the structure of the amino acid when the pH is low.

What strategy(ies) do we need in order to answer the question?

1. Determine whether the concentration of H^+ or OH^- is high when the pH is low.
2. Based on step 1, determine whether the NH_2 group or COOH group is altered.
3. Draw the structure of the amino acid based on step 2.

Answer



Essential and non-essential amino acids

As mentioned earlier in this lesson, there are currently 20 different types of amino acids. However, the human body is not capable of synthesising all of them. There are 11 types of amino acids that the human body can synthesise which are called **non-essential amino acids**. Being called “non-essential” does not mean that they are not important to the human body. It only means that we do not have to consume them to build proteins in our body. Conversely, the 9 remaining amino acids, are **essential amino acids** because they cannot be synthesised by the human body. To build proteins from these 9 amino acids inside our body, we have to consume them from foods or supplements.

Formation of dipeptides and polypeptides 4.2.1.2

OVERVIEW

Dipeptides and polypeptides are the products from the condensation reactions between 2-amino acids.

Tip If *n* = the number of amino acids used to form a polypeptide,

the number of water molecules produced = the number of peptide links formed = *n* – 1.

THEORY DETAILS

Proteins are formed by condensation reactions between 2-amino acids. The first products formed from the condensation reactions between two 2-amino acids are called **dipeptides** as “di” represents two 2-amino acids, while the first products formed from the condensation reactions between more than two 2-amino acids are called **polypeptides** as “poly” represents multiple 2-amino acids. As we learned in 7F, a condensation reaction results in the formation of a larger molecule from two smaller molecules, as well as the production of a water molecule. The same concept is applied to the formation of dipeptides and polypeptides. Figure 3 shows the formation of a dipeptide from a condensation reaction between two 2-amino acids.

As can be seen, the OH group of the COOH in a 2-amino acid reacts with the H atom of the NH_2 in another 2-amino acid. This results in the formation of a peptide link (CONH) and one water molecule. It is important to note that a dipeptide can be formed from two different or identical 2-amino acids. Therefore, R_1 and R_2 in figure 3 could be different or identical.

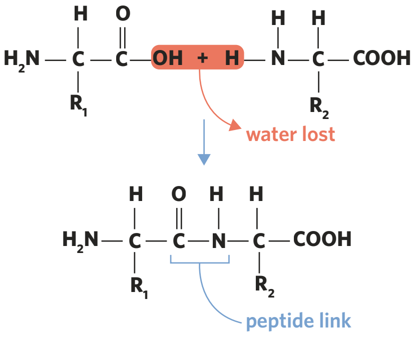


Figure 4 Condensation reaction between two 2-amino acids to form a dipeptide

Similarly, a polypeptide is formed from a condensation reaction between multiple (more than two) amino acids. As can be seen in figure 4, the COOH groups react with the NH_2 groups to form multiple peptide links (CONH). It is important to note that the number of water molecules produced is equal to the number of peptide links formed.

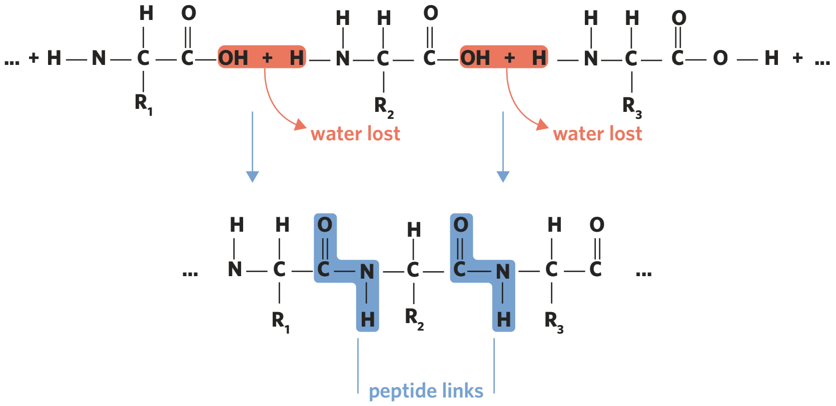


Figure 5 Condensation reaction between multiple amino acids to form a polypeptide

It’s important to note that when two amino acids react, because the amino and carboxyl groups present in the side chains of amino acids could take part in the formation of a peptide bond as well, there could be more than 1 type of product formed.

The different protein structures 4.2.1.3

OVERVIEW

There are four different structures of proteins: primary, secondary, tertiary and quaternary structures.

THEORY DETAILS

Primary structure

The simplest level of protein structure, the **primary structure**, is a sequence of amino acids linked by peptide bonds in a linear polypeptide chain. As there are 20 different types of amino acids, a lot of different polypeptide chains can be formed.

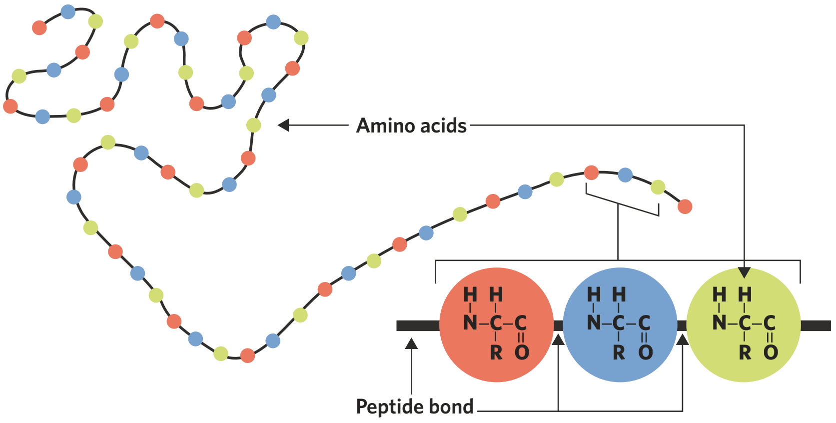


Figure 6 Primary structure of a protein

Secondary structure

The next level of protein structure, **secondary structure**, occurs when the primary structure polypeptide chains fold into different shapes as a result of hydrogen bonding within the polypeptide chain. As shown in figure 7, there are two main types of secondary structures: alpha-helix and beta-pleated sheet. The alpha-helix structure is maintained stable by the hydrogen bonds formed between the oxygen of the C=O of each peptide bond in the strand and the hydrogen of the N—H group of the peptide bond four amino acids below it in the helix. This forms a spiral structure. A beta-pleated sheet is formed by linking two or more adjacent strands of the polypeptide by hydrogen bonds between the oxygen of peptide bonds and the hydrogen of the N—H group of other peptide bonds. This forms a parallel sheet-like structure in the protein.

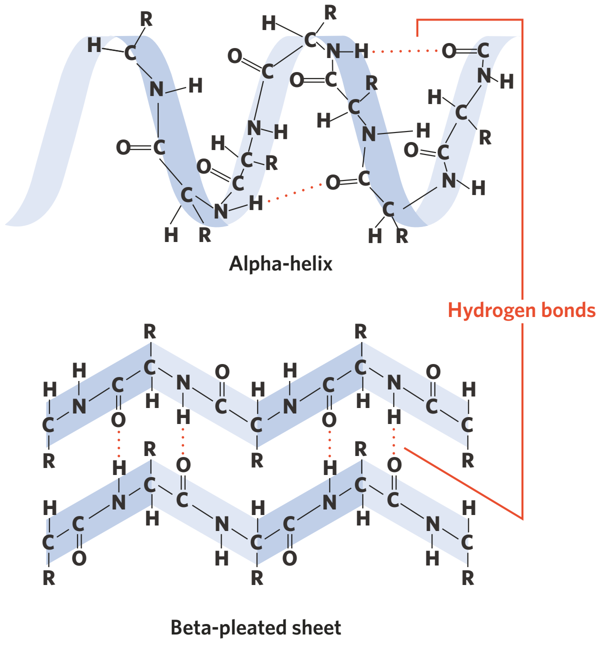


Figure 7 Secondary structure of a protein

Tertiary structure

The **tertiary structure** is the overall three-dimensional shape of a polypeptide chain. As can be seen in figure 8, a tertiary structure is stabilised by a combination of hydrogen bonding, ionic bonding, permanent dipole-dipole forces, disulfide bridges and dispersion forces between side chains of different amino acids in the polypeptide. Not all tertiary structures will contain all of these bonds; it will depend on the type of side chain present in the amino acids. A disulfide bridge (also known as disulfide bond or S—S bond) is a covalent bond between two sulfurs of amino acids whose R side chains contain sulfur(s). The tertiary structure of a protein is considered as the functional structure of protein. This means that proteins will lose their functions if their tertiary structures are disrupted.

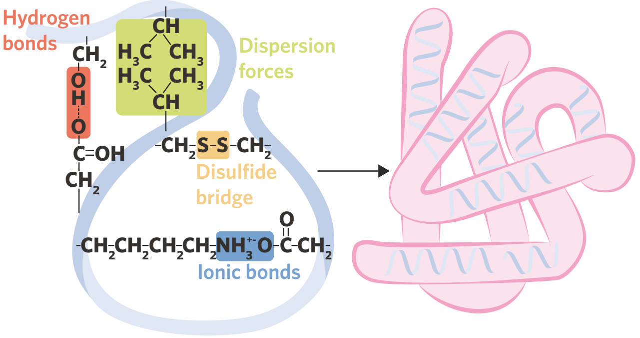


Figure 8 Tertiary structure of a protein

Quaternary structure

The **quaternary structure** is the combination and interactions between two or more three-dimensional polypeptide chains. It is important to note that not all proteins have quaternary structures. Polypeptide chains in a quaternary structure are called subunits. Figure 9 shows the quaternary structure of a protein.

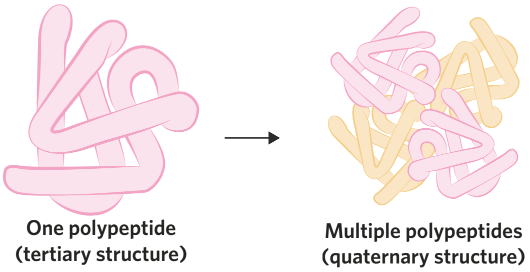


Figure 9 Quaternary structure of a protein

Haemoglobin is one protein which has quarternary structures found in the human blood. A haemoglobin molecule has four subunits: two alpha subunits and two beta subunits as shown in figure 10.

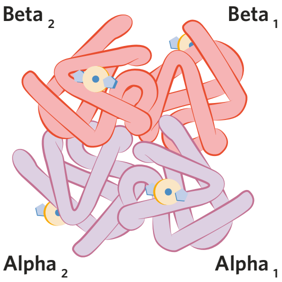


Figure 10 Quaternary structure of a haemoglobin molecule

Table 1 Protein structures and the bonds present in each structure

Structure	Bond stabilising the structure
Primary structure	Peptide bonds
Secondary structure	Hydrogen bonds
Tertiary structure	Hydrogen bonds, ionic bonds, permanent dipole-dipole forces, disulfide bridges and dispersion forces
Quaternary structure	Hydrogen bonds, ionic bonds, disulfide bridges,dispersion forces and permanent dipole-dipole forces

Theory summary

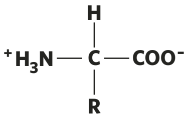
- Amino acid molecules are the building blocks of proteins with an amino and carboxyl functional group.
- The structure of an amino acid changes depending on the pH of the solution.
- In an acidic solution amino acids appear as a cation.
- In basic solutions amino acids appear as an anion.
- In a neutral solution amino acids appear as a zwitterion.
- When an amino acid is in the form known as a zwitterion, it has both positive and negative charges, with an overall neutral charge.
- Non-essential amino acids can be synthesised by the human body, whereas essential amino acids cannot.
- Dipeptides consist of two 2-amino acid molecules joined by a peptide bond formed in a condensation reaction.
- Polypeptides consist of more than two 2-amino acid molecules.
- There are four levels to the structure of a protein: primary, secondary, tertiary and quaternary.

9A QUESTIONS

Theory review questions

Question 1

The following structure is an example of



$$^{+}H_3N-\overset{H}{\underset{R}{C}}-COO^{-}$$

A tertiary structure.

B quaternary structure.

C zwitterion.

D peptide.

Question 2

In reference to the structure of proteins, hydrogen bonds can be found in

A primary structures only.
B alpha helices, beta pleated sheets, tertiary structures and quaternary structures only.
C alpha helices and primary structures only.
D primary structures and tertiary structures only.

Question 3

Aside from the 'R' side chain, the functional groups found in an amino acid are

A amino and hydroxyl.
B carboxyl and amide.
C carbonyl and esters.
D amino and carboxyl.

Exam style questions

Within lesson

Question 4 (1 MARK)

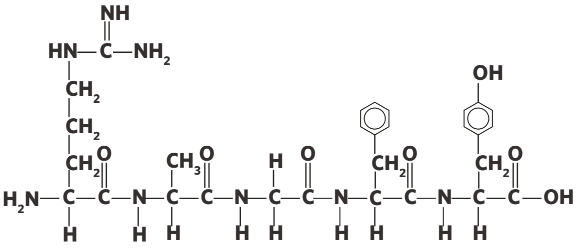
Botox is a neurotoxic protein that causes paralysis. The toxin acts by disrupting the disulfide bonds of cell receptors, which are made from proteins. By doing so, botox disrupts the

A primary structure.
B secondary structure.
C tertiary structure.
D all of the above.

Question 5 (1 MARK)

The number of peptide linkages found in this sequence is

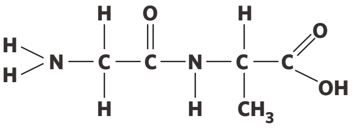
A 1
B 2
C 3
D 4



Question 6 (1 MARK)

The dipeptide shown is made from

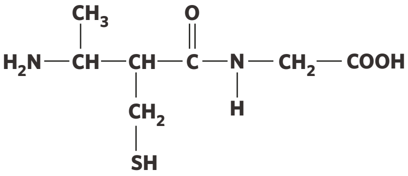
A asparagine and serine.
B glycine and alanine.
C alanine and asparagine.
D serine and glycine.



Question 7 (1 MARK)

The α-amino acid found in this dipeptide is

A alanine.
B serine.
C glycine.
D threonine.



Question 8 (5 MARKS)

Alanine behaves differently depending on the environment of the solution in which it is added to.

a Draw the structure of alanine in a solution with a pH of 9. (1 MARK)

b Alanine underwent a condensation reaction with asparagine. Draw the Ala-Asn product formed as a result of this reaction. (2 MARKS)

c This sequence was part of a longer chain that was then folded into β-pleated sheets. Describe the bonds that contribute to stabilising this structure. (2 MARKS)

Question 9 (3 MARKS)

Cysteine makes protein structures more rigid, and thereby more stable.

a Draw the structure of cysteine as a zwitterion. (1 MARK)

b Describe the bonding(s) that would occur in the tertiary structure of a protein as a result of cysteine. (2 MARKS)

Question 10 (8 MARKS)

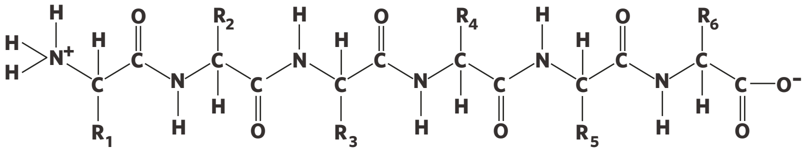
The DNA in our cells give instructions for the production of functional proteins found in our body. This process occurs progressively in different areas of the cell. Depending on the stage, the structure of the protein can look different.

The image below shows different forms of the same protein.

a Name each structure. (4 MARKS)

b Identify the bonds that hold each structure together. (4 MARKS)

i

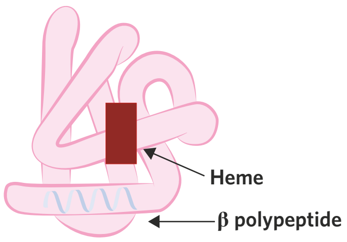


ii

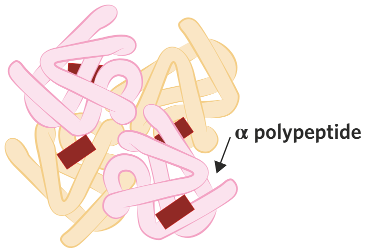
α helix

β sheet

iii



iv



Question 11 (8 MARKS)

Athletes of all levels have been known to take protein supplements to support their training. Below is a list of ingredients in a widely used protein powder.

Amino acid profile					
	Amount per serving		Amount per serving		Amount per serving
Isoleucine*^	1491 mg	Glutamic Acid	4677 mg	Proline	1863 mg
Leucine*^	2982 mg	Glycine	495 mg	Serine	1419 mg
Valine*^	1395 mg	Histidine*	444 mg	Threonine*	2127 mg
Alanine	1098 mg	Hydroxyproline	258 mg	Tryptophan*	462 mg
Arginine	582 mg	Lysine*	2310 mg	Tyrosine	798 mg
Aspartic Acid	3063 mg	Methionine*	627 mg	*Essential amino acids	
Cystine	183 mg	Phenylalanine*	816 mg	^Branched-chain amino acids	

a Of the amino acids found in the protein powder, some can be considered as essential amino acids. What is meant by the term 'essential amino acids'? (1 MARK)

b It's been said that the proteins found in these supplements can aid in protein synthesis and tissue repair. Draw the amino acid sequence Gly-His-Phe. (2 MARKS)

Multiple lessons

Question 12 (4 MARKS)

Due to the trends of supplemented protein intake, many foods claim to have increased levels of protein.

Bridie wanted to determine the protein content in a packet of chips that claimed to have 'only added glycine and glutamic acid'.

a After some extraction techniques, Bridie allowed for her sample to undergo mass spectrometry. She found that the molecular ion was 147 m/z. Identify and draw the amino acid that was present in her sample. (2 MARKS)

b To confirm, Bridie made another sample of her chips for HPLC analysis. Given that a polar stationary phase was used, which amino acid, glycine or glutamic acid would have the greatest retention time? Explain. (2 MARKS)

9B BREAKDOWN OF PROTEINS

Proteins are broken down by hydrolysis and denaturation, two important processes, that allow essential amino acids and nutrients from proteins to be accessible to the human body.

9A Structure of proteins	9B Breakdown of proteins	9C Enzymes	9D Structure and properties of vitamins

Study design dot point

- the distinction between denaturation of a protein and hydrolysis of its primary structure

Key knowledge units

Hydrolysis of proteins	4.2.7.1.1 & 4.2.5.1.3
Denaturation of proteins	4.2.7.1.2

Key terms and definitions of this lesson

- **Hydrolysis** breakdown of a compound by a chemical reaction with water
- **Metabolism** breakdown of food and its transformation into energy
- **Denaturation** process where proteins lose their quarternary, tertiary and/or secondary structure due to factors such as pH and temperature change

Lesson links

This lesson builds on:

▶ 7A – Structure of organic compounds

The primary structure of proteins is a sequence of amino acids.

Hydrolysis of proteins 4.2.7.1.1 & 4.2.5.1.3

OVERVIEW

Proteins can be chemically digested in a process known as hydrolysis, breaking the bonds that hold its 'building blocks' (amino acids) together.

THEORY DETAILS

Proteins are important macronutrients that are broken down and digested by the body to synthesise important organic molecules in a process known as **metabolism**.

Metabolism refers to the range of biochemical processes that occur within a living organism to sustain life. These processes break down food for nutrients and energy, particularly in the case of proteins, as the body cannot synthesise all of the 20 amino acids needed to build proteins without food. However, proteins are not broken down to the atomic level, they are rather broken into amino acids that the human body can use as the building blocks for bones, muscles, cartilage, blood and skin. The key chemical reaction that breaks down proteins is **hydrolysis.** The digestion of proteins requires specific enzymes. An example of this is pepsin, found in the stomach.

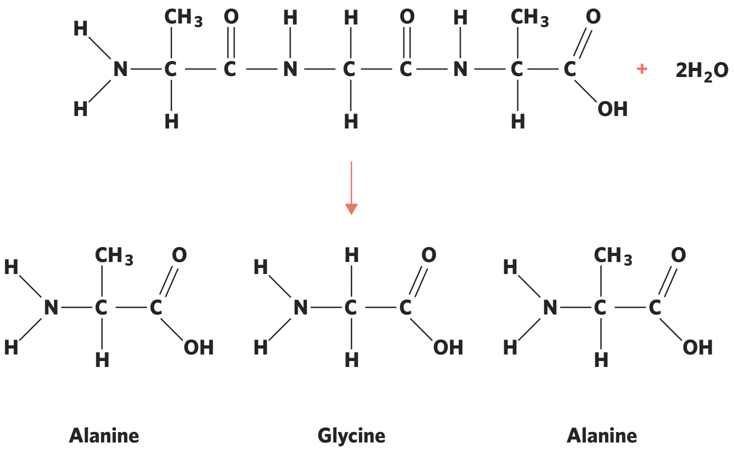


Figure 1 Hydrolysis reaction of peptide bonds

When proteins are hydrolysed, the carbon-nitrogen peptide bond is broken, causing the protein to be broken down into smaller compounds. As we can see in figure 1, amino acids are formed when this bond is broken, and for each peptide bond that is broken, one water molecule is consumed in the reaction.

As a general rule, proteins are hydrolysed to soluble amino acids. They are soluble so that they can be absorbed in the gastrointestinal tract and transported throughout the body to cells. Once they are inside the cells they can be reassembled into proteins by condensation reactions – the reverse of a hydrolysis reaction, as shown in figure 2.

$$\text{Protein} \xrightarrow{\text{Hydrolysis}} \text{Amino acids} \xrightarrow{\text{Condensation}} \text{Protein}$$

Figure 2 Summary of how proteins are metabolised by the body

Denaturation of proteins 4.2.7.1.2

OVERVIEW

Denaturation is the process by which proteins lose their secondary, tertiary and quaternary structure due to factors such as pH and temperature change.

THEORY DETAILS

We just looked at how the structure of proteins can be altered by the breaking of bonds via hydrolysis, now we will look at another process that disrupts the structure of proteins called **denaturation**.

Denaturation is the disruption or destruction of secondary, tertiary and quaternary structures of proteins. The most common causes of the denaturation of proteins are heat and a change in pH.

Heat increases the kinetic energy of the polypeptide chains. This causes the molecules to vibrate so rapidly that the hydrogen bonds between peptide links (secondary structure), interactions between amino acid side groups (tertiary structure) and the arrangement of protein units (quaternary structure) are disrupted. The bonds holding together the primary structure are not disrupted because denaturation isn't strong enough to break the covalent peptide bonds. Therefore, the primary structure of the protein remains the same, with only the secondary, tertiary and quaternary structures being disrupted, uncoiling the protein into a random shape. This change cannot be reversed with a decrease in temperature. A decrease in temperature also does not result in the denaturation of a protein.

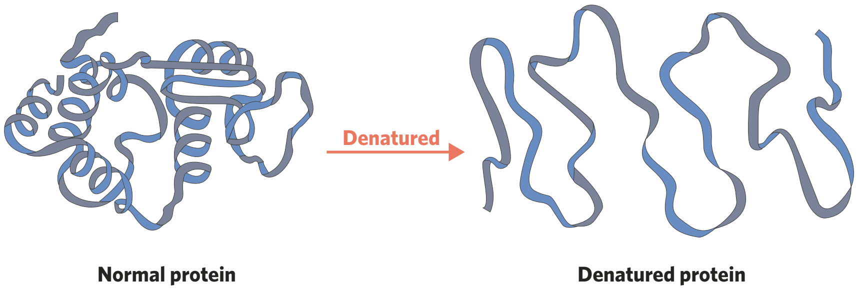


Figure 3 Denaturation of a protein's structure

A common result of the denaturation of a protein is a loss of biological activity. A real life example of this is the sterilisation of medical supplies and equipment by heating in order to denature the proteins in bacteria. When the proteins in bacteria are denatured, they lose biological activity and so are no longer harmful.

Proteins can also be denatured by a change in pH levels. For a protein to function properly and retain its overall three-dimensional shape, its environment must be at an optimum pH level. If the pH level drops below or increases above this level, the structure of the protein will be changed, sometimes permanently, with the same effect as heat, unfolding the protein so that it only retains its primary structure. This is because the ionic interactions in the protein are altered, having a domino effect that changes the other intermolecular forces, resulting in the unfolding of the protein. This will be explored further in lesson 9C.

An important difference between hydrolysis and denaturation is that hydrolysis involves breaking the covalent bonds in the peptide link. Denaturation however, involves only unfolding the protein, disrupting the secondary, tertiary and quaternary structures of the protein, leaving the primary structure intact.

Theory summary

- Proteins are broken down by hydrolytic reactions to yield essential amino acids that the body can then use to synthesise different organic molecules.
- Hydrolysis of proteins occurs during the digestion of food.
- Denaturation disrupts the secondary, tertiary and quaternary structures of a protein, but leaves the primary structure intact.
- Denaturation of proteins can occur due to a change in temperature or a change in pH, causing the protein to unfold.

9B QUESTIONS

Theory review questions

Question 1

A hydrolysis reaction occurs when

A a triglyceride is formed.

B water is consumed in the reaction.

C glucose and galactose form lactose.

D water is broken down in a reaction.

Question 2

Which of the following statements is correct about the denaturation of a protein?

A Denaturation involves the disruption of all bonds in the tertiary structure.

B The primary structure is disrupted when denaturation occurs.

C Denaturation involves the release of amino acids.

D Alcohol denatures proteins by disrupting the hydrogen bonding.

Question 3

Which of the following is **not** true about protein denaturation?

A It alters the primary structure of the protein.

B A change in temperature could cause protein denaturation.

C It results in a change in the shape of the protein.

D A change in pH may cause the protein to denature.

Exam-style questions

Within lesson

Question 4 (1 MARK)

Which of the following explains why medical tools are sterilised by heat?

A To change the pH levels of proteins

B To increase the temperature of proteins

C To inhibit the biological activity of bacteria

D To hydrolyse bacteria

Question 5 (2 MARKS)

A particular strain of E. coli causes severe food poisoning when ingested in meat and poultry. Explain one way you could prevent getting food poisoning from meat with E. coli bacteria.

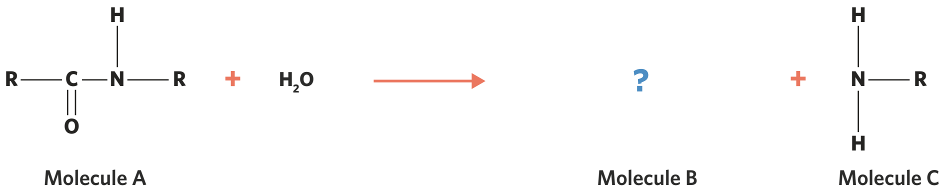
Question 6 (2 MARKS)

Pepsin is an enzyme that aids digestion of proteins in the stomach.

State one factor, other than pH, that would denature this enzyme and outline the effect this factor would have on protein digestion.

Question 7 (3 MARKS)

The following equation is an incomplete chemical reaction of protein hydrolysis.



$$R-C(=O)-N(H)-R + H_2O \rightarrow ? + H-N(H)-R$$

a Draw the formula for molecule B. (1 MARK)

b Circle the functional group that is hydrolysed in molecule A to form molecule B and molecule C. (1 MARK)

c What is the name of the functional group hydrolysed in molecule A to form molecule B and molecule C? (1 MARK)

Question 8 (4 MARKS)

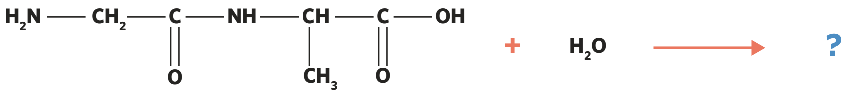
A scientist has developed a new drug to selectively cleave the covalent bonds between two sulfur atoms of non-adjacent amino acids in a polypeptide chain.

a What level of protein structure would be most directly affected by the drug? Explain why. (2 MARKS)

b Why would the primary structure not be affected by this drug? (2 MARKS)

Question 9 (5 MARKS)

A student was given the following reaction.



$$H_2N-CH_2-C(=O)-NH-CH(CH_3)-C(=O)-OH + H_2O \rightarrow ?$$

a Circle the peptide bond in the dipeptide. (1 MARK)

b Draw the hydrolysis reaction of this molecule, circling where the hydrogen atoms and oxygen atom of the water molecule have been added to form the products. (2 MARKS)

c Name the two products of this reaction. (2 MARKS)

Question 10 (2 MARKS)

The major protein component of hair is keratin, which can be formed from multiple polypeptide chains. Hair straighteners are commonly used tools which use heat to iron hair leaving it straight. Using your knowledge of chemistry, give an explanation for why straighteners cause hair to be temporarily straight.

Multiple lessons

Question 11 (4 MARKS)

The secondary and tertiary structures of proteins are generally much more easily disrupted than the primary structure.

a Explain why this is. (2 MARKS)

b How does this explain why denaturation doesn't affect the primary structure but does affect the secondary and tertiary structures? (2 MARKS)

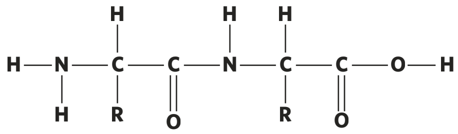
Question 12 (5 MARKS)

Depending on the process involved, chemical reactions can result in the production of bigger macromolecules.

a Explain the difference between hydrolysis and condensation reactions. (2 MARKS)

b What is the importance of these reactions in the human body? (1 MARK)

c Draw the products for the hydrolysis of the following protein, circling where the water molecule was added to form the products. (2 MARKS)



$$H-N(H)-C(H)(R)-C(=O)-N(H)-C(H)(R)-C(=O)-O-H$$

9C ENZYMES

In this lesson you will be learning about what enzymes are and how they function in the body to catalyse biological reactions.

9A Structure of proteins	9B Breakdown of proteins	9C Enzymes	9D Structure and properties of vitamins

Study design dot points

- enzymes as protein catalysts: active site; modelling of process by which enzymes control specific biochemical reactions (lock-and-key and induced fit models); consequences of variation in enzyme-substrate interaction (lock-and-key mechanism) due to the behaviour of a particular optical isomer; explanation of effects of changes in pH (formation of zwitterions and denaturation), increased temperature (denaturation) and decreased temperature (reduction in activity) on enzyme activity with reference to structure and bonding; action of enzymes in narrow pH ranges; and use of reaction rates to measure enzyme activity
- the principles of the action of coenzymes (often derived from vitamins) as organic molecules that bind to the active site of an enzyme during catalysis, thereby changing the surface shape and hence the binding properties of the active site to enable function as intermediate carriers of electrons and/or groups of atoms (no specific cases required)

Key knowledge units

Principles of enzymes	4.2.6.1
Effect of temperature on enzyme function	4.2.6.2.1
Effect of pH on enzyme function	4.2.6.2.2
Effect of isomers on enzyme function	4.2.6.2.3
Coenzymes	4.2.10.3

Key terms and definitions

- **Active site** region of an enzyme where the substrate molecule binds to the enzyme and undergoes a chemical reaction
- **Substrate** molecule which an enzyme acts upon
- **Lock and key model** theory of enzyme activity where the substrate perfectly fits the active site of the enzyme
- **Induced-fit model** theory of enzyme activity where the active site slightly changes shape to bind to the substrate
- **Enzyme-substrate complex** name for the unit which has the substrate bonded to the active site of an enzyme
- **Optimal temperature** temperature when enzyme activity is at its greatest
- **Protonation** gain of a proton
- **Deprotonation** loss of a proton
- **Acidic amino acid** amino acid with a carboxyl group in its side chain
- **Basic amino acid** amino acid with an amino group in its side chain
- **Coenzyme** organic molecule that attaches to the active site of an enzyme and changes the surface shape to enable the substrate to bind

Lesson links

This lesson builds on:

▶ 5B – Rates of reaction

Enzymes can affect the rate of reaction.

▶ 9A – Structure of proteins

All enzymes are proteins.

▶ 9B – Breakdown of proteins

Enzymes, since they are proteins, are able to be broken down.

Principles of enzymes 4.2.6.1

OVERVIEW

Enzymes are biological catalysts made of proteins that play an essential role in the functioning of the human body. There are currently two models proposed to explain how enzymes operate.

THEORY DETAILS

Enzymes are crucial to the body because they catalyse chemical reactions necessary to sustain life that would otherwise occur too slowly. Specifically, an enzyme catalyses a reaction by providing an alternate reaction pathway that requires a lower activation energy, as can be seen in the energy profile diagram in figure 1.

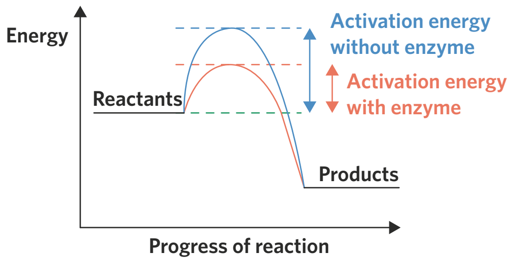


Figure 1 Energy profile diagram of a reaction with and without an enzyme

An enzyme functions by binding to the reactant(s) of a reaction, known as the **substrate**(s). The region of the enzyme where the substrate binds is known as the **active site,** shown in figure 2.

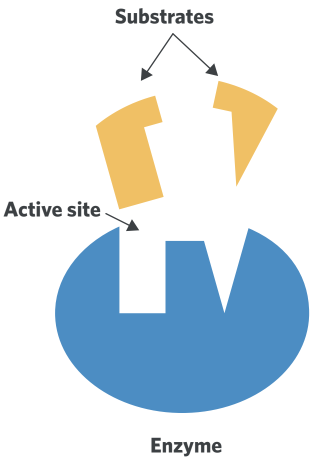


Figure 2 The general model of an enzyme

It is important to note that enzymes are not used up in the reactions which they catalyse and do not change the amount of product produced in a reaction – they simply speed up the rate of reaction.

Unlike inorganic catalysts, enzymes are highly specific in that each enzyme is only responsible for catalysing one or a small number of chemical reactions. This explains why there are an immense number of different enzymes catalysing reactions in the body.

The size, shape, chemical behaviour and three-dimensional nature of the active site is very important to the functioning of the enzyme, as for the substrate to successfully bind to the active site, the substrate must form a temporary bond with the enzyme.

There are two major models that scientists have developed to explain enzyme activity. The first is the **lock and key model** which, as the name suggests, is where the substrate fits perfectly into the active site of the enzyme, just as a key perfectly fits a lock. As shown in figure 3, the shape of the substrate is perfectly complementary to the shape of the enzyme's active site. After successful binding, the entire structure is known as an **enzyme-substrate complex.** As a complex, the enzyme's action will begin, which may catalyse a reaction breaking down larger molecules into smaller ones (catabolism), or building larger molecules from smaller ones (anabolism). After the reaction has occurred, the enzyme will release the substrate and it is free to bind to a new substrate.

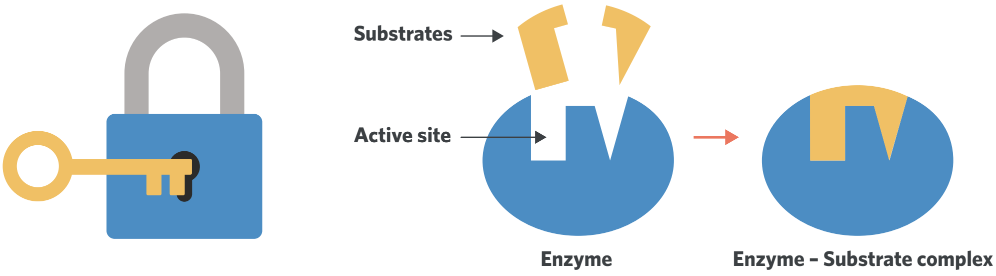


Figure 3 Diagram representing the lock and key model

Another model of enzyme activity is known as the **induced-fit model.** This model proposes that the shape of the substrate is not perfectly complementary to the shape of the active site. In turn, to overcome this, the active site adjusts its shape slightly to allow the substrate to bind. After the substrate detaches from the enzyme, the active site returns to its original shape as shown in figure 4. Stage A emphasises the active site's shape not complementing that of the substrate and stage D reveals how the enzyme's active site returns to its normal shape after the reaction has occurred.

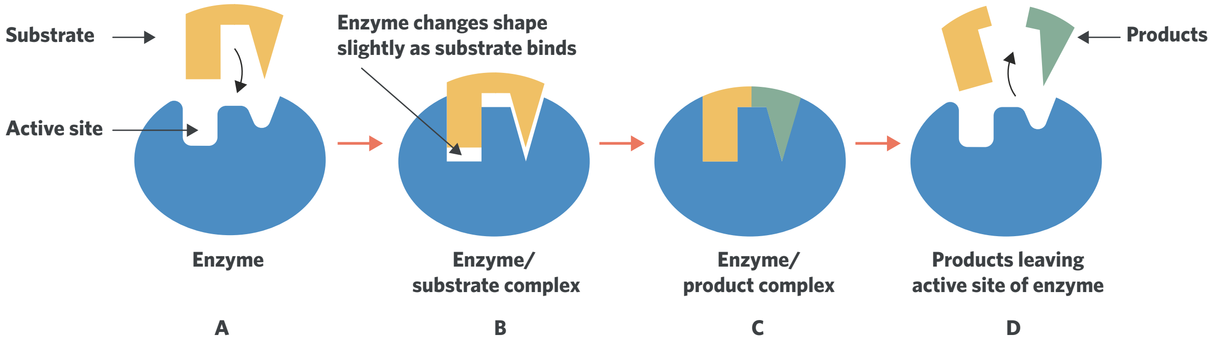


Figure 4 Diagram representing the induced fit model

Since enzymes are catalysts, one way to determine the activity of an enzyme is to measure the rate of the reaction which the enzyme catalyses. Any changes in the rate of a reaction will indicate that enzyme activity has been changed. For example, if a scientist is measuring a person's protein digestion rate and they see that it is slowing down, this could indicate that enzyme activity has been impaired as enzymes are needed in order to digest proteins.

Effect of temperature on enzyme function 4.2.6.2.1

OVERVIEW

Enzyme activity is heavily dependent on the temperature of the chemical reaction.

THEORY DETAILS

As previously discussed in lesson 5B, an increase in temperature causes an increase in the rate of reaction. However, the activity of enzymes do not always increase in response to an increase in temperature.

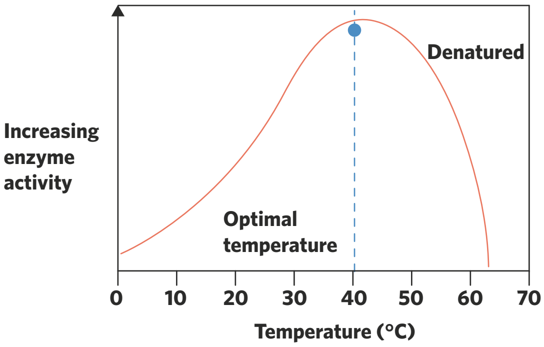


Figure 5 Graph of enzyme activity and temperature

As we can see in figure 5, as temperature increases, there is a general increase in enzyme activity. This is consistent with our knowledge of reaction rates, because at higher temperatures, not only is the average kinetic energy of the particles greater, but there are also more collisions per unit of time between enzymes and their respective substrate. However, after reaching the **optimal temperature** at which an enzyme's activity is at its greatest, the enzyme activity begins to decrease rapidly, and eventually reaches zero. We can explain this in terms of the chemical composition of enzymes. Enzymes are proteins and therefore are able to be denatured at high temperatures. As we learnt in 9B, denaturation is the process whereby the secondary, tertiary and quaternary (if applicable) structures of the enzyme which define the shape of the active site are disrupted by the increase in temperature. This causes irreversible structure damage meaning the enzyme is unable to function. Therefore, the function of an enzyme is sensitive to temperature. For enzymes in humans, the optimum temperature is generally the temperature of the body.

Effect of pH on enzyme function 4.2.6.2.2

OVERVIEW

Since pH can affect an enzyme's tertiary (and quaternary if present) structure, its bonding capability to a substrate may also be impacted upon. In turn, enzyme activity is also dependent on the pH of the environment in which it functions.

THEORY DETAILS

As we have explored in the earlier parts of this chapter, the active site of an enzyme binds to a substrate. Figure 6 illustrates that the side groups of amino acids play an important role in this temporary act of binding. Furthermore, as explored in chapter 9A, the side groups of amino acids also contribute to the stability of a protein's tertiary structure.

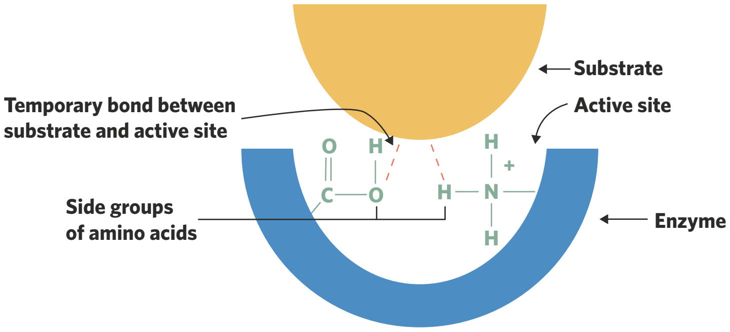


Figure 6 Diagram of substrate-enzyme interaction

The properties of the side groups on different amino acids is very important, in particular, whether they are acidic or basic.

An **acidic amino acid,** such as aspartic acid in figure 7, has a carboxyl group in its side chain, circled on the diagram.

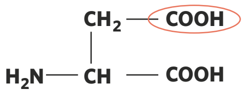
Aspartic acid	**Asp**	 $H_2N-\overset{\displaystyle CH_2-COOH}{\overset{\mid}{CH}}-COOH$

Figure 7 VCAA data book entry for aspartic acid

This means, in a basic solution where the pH is greater than 7, this carboxyl group will lose a hydrogen atom and have a negative charge as shown in figure 8. This is known as **deprotonation.**

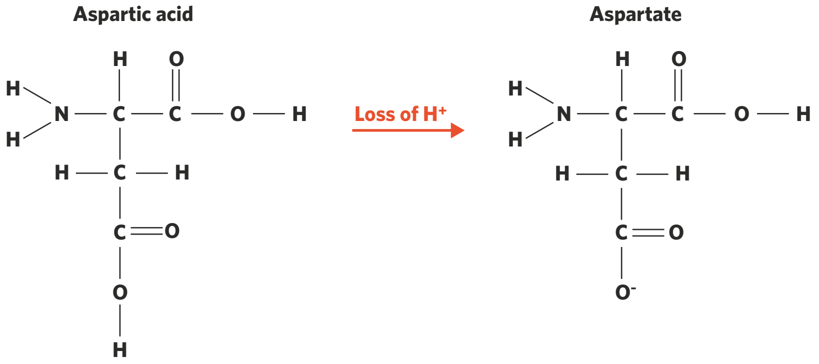


Figure 8 The deprotonation of aspartic acid

Furthermore, a **basic amino acid**, such as lysine in figure 9, has an amino functional group in its side chain.

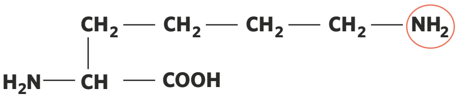
Lysine	**Lys**	 $H_2N-\overset{\displaystyle CH_2-CH_2-CH_2-CH_2-NH_2}{\overset{\mid}{CH}}-COOH$

Figure 9 VCAA data book entry for lysine

In an acidic solution, where the pH is less than 7, a basic amino acid will gain a proton and become positively charged as shown in figure 9. This process is termed **protonation.**

Figure 10 The protonation of lysine

A change in the pH in the enzyme's environment may alter enzyme activity. This is because any changes in the charges of the side chains of an enzyme's constituent amino acids, shown in figure 8 and figure 10, can lead to different interactions between an enzyme and its substrate due to disruption to the enzyme's tertiary and possibly secondary and quaternary structures. Consequently, most enzymes function only in a narrow pH range.

Effect of isomers on enzyme function 4.2.6.2.3

OVERVIEW

Due to the specific chemical composition of an enzyme's active site, enzymes are able to distinguish between enantiomers which means that enzymes will only catalyse a reaction involving one of the enantiomers, not both.

THEORY DETAILS

The active site of an enzyme is three-dimensional. This means that for an enzyme to function as a catalyst, the substrate has to complement the three-dimensional shape of the enzyme's active site. As discussed in 7D, if a molecule is chiral, it will exist in multiple forms known as enantiomers; compounds with the exact same sequence of bonded atoms but a different arrangement in three-dimensional space. Figure 11 illustrates this concept, as the enzyme has a specific three-dimensional shape of its active site, meaning it can only operate with one enantiomer.

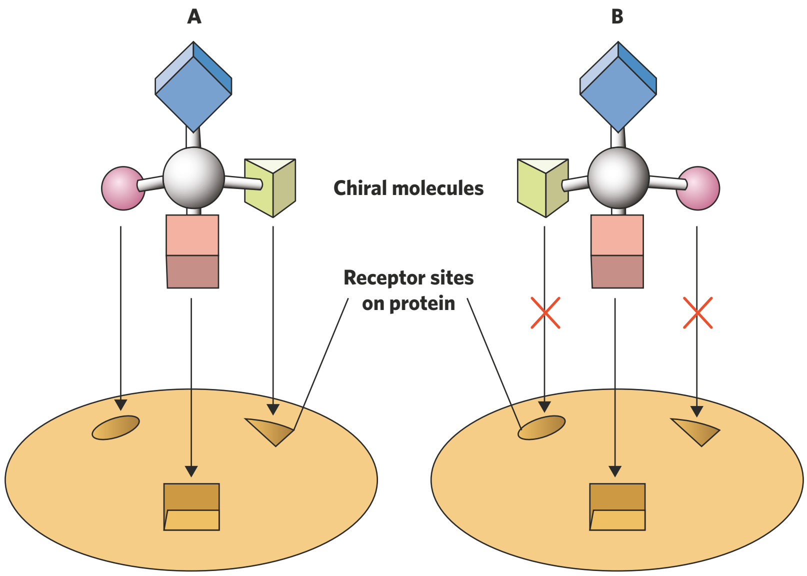


Figure 11 A visual representation of the different behaviours of enantiomers with enzymes

As figure 11 demonstrates, molecule A is a perfect match for the enzyme's active site. However, molecule B, which is the enantiomer of molecule A, is not able to fit because the enzyme's active site is specific to the three-dimensional arrangement of atoms in molecule A. This specificity is due to the importance of the temporary interactions between an enzyme and its substrate and if anything is slightly changed, the enzyme will not be able to function.

Coenzymes 4.2.10.3

OVERVIEW

Coenzymes are small molecules which cannot catalyse a reaction by themselves. However, they are crucial for some enzymes to become active because they temporarily bind to the active site of an enzyme, allowing a substrate to bind.

THEORY DETAILS

Coenzymes are small organic molecules that temporarily bind to the active site of an enzyme. They enable the enzyme's active site to be modified to suit the shape of the substrate and therefore alter the binding properties of the enzyme. They also serve the important purpose of acting as a carrier of groups of atoms and/or electrons. An illustration of the function of a coenzyme is shown below in figure 12.

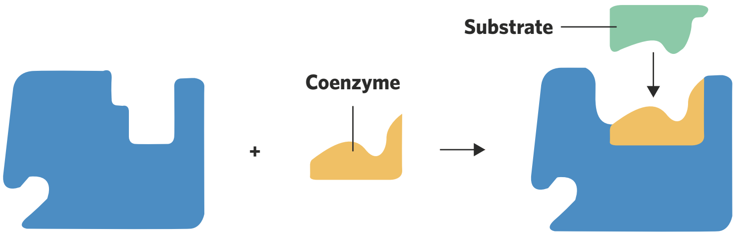


Figure 12 Action of a coenzyme in aiding catalysis

As can be seen, the coenzyme binds with the enzyme, resulting in a slightly different shape. This then allows for the substrate to have the correct shape and bonding interactions which otherwise, without the coenzyme, would not be possible. Coenzymes are often derived from vitamins and are essential in the body to allow an enzyme to become active and catalyse a reaction.

Theory summary

- Enzymes are biological catalysts which consist of an active site which binds to a substrate.
- The lock and key model proposes that a substrate fits perfectly into the active site of an enzyme.
- The induced-fit model proposes that the active site of an enzyme temporarily changes shape to accommodate a substrate.
- An increase in temperature increases the enzyme activity up to the optimal temperature where afterwards, there is a sharp decrease due to denaturation of the enzyme.
- A change in pH affects enzyme function because it can cause an enzyme to become denatured.
- Coenzymes are small molecules which bind to the active site of an enzyme, allowing it to become active and catalyse a reaction.

9C QUESTIONS

Theory review questions

Question 1

Which of the following statements is incorrect regarding enzymes?

A Enzyme activity differs with a change in temperature.

B Enzymes are biological catalysts.

C Enzymes are consumed in chemical reactions.

D Enzyme activity differs with a change in pH.

Question 2

The lock and key model states that

A an enzyme will change the shape of its active site to fit the substrate.

B the substrate perfectly fits the enzyme's active site.

C an enzyme can not differentiate between optical isomers.

D an enzyme can only be used once.

Question 3

A coenzyme is

A a vitamin that binds to the active site of an enzyme.

B a molecule that binds to the substrate.

C permanently bound to the active site of an enzyme.

D a small organic molecule which modifies the properties of an enzyme's active site.

Exam style questions

Within lesson

Question 4 (1 MARK)

Which of the following does not affect the rate of a reaction involving enzymes?

A A change in pH

B An increase in the concentration of an enzyme when all the substrate molecules are bound

C A change in temperature

D An increase in the concentration of an enzyme when not all the substrate molecules are bound

Question 5 (1 MARK)

An enzyme

A always has an active site which can never change its shape.

B is consumed in a reaction.

C is always active.

D is specific to a certain enantiomer.

Question 6 (1 MARK)

Coenzyme M is very important in the body as a carrier of electrons.

Coenzyme M

A is required for all enzymes to become active.

B is irreversibly changed in a reaction.

C forms a complex with an enzyme.

D is a large non-organic molecule.

Question 7 (4 MARKS)

There are currently slightly different theories that explain the function of enzymes. With reference to labelled diagrams, explain the

a lock and key model. (2 MARKS)

b induced-fit model. (2 MARKS)

Question 8 (3 MARKS)

A chemist has designed a drug that exists as 2 enantiomers in a 50:50 ratio. In order for it to have the desired effect, the drug needs to be able to be metabolised by the body. However, the chemist soon discovers that only half the drug is metabolised by the body. Using your knowledge of optical isomers and enzymes, suggest a reason why this might be the case.

Multiple lessons

Question 9 (4 MARKS)

Hyperthermia is a medical condition where the body's temperature exceeds the normal range and hypothermia is a medical condition where the body's temperature is below that of the normal range. With reference to enzyme activity and temperature, justify why doctors consider both these conditions to be life-threatening.

Question 10 (7 MARKS)

Jasmine, a VCE chemistry student, would like to determine the effect of pH on enzyme activity. She uses the enzyme lipase which is essential in the breakdown of lipids. This enzyme has an optimum pH range of 4.0–5.0 and she sets up 3 test tubes each with a few drops of lipase. One test tube has a pH of 1.0, the second with a pH of 4.5 and a third with a pH of 14.0. She then places a cube of fat of the same size in each test tube.

a Using your knowledge of pH and enzyme activity, predict what she would observe in each test tube, justifying your reasons. (2 MARKS)

b Does this experiment have control test tubes? If not, explain what could be done to improve the validity of the results. (2 MARKS)

c The enzyme alpha-amylase is produced by the salivary glands and secreted into the mouth. Explain why alpha-amylase can only function in the mouth, given that different parts of the digestive tract all vary with respect to pH. (2 MARKS)

d What structure of a protein is changed when an enzyme becomes denatured? (1 MARK)

9D STRUCTURE AND PROPERTIES OF VITAMINS

In this lesson you will be learning about the chemical structure and properties of organic compounds known as vitamins.

9A Structure of proteins	9B Breakdown of proteins	9C Enzymes	9D Structure and properties of vitamins

Study design dot point

- vitamins: inability of humans to synthesise most vitamins (except Vitamin D) making them essential dietary requirements; comparison of structural features of Vitamin C (illustrative of a water-soluble vitamin) and Vitamin D (illustrative of a fat-soluble vitamin) that determine their solubility in water or oil.

Key knowledge units

Structure and properties of vitamins	4.2.4.1

Key terms and definitions

- **Vitamin** organic molecules needed in small quantities for normal bodily functions
- **Essential vitamin** vitamin that cannot be produced by the human body and therefore must be consumed in one's diet
- **Non-essential vitamin** vitamin that can be manufactured by the human body

Structure and properties of vitamins 4.2.4.1

OVERVIEW

Vitamins are organic compounds with a broad range of chemical structures and functions in the human body.

THEORY DETAILS

Vitamins are organic compounds that the human body requires on a regular basis in small amounts to allow the body to function properly. Almost all of the 13 vitamins must be taken in through one's diet since they cannot be produced by the body. These vitamins are known as **essential vitamins.** Vitamins that can be made by the body such as vitamin D, which is synthesised from exposure to sunlight, are instead classified as **non-essential.**

Vitamins perform a number of vital different roles including acting as a source of coenzymes, aiding the immune system or preventing harmful chemical reactions by acting as antioxidants. Such a diverse range of roles is possible due to the wide variety of chemical structures that exist amongst vitamins as shown in figure 1.

However, all vitamins can be divided into two categories: water-soluble and fat-soluble.

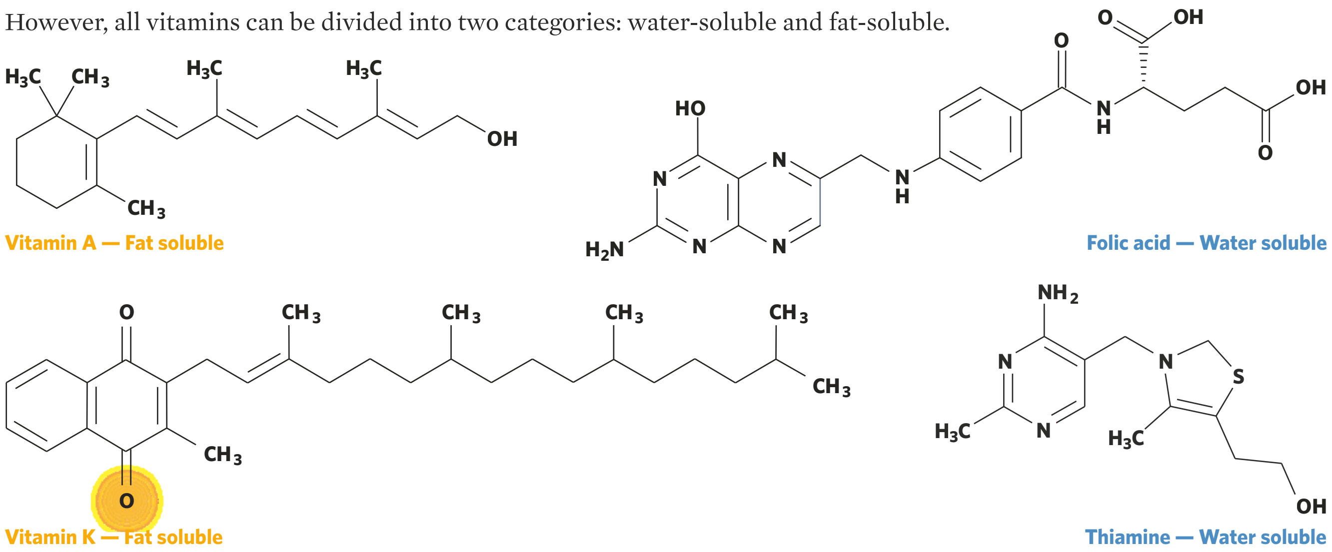

Vitamin A — Fat soluble
Folic acid — Water soluble
Vitamin K — Fat soluble
Thiamine — Water soluble

Figure 1 Structures of different vitamins and their solubilities

Water-soluble vitamins are polar substances capable of forming hydrogen bonds with water. Water-soluble vitamins such as thiamine and folic acid (figure 1) will usually have a large number of functional groups containing the elements oxygen and nitrogen. Since they dissolve in an aqueous solution, these vitamins are readily absorbed into the bloodstream with any excess vitamins then excreted from the body in urine. Since they cannot be stored for long periods, this means that the body needs to constantly replenish its supply of water-soluble vitamins through its dietary intake. The water-soluble vitamin C (shown in figure 2 forming hydrogen bonds with water) is crucial to the proper functioning of the immune system and acts as an antioxidant to prevent harmful chemical reactions in the body's cells and tissues.

Tip Just like all other organic compounds, vitamins follow the 'like dissolves like' rule for solubility.

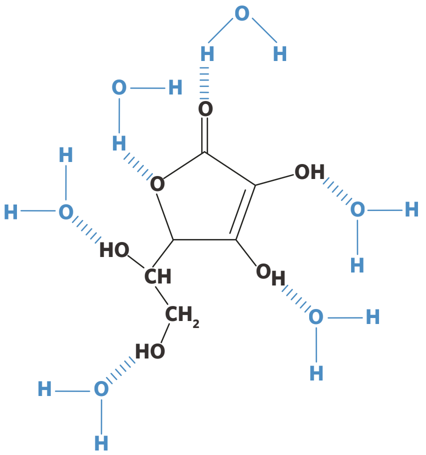


Figure 2 The essential, water-soluble vitamin C forms hydrogen bonds with water when in aqueous solution

Fat-soluble (also referred to as lipid-soluble) vitamins are largely non-polar compounds with a high density of carbon and hydrogen. Examples of fat-soluble vitamins include vitamin A, vitamin K (figure 1) and vitamin D (figure 3). Although some fat-soluble vitamins contain polar functional groups, given the overall size of the molecule they become relatively non-polar, interacting through dispersion forces. This allows fat-soluble vitamins to bond to non-polar lipids in the body's fatty tissue. As a result, since they are soluble in fatty tissue, they can be stored for much longer periods of time than water-soluble vitamins. However, this means that consuming an excess of fat-soluble vitamins will lead to an accumulation in tissues that can be toxic for the body.

Tip Structural formulas for Vitamin C and two different forms of Vitamin D are given in the VCAA data book.

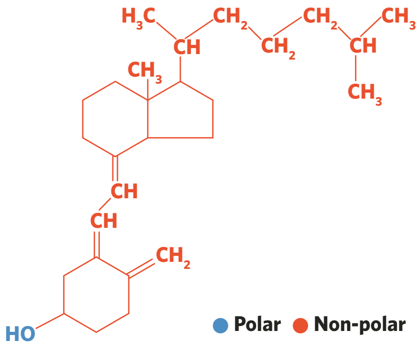


Figure 3 Structure of the non-essential, fat-soluble vitamin D

Theory summary

- Vitamins are organic compounds with a diverse range of structures and functions.
- Vitamins are either essential or non-essential nutrients depending on whether they can be produced by the body.
- Vitamins can be classified as either water-soluble or fat-soluble.
- Water-soluble vitamins are highly polar molecules.
- Fat-soluble vitamins are mostly non-polar.
- Water-soluble vitamins are needed on a regular basis, whereas fat-soluble vitamins can be stored in the body for much longer periods of time.

9D QUESTIONS

Theory review questions

Question 1

Why is it important to eat foods containing water-soluble vitamins on a daily basis, but this is not true for fat-soluble vitamins?

A Fat-soluble vitamins cannot be used by humans and therefore are not necessary.

B All water-soluble vitamins are essential, whereas fat-soluble vitamins are all non-essential.

C Water-soluble vitamins cannot be stored, whereas fat-soluble vitamins can be.

D Fat-soluble vitamins are not contained in food.

Question 2

The dominant intermolecular forces in vitamin C and vitamin D respectively are

A ion-dipole bonding, dispersion forces.

B hydrogen bonding, dispersion forces.

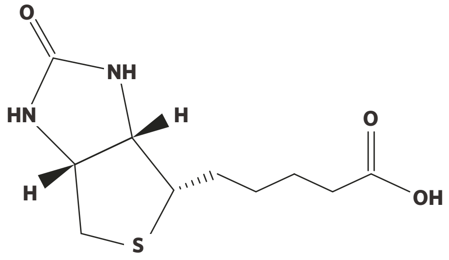
C hydrogen bonding, hydrogen bonding.

D dispersion forces, hydrogen bonding.

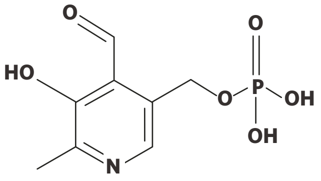
Question 3

Which of the following vitamins will be soluble in oil?

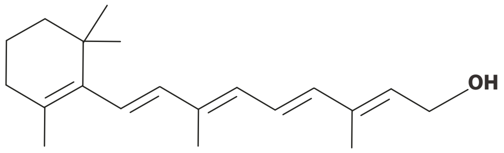
I



II



III



A I and III only

B III only

C I, II and III

D None of the above

Exam-style questions

Within lesson

Question 4 (1 MARK)

The condition hypervitaminosis occurs as a result of dangerously high vitamin levels in the body over a prolonged period of time. Which class of vitamins would most likely be the cause of this condition? Why?

A Water-soluble. They can enter the bloodstream and circulate throughout the whole body, whereas fat-soluble vitamins only ever reside in fatty tissue.

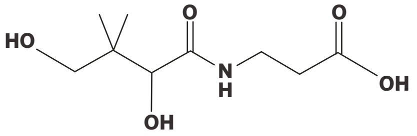
B Water-soluble. They are considered toxic to humans.

C Fat-soluble. They are considered non-essential vitamins and therefore are not usually required in large amounts.

D Fat-soluble. They can be stored in fatty tissue whereas water-soluble vitamins are eliminated easily.

Question 5 (3 MARKS)

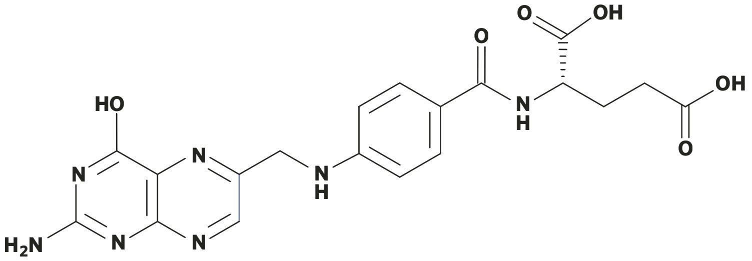
Name all functional groups present in a molecule of Vitamin B5. Specify each functional group's primary, secondary or tertiary nature.



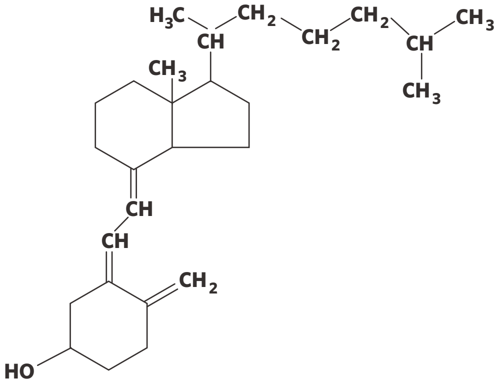
Question 6 (6 MARKS)

Are the following vitamins fat-soluble or water-soluble? Explain.

a (3 MARKS)



b (3 MARKS)



Multiple lessons

Question 7 (1 MARK)

Which of the following is true for a molecule of Vitamin C?

A It has two chiral carbons.

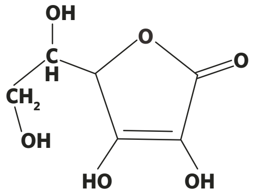
B It has the same molecular formula as its empirical formula.

C It has a strong broad peak in the range of 2300–2400 cm^{-1} on its infrared spectrum.

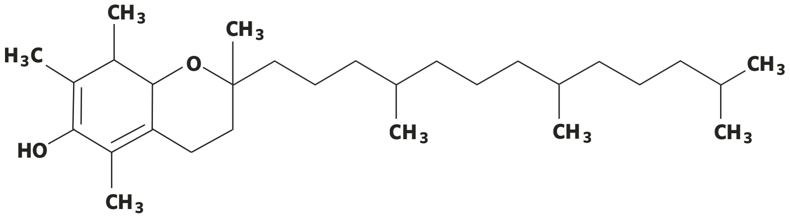
D In HPLC, it would desorb into a methanol mobile phase less than 3-methylpentane.

Question 8 (1 MARK)

What is the empirical formula of vitamin C?



Question 9 (4 MARKS)



a On the given molecule of Vitamin E, circle all chiral centres. (1 MARK)

b Describe the solubility of Vitamin E in water. (3 MARKS)

EXPERIMENT

BREAKDOWN OF PROTEINS

Lani is studying chemistry at school and she is curious about the effect of temperature on enzyme function. She is specifically interested in the function of the enzyme protease in the breakdown of proteins and so decides to set up the following experiment.

Materials

- 1% standard protease solution
- 5 × small 2 cm × 2 cm × 2 cm cubes of gelatin (substance rich in protein)
- 5 × test tubes
- Ice
- 5 thermometers
- 5 × 100 mL beakers
- Kettle
- Tweezers
- Timer
- Scales
- Paper towel
- Pasteur pipette
- Test tube rack
- Distilled water

Method

1 Weigh each of the cubes of gelatin and record their mass.
2 Label each of the test tubes A–E and place them in the test tube rack.
3 Use tweezers to add a cube of gelatin into each of the 5 test tubes.
4 Label each of the beakers A–E and place a thermometer in each.
5 Use the ice, distilled water and hot water boiled from the kettle to fill each of the 5 beakers A–E with 50 mL of water of temperature 10 °C, 20 °C, 30 °C, 40 °C and 50 °C respectively.
6 Using a pipette, place 3 drops of the protease solution into each test tube.
7 Immediately afterwards, gently lower each of the test tubes into the 100mL beakers of water at different temperatures and start the timer.
8 After 30 minutes has elapsed, remove the test tubes from the beakers and, using tweezers, place each cube of gelatin (if still present) on a paper towel to dry.
9 Record the final mass of each cube of gelatin after drying.

Results

	Gelatin cube in test tube A	**Gelatin cube in test tube B**	**Gelatin cube in test tube C**	**Gelatin cube in test tube D**	**Gelatin cube in test tube E**
Initial mass (g)					
Final mass (g)					
Change in mass (g)					

QUESTIONS

Question 1 (3 MARKS)

List the dependent, independent and controlled variables in this experiment.

Question 2 (4 MARKS)

When Lani carried out the experiment, her results were as follows:

	10 °C	**20 °C**	**30 °C**	**40 °C**	**50 °C**
Initial mass (g)	2.1	1.9	2.0	2.2	2.3
Final mass (g)	1.8	1.4	1.2	0.2	0
Change in mass (g)	0.3	0.5	0.8	2	2.3

Are the results for the beakers with water of 10 °C, 20 °C, 30 °C and 40 °C consistent with your knowledge of the effect of temperature on enzyme function? Explain why or why not.

Question 3 (3 MARKS)

Is the result for the beaker with water of 50 °C consistent with your knowledge of the effect of temperature on enzyme function? Explain why or why not.

Question 4 (2 MARKS)

Given that gelatin has a low melting point, suggest a reason why the results of this experiment may not be valid.

Question 5 (2 MARKS)

Identify one area of weakness in the experimental design and suggest a possible improvement to address it.

ANSWERS

1 Dependent – mass of cube of gelatin after 30 minutes.
Independent – temperature of water in the beaker.
Controlled – amount of protease in each test tube, time in the solution, initial size and surface area of the cube of gelatin.

2 [These results are consistent with our knowledge of enzyme function.[1]][This is because the change in mass of the gelatin cube increased as temperature increased, indicating that the rate of reaction has increased.[2]][The rate of reaction has increased because as temperature increases, the average kinetic energy of the molecules increases, which leads to a higher proportion of successful collisions with sufficient energy in a given amount of time.[3]][In this experiment, this increase in collisions occurs between the enzyme and its substrate per unit of time, demonstrating an increased rate of reaction.[4]]

✓ ✗ I have stated whether these results are consistent with the theory of enzyme function.[1]

✓ ✗ I have identified the experimental results that indicate an increased rate of reaction.[2]

✓ ✗ I have described the effect of temperature on the kinetic energy of reactant molecules.[3]

✓ ✗ I have linked kinetic theory to the reaction occurring in the experiment.[4]

3 [These results are not consistent with our knowledge of enzyme function.[1]][This is because after the optimal temperature of an enzyme of approximately 40 °C, enzyme activity rapidly decreases due to denaturation causing a permanent change in the protein's structure, altering its active site until it can no longer bind with the substrate and catalyse the breakdown of protein.[2]][Therefore, at 50 °C, there should not be such a large change in mass because the enzyme protease would have been denatured and unable to function effectively.[3]]

✓ ✗ I have stated whether these results are consistent with the theory of enzyme function.[1]

✓ ✗ I have described the effect of above optimal temperatures on enzyme structure with reference to the mechanism of enzyme-substrate catalysis.[2]

✓ ✗ I have outlined how enzyme denaturation should have affected experimental results.[3]

4 [Validity is a measure of whether a scientific experiment can support its conclusions. The results of this experiment are invalid because since the melting point of gelatin is low, it may be the temperature of the solution rather than differing levels of enzymatic activity that is responsible for the melting of the gelatin.[1]][This would lead to an inaccurate mass change solely due to enzyme function (as was the case for the test tube immersed in water of 50°C).[2]]

✓ ✗ I have identified the variable that makes the experiment invalid.[1]

✓ ✗ I have described how this variable has impacted the experiment's results.[2]

5 [One area of weakness is the fact that the low melting point of gelatin is affecting the validity of the experiment.[1]][This could be improved by choosing a source of protein that is more resistant to temperature change rather than gelatin.[2]]

✓ ✗ I have identified an area of weakness in the experiment.[1]

✓ ✗ I have stated a method of improving the experiment that addresses this weakness.[2]

CHAPTER 9 QUESTIONS

MULTIPLE CHOICE (10 MARKS)

Question 1

Which of the following is true of amino acids?

A In basic solutions, the amino group attached to the α-carbon exists in the $-NH_3^+$ form.
B Amino acids only contain the elements C, H, O and N.
C All amino acids are chiral.
D Amino acids are amphiprotic.

Question 2

Which of the following is the correct semi-structural formula for the dipeptide Asp-Ser?

A $H_2NCH(CH_2COOH)CONHCH(CH_2SH)COOH$
B $H_2NCH(CH_2COOH)CONHCH(CH_2OH)COOH$
C $H_2NCH(CH_2OH)CONHCH(CH_2COOH)COOH$
D $H_2NCH(CH_3)CNOHCH(CH_2COOH)COOH$

Question 3

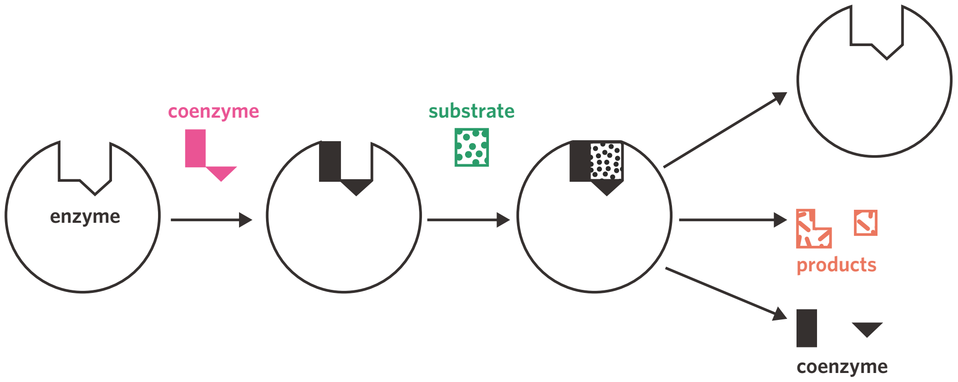
Achatin-1 (Gly-Phe-Ala-Asp) is a peptide that acts as a neuroexcitatory agent and is produced by the African Giant Snail.

Which of the following are the correct structures for the two terminal ends of Achatin-1 at a very low pH?

A	$-NH_3^+$	$-COOH$
B	$-NH_3^+$	$-COO^-$
C	$-NH_2$	$-COOH$
D	$-NH_2$	$-COO^-$

Question 4

In preparation for his chemistry exam, Tom created the diagram below to summarise the lock-and-key model for coenzyme catalysis. Unfortunately, he has made a significant mistake.



Which of the following correctly identifies the mistake in Tom's diagram?

A The coenzyme binds to the enzyme and changes the shape of the active site.
B This diagram actually describes the induced fit model for enzyme catalysis.
C The enzyme's structure is significantly changed in the reaction.
D The coenzyme has broken apart in the reaction.

Question 5

The protein haemoglobin acts as an oxygen carrier in the bloodstream and consists of four subunits that form its complex quaternary structure. A student tested four separate samples of pure haemoglobin in the form of 1M aqueous solutions.

In which of the following tests would the primary structure of haemoglobin most likely be interrupted?

A Blend the solution at very high speed

B Boil the solution at high temperature and analyse the gas(es) evolved

C Add hydrochloric acid to the solution followed by the enzyme pepsin, then heat the solution

D Add methanol that will disrupt the hydrogen bonding in haemoglobin

Question 6

Which of the following is a correct statement about the process of protein denaturation?

A Denaturation can be observed by the release of peptides.

B Changes in pH result in denaturation by disrupting the protein's primary structure.

C Denaturation is an irreversible process.

D Denaturation involves the disruption of all bonds in the protein's tertiary structure.

Question 7

A chemist managed to isolate a single molecule of each of the amino acids alanine, glycine and leucine. How many unique tripeptides could she form using just a single molecule of each of these amino acids?

A 36

B 12

C 6

D 3

Question 8

In organic chemistry, a compound with n chiral centres will have 2^n optical isomers. How many optical isomers will the dipeptide Trp-Thr have?

A 2

B 4

C 8

D 16

Question 9

Aqueous solutions of the amino acids aspartic acid and alanine react together in a condensation reaction that produces one water molecule. How many different compounds could be created?

A 5

B 2

C 3

D None of the above

Question 10

Which of the following is NOT a functional group that could be found in a protein?

A Benzene ring

B Disulfide linkage

C Amide

D Ether linkage

SHORT ANSWER (31 MARKS)

Question 11 (7 MARKS)

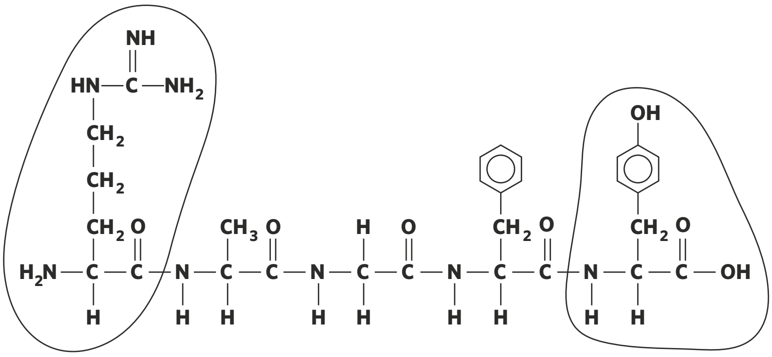
A protein's overall shape is maintained by intermolecular forces in its secondary, tertiary and quaternary structure.

a Describe the different intermolecular forces involved in a protein's secondary and tertiary structure. (4 MARKS)

b The protein transferrin is used as an iron carrier in the bloodstream. A sample of transferrin was isolated and then dissolved in a solution with a pH of 2.3. After a few minutes, significant 'clumps' were observed in the solution. Explain this observation. (3 MARKS)

Question 12 (5 MARKS)

A section of a polypeptide chain is shown below.



Adapted from VCAA 2016 Exam 2 Section A Q23

a What is the name given to the link between each amino acid residue? (1 MARK)

b State the name given to the reaction that formed this polypeptide. (1 MARK)

c Name the amino acids that have been circled in this polypeptide chain. (2 MARKS)

d The amino acid residue of cysteine is present in another section of this polypeptide. Draw the skeletal formula of cysteine as it would appear in a solution of high pH. (1 MARK)

Question 13 (2 MARKS)

The two amino acids serine and phenylalanine can combine together in a condensation reaction to form a dipeptide.

a Draw the structural formula of the dipeptide Phe-Ser as it would appear in a solution of neutral pH. (1 MARK)

b If the amino acid lysine were combined with this dipeptide, what would be the overall charge on the tripeptide, assuming no change in pH? (1 MARK)

Question 14 (11 MARKS)

The enzyme 24-hydroxylase catalyses the breakdown of the active form of vitamin D in the body.

a Given that vitamin D is a chiral molecule, explain why this enzyme would not break down a different optical isomer of vitamin D. (2 MARKS)

b With specific reference to the energy of the reactant molecules, describe how an enzyme catalyst acts to increase the rate of a chemical reaction. (3 MARKS)

c Describe the process of this enzyme catalysis if 24-hydroxylase acted via

  i the lock and key model. (2 MARKS)

  ii the induced fit model (2 MARKS)

d If 24-hydroxylase required a coenzyme to function effectively, explain how the enzyme and coenzyme would interact together to catalyse the reaction. (2 MARKS)

KEY SCIENCE SKILL QUESTION

Question 15 (6 MARKS)

Sharni wants to determine the concentration of Vitamin C in orange juice. She decides to set up a titration using the fact that Vitamin C reduces iodine to iodide and the presence of iodine can be determined using starch – a chemical that turns purple/black in the presence of iodine but not iodide. She decides to use a 100 mL beaker of orange juice with a couple of drops of starch indicator in it. She then gradually adds drops of iodine. At some point, the solution instead of being an orange colour turns dark purple.

a What might this indicate and how might Sharni be able to determine the concentration of vitamin C using this method? (3 MARKS)

b Provide one example of a dependent, independent and controlled variable in this experiment. (3 MARKS)

UNIT 4 AOS 2, CHAPTER 10

Food chemistry (part 2): carbohydrates, fats and calorimetry

10

Key knowledge

- carbohydrates: formation of disaccharides from monosaccharides, and of complex carbohydrates (specifically starch and cellulose) as condensation polymers of monosaccharides; glycosidic links; storage of excess glucose in the body as glycogen; comparison of glucose, fructose, sucrose and the artificial sweetener aspartame with reference to their structures and energy content
- hydrolysis of starch in the body: explanation of the ability of all humans to hydrolyse starch but not cellulose, and of differential ability in humans to hydrolyse lactose; glycaemic index (GI) of foods as a ranking of carbohydrates based on the hydrolysis of starches (varying proportions of amylose and amylopectin) to produce glucose in the body
- glucose as the primary energy source, including a balanced thermochemical equation for cellular respiration
- fats and oils (triglycerides): common structural features including ester links; distinction between fats and oils with reference to melting points; explanation of different melting points of triglycerides with reference to the structures of their fatty acid tails and the strength of intermolecular forces; chemical structures of saturated and unsaturated (monounsaturated and polyunsaturated) fatty acids; distinction between essential and non-essential fatty acids; and structural differences between omega-3 fatty acids and omega-6 fatty acids
- metabolism of food as a source of energy and raw materials: general principles of metabolism of food involving enzyme-catalysed chemical reactions with reference to the breakdown of large biomolecules in food by hydrolytic reactions to produce smaller molecules, and the subsequent synthesis of large biologically important molecules by condensation reactions of smaller molecules
- hydrolysis of fats and oils from foods to produce glycerol and fatty acids; oxidative rancidity with reference to chemical reactions and processes, and the role of antioxidants in slowing the rate of oxidative rancidity
- the principles of calorimetry; solution and bomb calorimetry, including determination of calibration factor and consideration of the effects of heat loss; and analysis of temperature-time graphs obtained from solution calorimetry.
- the comparison of energy values of carbohydrates, proteins and fats and oils

10A STRUCTURE OF CARBOHYDRATES

In this lesson we will be learning about the structure of carbohydrates and the relationship between simple and complex carbohydrates by examining their building blocks.

10A Structure of carbohydrates	10B Breakdown and importance of carbohydrates	10C Structure of fats and oils	10D Breakdown of fats and oils	10E Properties of fats and oils	10F Calorimetry	10G Energy in food

Study design dot point

- carbohydrates: formation of disaccharides from monosaccharides, and of complex carbohydrates (specifically starch and cellulose) as condensation polymers of monosaccharides; glycosidic links; storage of excess glucose in the body as glycogen; comparison of glucose, fructose, sucrose and the artificial sweetener aspartame with reference to their structures and energy content

Key knowledge units

The building blocks of carbohydrates	4.2.2.1
Complex carbohydrates	4.2.2.2

Key terms and definitions

- **Carbohydrate** molecule made up of carbon, hydrogen and oxygen with the general formula of $C_a(H_2O)_b$
- **Monosaccharide** smallest building block of carbohydrates consisting of only one sugar molecule. eg. glucose, fructose and galactose
- **Disaccharide** carbohydrate formed from a condensation reaction between two monosaccharides and joined by a glycosidic linkage
- **Polysaccharide** complex carbohydrate formed from the condensation of multiple monosaccharides that are joined together by glycosidic linkages
- **Glycosidic linkage** ether (-O-) linkage that joins two monosaccharides
- **Aspartame** powerful artificial sweetener used instead of sucrose
- **Starch** polysaccharide made up of multiple α-glucose monosaccharides. Starch can exist in two forms: amylopectin and amylose
- **Amylopectin** highly branched form of starch
- **Amylose** tightly coiled, unbranched form of starch
- **Cellulose** polysaccharide composed of β-glucose that is indigestible to humans and found in the cell walls of plants
- **Glycogen** highly branched polysaccharide made up of glucose monosaccharides that is used by animals for energy storage

The building blocks of carbohydrates 4.2.2.1

OVERVIEW

The primary building blocks of carbohydrates are simple ‘ring sugars’ known as monosaccharides.

THEORY DETAILS

Carbohydrates are a special class of macromolecules that are made up of carbon, hydrogen and oxygen. However, what sets them apart from molecules like alcohols, which also contain only these three elements, is that they have their general molecular formulas in the form $C_a(H_2O)_b$, where a and b are whole numbers. This requirement means that carbohydrates have a high density of oxygen (primarily in the form of hydroxyl –OH groups), which will have interesting implications for how they interact with both other carbohydrates and molecules like water when dissolved in solution.

Monosaccharides, which are the smallest building blocks of carbohydrates, exist as cyclic organic compounds, or ‘rings’ when dissolved in solution. The various hydroxyl groups are represented as either pointing above or below the hydrocarbon ring. In the molecule of the monosaccharide glucose in figure 1, the Greek letter alpha, α, denotes that the hydroxyl group on carbon 1 is pointing downwards. The molecule β-glucose instead has this hydroxyl group pointing upwards.

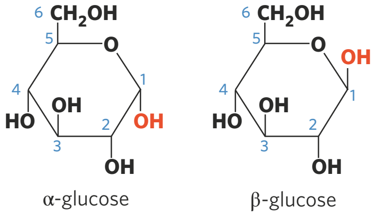

α-glucose β-glucose

Figure 1 A representation of the α and β forms of the common monosaccharide glucose

In figure 2, there are three monosaccharides that all have the same structural formula $C_6H_{12}O_6$ but have different bonding arrangements, meaning that they exist as the structural isomers glucose, fructose and galactose. Unlike glucose and fructose, which are commonly found in fruits and living systems, galactose does not exist as a free molecule in nature. It is instead found primarily as a breakdown product of the lactose found in milk.

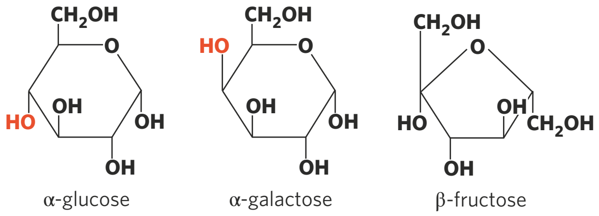

α-glucose α-galactose β-fructose

Figure 2 Structures of the common monosaccharides glucose, fructose and galactose

From earlier studies, we know that polar compounds will dissolve in polar solvents and non-polar compounds will dissolve readily in non-polar solvents. The many hydroxyl groups on monosaccharides mean that they have strong intermolecular forces due to hydrogen bonding with water molecules. Therefore, monosaccharides have very high solubility in water (a polar solvent), which can surround it and form a number of hydrogen bonds as shown in figure 3.

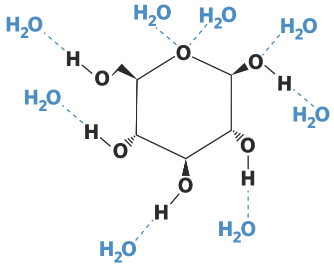
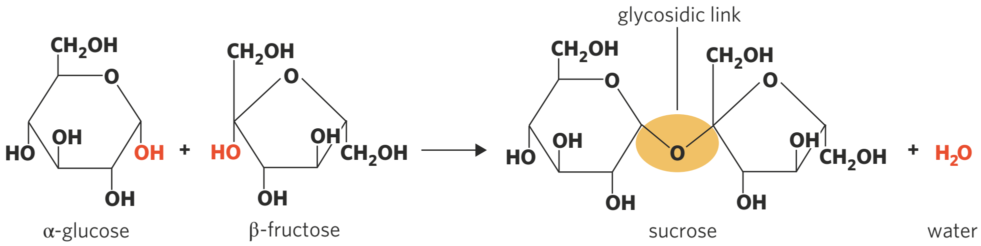


Figure 3 The five hydroxyl groups of the monosaccharide glucose readily form hydrogen bonds with water, which allows it to dissolve readily in this polar solvent.

Using these three simple monosaccharide rings as our basic structural units, we can increase the complexity of carbohydrates by linking two of them together to form what is known as a disaccharide. A familiar **disaccharide** results from the reaction between glucose and fructose to produce sucrose with molecular formula $C_{12}H_{22}O_{11}$, as shown in figure 4.

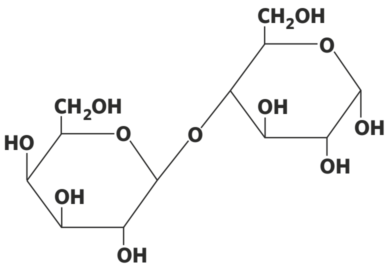


α-glucose β-fructose sucrose water

Figure 4 Monosaccharides α-glucose and β-fructose combine to form the disaccharide sucrose and a free water molecule in a condensation reaction

However, we notice that the molecular formula of sucrose is not as simple as 2 × $C_6H_{12}O_6$ and that the two hydroxyl groups from the glucose and fructose have been replaced by an ether -O- link between the two monosaccharides. A free H_2O molecule is also formed just like during condensation reactions involving amino acids in chapter 9. This ether linkage is also referred to as a **glycosidic linkage** and is specific to the oxygen ‘bridge’ that forms between two ring sugars.

This means that every time we add another ‘link’ to our ‘sugar chain’ we have a condensation reaction where a water molecule is produced and a glycosidic linkage is formed. Some other common disaccharides include lactose and maltose, as shown in figure 5, both of which are formed from condensation reactions. The disaccharide α-lactose is commonly found in milk and is formed from the condensation reaction between α-glucose and β-galactose. Maltose exists in barley and as a digestion product of larger carbohydrate chains. It is formed from two α-glucose units.


α-lactose

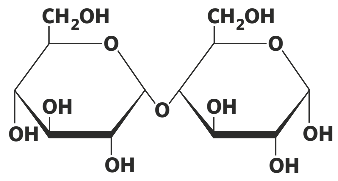

maltose

Figure 5 Two other common disaccharides: maltose and α-lactose

We now turn to another feature of carbohydrates commonly associated with these kinds of simple sugars. All of the disaccharide sugars above have varying levels of sweetness when eaten and their relative energy contents are shown in table 1. However, perhaps the one that is most common is sucrose. Sucrose is instantly recognisable as a white crystalline solid with a high solubility in water and for its sweet taste. However, consuming large amounts of sucrose leads to a wide range of health problems due to the fact that any excess energy consumed is stored in the body as fat. This has lead to an increase in the use of powerful artificial sweeteners in order to reach the same level of sweetness with a much lower energy content. The commonly used artificial sweetener **aspartame** has a similar energy content to sucrose (17 kJ/g) but is actually 200 times sweeter, which means it can achieve the same effect only with much smaller quantities. The structure of aspartame is shown in figure 6. It is worth noting that although aspartame is sweet like sucrose and other simple sugars, it is not a carbohydrate. This becomes quite obvious from the amide group that joins amino acids aspartic acid and phenylalanine and the ester linkage formed with methanol, resulting in its molecular formula $C_{14}H_{18}N_2O_5$.

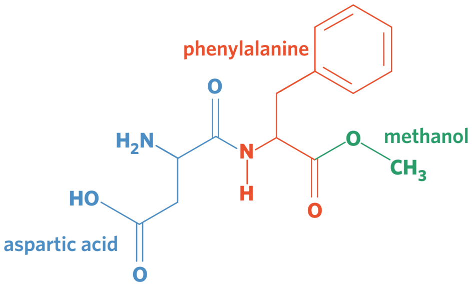


Figure 6 Structure of the artificial sweetener aspartame

Table 1 A summary of the energy content of various sugars and aspartame

Sugar / sweetener	Structure	Relative sweetness	Energy content (kJ/g)
glucose	monosaccharide	0.74	16
fructose	monosaccharide	1.75	16
sucrose	disaccharide glucose + fructose	1.0	16
aspartame	artificial non-carbohydrate	150–200	16.7

Complex carbohydrates 4.2.2.2

OVERVIEW

Complex carbohydrates are **polysaccharides** made up of many individual monosaccharides.

THEORY DETAILS

Beyond two-ring sugars (disaccharides), more monosaccharides can be added to form much more complicated polysaccharides that may have hundreds or even thousands of monosaccharide units as shown in figure 7. Every time a monosaccharide is added to this chain there is a condensation reaction and another H_2O molecule is produced. With this increase in complexity we can move from what are known as simple carbohydrates with only a few rings connected in a single, unbranched chain to ones that have hundreds more rings and can be connected through various branching patterns that form intricate and tangled networks. These molecules are known as complex carbohydrates.

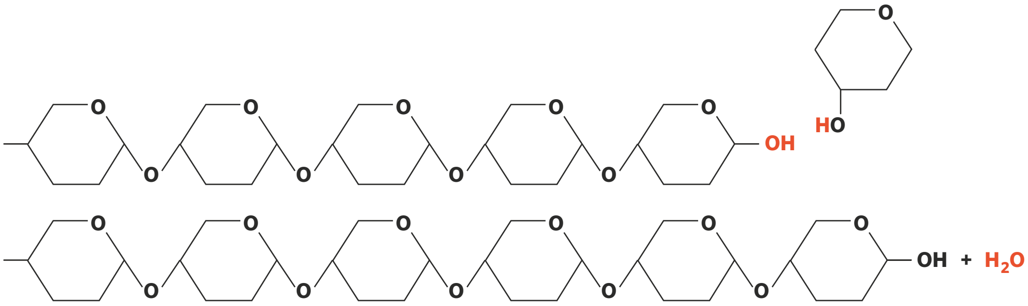


Figure 7 Formation of polysaccharides (ethyl alchohol groups omitted for clarity)

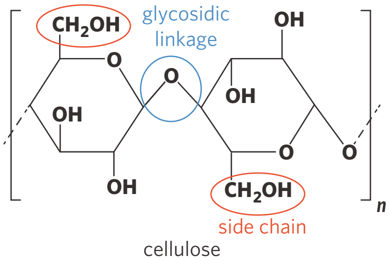


Figure 8 The repeating unit of cellulose

In this course we will only focus on the polysaccharides that use glucose as a monomer (primary building block). However, they all vary in the bonds that form between the individual monosaccharides, which will affect how the overall polymer structure fits together. The most simple polymer of glucose is **cellulose**, which is commonly found in the cell wall of plants.

The structure of cellulose is shown in figure 8. The subscript *n* indicates that the molecule actually exists as a much longer chain continuing horizontally to the left and right with repeating units of the monomer.

Looking at the glucose unit on the left in figure 8, the bond that forms the glycosidic linkage is pointing upwards (highlighted in blue), indicating that cellulose uses β-glucose as its monomer (repeating unit). In fact, it is the only one of the polysaccharides we will look at that uses β-glucose as its monomer – all the others will use α-glucose. It can also be seen that the bulky CH_2OH groups that branch off the rings are pointing in opposite directions (highlighted in red). This means that when long chains of cellulose are nearby, they can ‘lock’ into each other like puzzle pieces and form very strong intermolecular bonds.

Another common polysaccharide is **starch**, which is found primarily in rice, wheat, bread and root vegetables such as potatoes and cassava. It exists in two main forms: **amylose** and **amylopectin**.

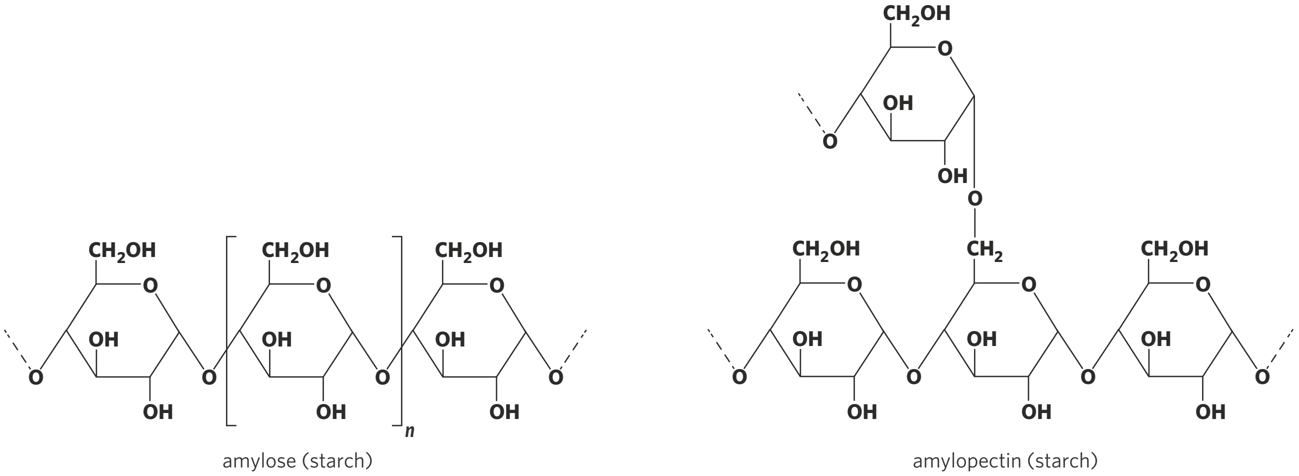


Figure 9 The repeating units of amylose and amylopectin. Note the branching nature of amylopectin.

The structures of amylose and amylopectin are shown in figure 9. At first glance, amylose looks very similar in structure to cellulose with its linear chain and regular arrangement. However, if we look more closely, we notice that unlike cellulose all the CH_2OH groups in amylose are pointing in the same direction. This means that chains of amylose don’t fit as neatly together and instead form tightly coiled helices consisting of thousands of α-glucose units.

Amylopectin, on the other hand, is noticeably different in structure. This is due to additional covalent bonds that form between glucose units and side chains attached to the carbon from the CH_2OH group resulting in highly branched, non-linear polymers with very complicated intermolecular forces. These side chain branches in amylopectin occur roughly once every 20 glucose units.

While starch and cellulose are found in plants, **glycogen** is used as an energy storage molecule in animals including humans and its overall structure is shown in figure 10. It is identical in structure to amylopectin, but the side chain branches occur roughly twice as often (approximately every 10 glucose units), resulting in an even greater amount of branching.

All these differences in structure have a large impact on how easily each polysaccharide can be broken back down into its glucose monomers by the human body (these differences will be discussed in detail in lesson 10B). A summary of all these different polymers of glucose is shown in table 2.

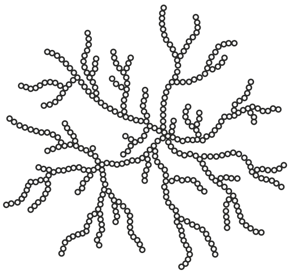
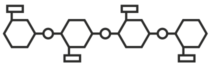
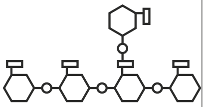
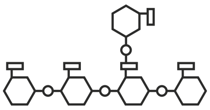
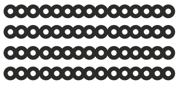
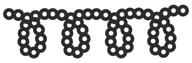
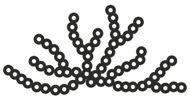
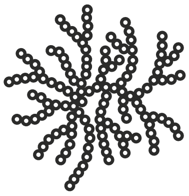


Figure 10 Overall structure of glycogen

Table 2 Summary of the structures of glucose polymers

	Cellulose	**Starch**		**Glycogen**
		Amylose	Amylopectin	
Source	Plant	Plant	Plant	Animal
Subunits	β-glucose	α-glucose	α-glucose	α-glucose
Bonds	1-4	1-4	1-4 and 1-6	1-4 and 1-6
Branches	No	No	Yes (~per 20 subunits)	Yes (~per 10 subunits)
Diagram				
Shape				

Theory summary

- The structural isomers glucose, fructose and galactose are the three key monosaccharide building blocks of more complex sugars.
- Carbohydrates are formed in condensation reactions that produce a water molecule and are joined by glycosidic linkages.
- Monosaccharides are highly soluble in polar solvents like water due to their numerous polar hydroxyl groups.
- Aspartame is an artificial sweetener that is much sweeter than sucrose.
- Starch, cellulose and glycogen are polymers of glucose each with different overall structures due to their specific bonding patterns. Two forms of starch are amylose and amylopectin.

10A QUESTIONS

Theory review questions

Question 1

A list of carbohydrates in decreasing molar mass is

A glycogen, sucrose, fructose
B fructose, glucose, galactose
C cellulose, galactose, glucose
D starch, lactose, cellulose

Question 2

An unknown polysaccharide is found to be a polymer of β-glucose. Which of the following gives the likely identity of the compound and its branching structure?

A Cellulose, branched
B Cellulose, unbranched
C Amylopectin, branched
D Amylopectin, unbranched

Question 3

Which of the following has only compounds made from glucose?

A Amylose, amylopectin, aspartame, glycogen
B Amylase, amylopectin, cellulase, glycogen
C Cellulose, aspirin, glycogen, aspartame
D Amylopectin, cellulose, amylose, glycogen

Question 4

Which of the following lists the correct number of each functional group in a molecule of sucrose $C_{12}H_{22}O_{11}$?

A 1 ether, 10 hydroxyl
B 3 carbonyl, 8 hydroxyl
C 1 ester, 10 hydroxyl
D 3 ether, 8 hydroxyl

Exam-style questions

Within lesson

Question 5 (1 MARK)

Amylose is a polymer made from glucose, $C_6H_{12}O_6$. A particular form of amylose is found to have a molar mass of 3.297×10^5 g mol^{-1} (correct to 4 significant figures). A molecule of this form of amylose is best described as

A an addition polymer of 2035 glucose molecules.
B an addition polymer of 1832 glucose molecules.
C a condensation polymer of 2035 glucose molecules.
D a condensation polymer of 1832 glucose molecules.

Question 6 (1 MARK)

The monosaccharides glucose and fructose and the disaccharide lactose are combined in such a way that they form a 4-membered cyclic ring. Calculate the molar mass of this compound.

Question 7 (2 MARKS)

Compare the solubility of the carbohydrate sucrose with the hydrocarbon pentane in aqueous solution. Justify your answer with specific reference to intermolecular bonding.

Question 8 (4 MARKS)

A sample of glycogen is found to be made up of 650 glucose molecules each having the molecular formula $C_6H_{12}O_6$ and molar mass 180 g mol^{-1}.

a **i** Write a balanced equation for the formation of this glycogen molecule from the individual glucose monomers in an aqueous solution. (1 MARK)

ii What is the name given to this kind of reaction? (1 MARK)

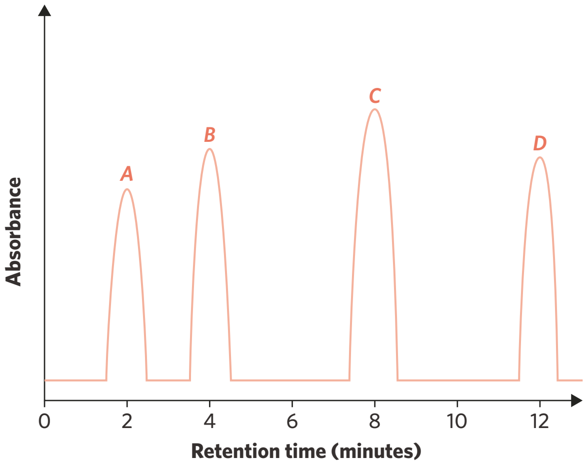
b Identify the two different possible names given to the functional group that forms between the glucose monomers. (1 MARK)

c What would be the molar mass of this glycogen molecule? (1 MARK)

Multiple lessons

Question 9 (7 MARKS)

In a routine laboratory experiment, Andrew was using HPLC with a polar mobile phase and a non-polar stationary phase to identify a mixture of straight chain carboxylic acids from a sample of lake water. However, unbeknownst to Andrew, the sample was contaminated by the remnants of a honey sandwich that he had brought into work earlier that day.



a Give the names of two possible carbohydrates present in this honey sandwich. (2 MARKS)

b Identify which peak on the chromatogram is likely the result of this contaminant. Explain. (4 MARKS)

c In a nearby chemical factory, scientists were manufacturing an artificially sweetened form of honey using the compound aspartame. Suggest a possible reason for this decision. (1 MARK)

Question 10 (5 MARKS)

a Draw the molecule aspartame. Circle and name all functional groups present in the compound. (2 MARKS)

b Why is it that food and drink products containing aspartame can be labelled as being 'sugar free' and advertised as 'containing low kilojoules'? (3 MARKS)

10B BREAKDOWN AND IMPORTANCE OF CARBOHYDRATES

In this lesson, we will learn how carbohydrates in food are broken down in the body to provide energy for metabolic reactions.

10A Structure of carbohydrates	10B Breakdown and importance of carbohydrates	10C Structure of fats and oils	10D Breakdown of fats and oils	10E Properties of fats and oils	10F Calorimetry	10G Energy in food

Study design dot points

- hydrolysis of starch in the body: explanation of the ability of all humans to hydrolyse starch but not cellulose, and of differential ability in humans to hydrolyse lactose; glycaemic index (GI) of foods as a ranking of carbohydrates based on the hydrolysis of starches (varying proportions of amylose and amylopectin) to produce glucose in the body
- glucose as the primary energy source, including a balanced thermochemical equation for cellular respiration

Key knowledge units

Hydrolysis of carbohydrates	4.2.2.3 & 4.2.5.1.1
Importance of carbohydrates	4.2.8.1
Energy from glucose	4.2.12.1

Key terms and definitions

- **Metabolism** breakdown of food and its transformation into energy
- **Cellular respiration** metabolic process by which glucose is converted into energy for cells
- **Glycaemic Index (GI)** number representative of the way a food affects the blood glucose level
- **Amylase** enzyme that catalyses the hydrolysis of starch
- **Lactase** enzyme that catalyses the hydrolysis of lactose
- **Cellulase** enzyme that catalyses the hydrolysis of cellulose

Lesson links

This lesson builds on:

▶ 9B – Breakdown of proteins

Both proteins and carbohydrates are broken down via the process of hydrolysis.

▶ 9C – Enzymes

Enzymes are required for the digestion of carbohydrates.

▶ 10A – Structure of carbohydrates

The structure of carbohydrates affects the way in which they are broken down.

Hydrolysis of carbohydrates 4.2.2.3 & 4.2.5.1.1

OVERVIEW

Carbohydrates, a major component of the food we eat, are an essential energy source and are broken down in the body by the process of hydrolysis. This process involves the addition of water and the presence of enzymes to convert carbohydrates into a form we can use for energy, monosaccharides.

THEORY DETAILS

Carbohydrates in our food are broken down by digestion into monosaccharides, a useful form for the body to use as energy. The most common carbohydrate in the food we eat is starch, a polysaccharide studied in lesson 10A. The breakdown of starch begins in the mouth with the enzyme **amylase** present in saliva as a catalyst. Chewing increases the surface area of the food, and provides a greater area for amylase to act on, increasing the rate of breakdown. As shown in figure 1, starch is broken into smaller disaccharides known as maltose, before moving onto the next stage of digestion.

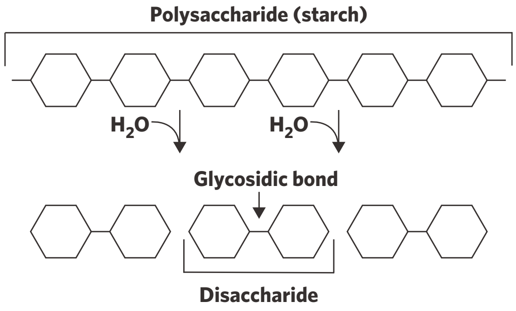


Figure 1 Breakdown of starch into disaccharides (maltose)

The breakdown of starch into disaccharides and further into monosaccharides occurs via hydrolysis. We recall from lessons 7F and 9B that a hydrolysis reaction involves the use of water to break down a molecule into its building blocks. The same concept is applied to the hydrolysis of carbohydrates. In the presence of water, the glycosidic bond in a disaccharide is broken forming two monosaccharides, as demonstrated in figure 2.

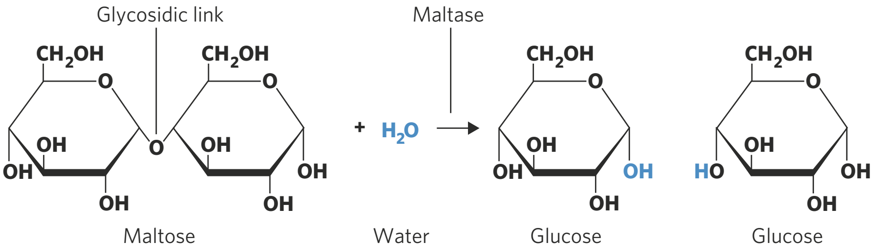


Figure 2 Breakdown of a disaccharide into monosaccharides

1 Worked example

Draw and name the products of the hydrolysis of sucrose.

What information is presented in the question?

Sucrose, hydrolysis reaction

What is the question asking us to do?

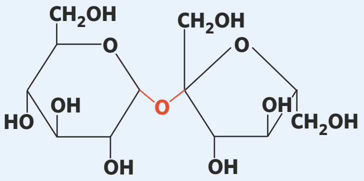
Draw and name the products

What strategy(ies) do we need in order to answer the question?

1. Use the data book to find the structure of sucrose.
2. Identify visually where the glycosidic bond is (the location water will be added).
3. Draw the components after hydrolysis.
4. Use the data book to identify the names of these components.

Answer

The structure of sucrose is given in the data book.

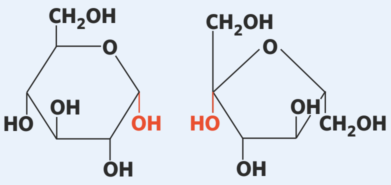


sucrose

During hydrolysis, water will be added to the glycosidic bond, coloured in red.

So, after hydrolysis, the left ring will have an OH group at the right red location and the right ring will have an OH group at the red location.

We can visually match the structure of these rings to the molecules we are given in the data book.



α-glucose β-fructose

Glucose and fructose match the structure of the monosaccharides we are looking for.

A variety of enzymes in the small intestine catalyse hydrolysis reactions, breaking down disaccharides into monosaccharides. We can see in table 1 that each disaccharide has a particular enzyme that is responsible for its hydrolysis. As we learned in lesson 9C, enzymes are highly specific in their active site, therefore, each of the enzymes below can only act on a specific disaccharide, or substrate.

Tip Instead of memorising which monosaccharides make up each disaccharide, we can use the structure of the disaccharide in the data book to deduce its components.

Table 1 Common disaccharides and the enzymes that catalyse their hydrolysis

Disaccharide	sucrose	lactose	maltose
Enzyme for hydrolysis	sucrase	lactase	maltase

It is important to note that the number of water molecules added during hydrolysis is equal to the number of glycosidic bonds broken; which is one less than the number of monomers in the chain. We can see in figure 3, that for a 6 unit polysaccharide, there are 5 glycosidic bonds broken, and thus 5 water molecules are required.

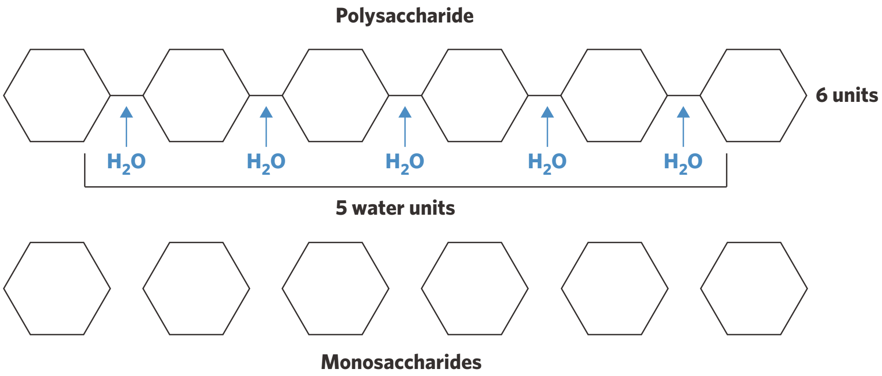


Figure 3 Illustration of the relationship between the number of water molecules required and the number of monomers in a polysaccharide

The monosaccharides produced by this reaction are now ready to be absorbed into the bloodstream for transport to various cells around the body.

2 Worked example

A polysaccharide composed of glucose molecules ($C_6H_{12}O_6$) has a molar mass of 3.2418×10^4 g mol^{-1}. If the polysaccharide is hydrolysed, how many glucose monomers will be produced?

What information is presented in the question?

Each monosaccharide is glucose. The total molar mass of the polysaccharide is 3.2418×10^4 grams per mole.

What is the question asking us to do?

Calculate how many glucose monomers are in the polysaccharide.

What strategy(ies) do we need in order to answer the question?

We need to work backwards.

1. Write a general equation for the sum of the molar masses of all the individual monomers.
2. Determine the number of water molecules that would be required to make the polysaccharide.

Answer

Let the number of glucose molecules be *Q*

Then the molar mass of the polysaccharide would be $M(\text{glucose}) \times Q - (Q-1) \times M(\text{water})$

We also know the molar mass of the polysaccharide is 32 418 g mol^{-1}

So $180\ Q - 18(Q-1) = 3.2418 \times 10^4$

Therefore $Q = 200$

So 200 glucose monomers will be produced.

Importance of carbohydrates 4.2.8.1

OVERVIEW

Not all carbohydrates are able to be digested in the body, and of those that are, we can quantify the rate at which digestion occurs through the glycaemic index (GI).

THEORY DETAILS

Cellulose

Cellulose must be broken down in the digestive system from its polysaccharide form in order to be used for energy. However, as we learnt in 10A, cellulose is composed of β-glucose units, as opposed to the α-glucose makeup of starch. Due to the difference in the glycosidic linkage, the breakdown of cellulose requires a different enzyme to starch. Humans do not produce the enzyme **cellulase** that is required to execute the hydrolysis of cellulose, so for the most part, we cannot digest cellulose. Therefore, the consumption of cellulose does not yield energy or nutrients but is still important for our digestive health as a source of fibre.

Lactose

Lactose, a disaccharide commonly found in milk, is digested by the enzyme **lactase** in the small intestine. The role of this enzyme is to hydrolyse the disaccharide lactose into two monosaccharides, so it can be used by the body. However, a large proportion of the human population does not produce lactase after infancy. In these circumstances lactose cannot be digested and the consumption of high-lactose products such as milk and yogurt can cause digestive discomfort. Humans with this issue are described as lactose intolerant.

Glycaemic Index

Many of us may already be familiar with the term GI, as many supermarket foods brand “low GI” cereals and bread as a healthier option. **Glycaemic index** (GI) is a number used to predict how a carbohydrate-containing food will affect your blood glucose over a certain period of time. A substance that has a high glycaemic index produces a rapid increase in blood glucose, as it is broken down quickly into glucose. However, a substance with a low glycaemic index produces a more gradual increase in blood sugar, because it is broken down slowly. These differences can be seen in figure 4, where the high GI food causes a quick spike in blood sugar in the first hour, and the low GI food causes a gradual increase in blood sugar.

The scale of GI uses pure glucose as a reference, with the GI of glucose assigned the value of 100. When a food source is assigned a GI, it is simply a comparison of the rate of breakdown to that of glucose. Since the scale is only arbitrary, GI does not have a unit.

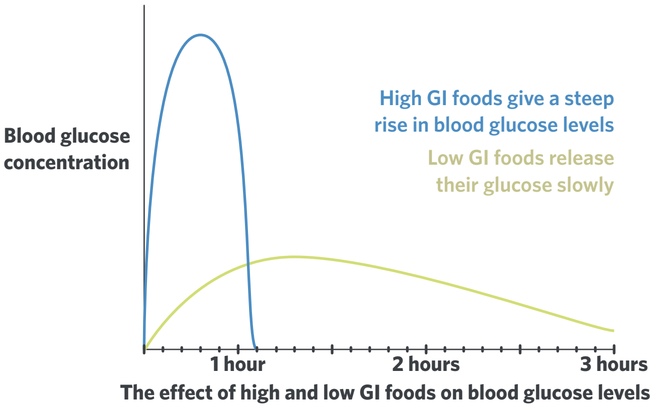


Figure 4 Comparison of the effect on blood glucose level of high GI food versus low GI food

Foods that are less processed, such as wholemeal and grain bread, have a lower GI than foods such as white bread, as can be observed in table 2. These low GI foods are branded as healthier, because they provide stable blood sugar levels.

Table 2 Examples of common foods and their GI

GI	Common foods
Low (less than 55)	Soy, beans, pasta, lentils, grain bread
Medium (between 55 and 70)	Juice, honey, processed cereal
High (greater than 70)	White bread, potatoes, short-grain rice

Amylose vs amylopectin

As we learned in lesson 10A, there are two main types of starch; amylose and amylopectin. Due to the differences in their structures, these two types of starch are digested differently. Amylose is packed tightly into neat, linear stacks with strong intermolecular bonding. This results in a small surface area available for water and enzymes to act on. In turn, the digestion of amylose occurs slowly, and foods high in amylose are low GI.

In comparison, the branches of amylopectin cause more space between molecules as they cannot pack tightly, reducing the strength of intermolecular forces. As a result, water and amylase have easier access to amylopectin molecules, and digestion of amylopectin occurs faster. This means foods high in amylopectin are high GI.

We can use the relative proportions of amylose and amylopectin in food as an indication of the overall GI:

- A higher proportion of amylose gives a lower GI.
- A higher proportion of amylopectin gives a higher GI.

Tip The structure of amylose and amylopectin can be found in your data book. From the structure, we can deduce their relative GI.

Table 3 Comparison of breakdown of amylose and amylopectin

Comparison	Amylose	Amylopectin
Structure	linear	branched
Packing	tight	loose
Relative GI	low	high

3 Worked example

Food sample A contains a carbohydrate content of 30% amylose and 70% amylopectin.

Food sample B contains a carbohydrate content of 70% amylose and 30% amylopectin.

Which food has a higher GI? Explain your answer.

What information is presented in the question?

The percentage of amylose and amylopectin in each food.

What is the question asking us to do?

Determine which food has a higher GI.

What strategy(ies) do we need in order to answer the question?

Sample B has a higher proportion of amylose.

Answer

Compared to amylose, which has a linear structure, amylopectin has a branched structure, leading to the structure not being able to pack as closely. As a result, amylase and water are able to easily access and break the appropriate bonds, resulting in the formation of glucose. Glucose is able to enter the bloodstream at a quicker rate, leading to a high GI. As Sample A has a higher proportion of amylopectin compared to Sample B, Sample A would have a higher GI.

Energy from glucose 4.2.12.1

OVERVIEW

Glucose, an important monosaccharide, is absorbed into the bloodstream and transported to cells, where the process of cellular respiration converts this molecule into energy.

THEORY DETAILS

The purpose of digestion is to obtain energy from food. After polysaccharides are broken down into monomers such as glucose,they are converted into energy by a process known as cellular respiration. The equation for this reaction is given in figure 5. It is crucial that polysaccharides and disaccharides are broken down into glucose as cellular respiration requires the presence of glucose.

Cellular respiration

$$\text{glucose} + \text{oxygen} \longrightarrow \text{carbon dioxide} + \text{water} + \text{energy}$$

$$C_6H_{12}O_{6\,(aq)} + 6O_{2\,(g)} \longrightarrow 6CO_{2\,(g)} + 6H_2O_{\,(l)} + \text{energy}$$

Figure 5 Equation for cellular respiration

In a world where food is often easily accessible, humans often take in more energy than needed at a particular time. This excess energy from food can be stored for later use by the conversion of glucose into glycogen. We recall from 10A that glycogen is a highly branched polysaccharide composed of many glucose units. It is stored as an energy reserve and can be readily converted back to glucose when required. The flow chart in figure 6 shows the transformation of a carbohydrate during different stages of digestion and **metabolism**. The last step, conversion to glycogen, only occurs when energy is in excess.

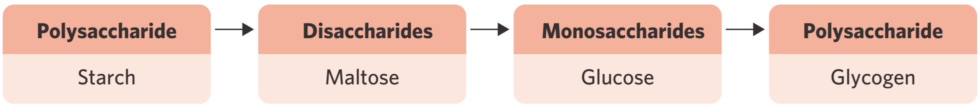


Figure 6 Process of starch metabolism in the body

Theory summary

- Carbohydrates are broken down by hydrolysis which requires one water molecule per glycosidic bond.
- Starch is broken down into disaccharides in the mouth by amylase.
- Sucrase, lactase and maltase break down sucrose, lactose and maltose respectively into monosaccharides.
- Humans cannot digest cellulose due to the absence of the enzyme cellulase.

- Humans with lactose intolerance cannot digest lactose due to the absence of the enzyme lactase.
- GI is a measure of the ability of a food to increase blood glucose levels over time and is indicative of how fast the carbohydrate is broken down.
- Amylose packs tightly, so breaks down slowly. So, a higher amylose to amylopectin ratio in food results in a lower GI.
- Glucose is converted into energy in cells by cellular respiration.
- Excess glucose is stored as glycogen.

10B QUESTIONS

Theory review questions

Question 1

Some humans are not able to digest lactose because

A lactose is not a carbohydrate.
B the solubility of lactose in their gut is low.
C there is too much water in the digestive system.
D they do not synthesise the necessary enzyme.

Question 2

Amylase is an enzyme found in saliva in the mouth, and is responsible for the breakdown of starch. Which of the following best describes the reaction occurring?

A Hydrolysis reaction **B** Polymerisation reaction **C** Condensation reaction **D** Hygroscopic reaction

Question 3

Maltose, a disaccharide, can be broken down into two glucose molecules. If the molecular formula of glucose is $C_6H_{12}O_6$, then the formula for maltose is

A $C_{12}H_{22}O_{14}$ **B** $C_{12}H_{20}O_{12}$ **C** $C_{12}H_{18}O_{11}$ **D** $C_{12}H_{22}O_{11}$

Question 4

After digestion, glucose is transported to cells where it is used as an energy source. Within the cell, glucose is broken down in the presence of oxygen and converted to energy, a process known as cellular respiration. Which of the following correctly demonstrates this reaction?

A glucose + water → oxygen + sucrose + energy
B glucose + water → carbon dioxide + oxygen + energy
C glucose + oxygen → carbon dioxide + water + energy
D glucose + oxygen → sucrose + oxygen + energy

Exam-style questions

Within lesson

Question 5 (1 MARK)

Which of the following could be produced from the hydrolysis of sucrose in the human digestive system?

A Fructose **B** Oxygen **C** Water **D** Cellulose

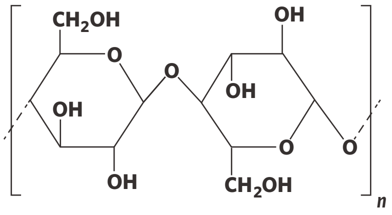
Question 6 (1 MARK)

A complex carbohydrate is composed of 220 units of fructose. The molar mass of the carbohydrate is

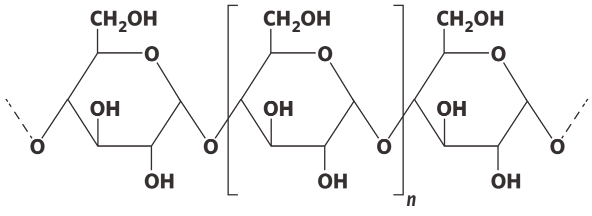
A 39 600 g mol^{-1} **B** 35 658 g mol^{-1} **C** 35 640 g mol^{-1} **D** 37 912 g mol^{-1}

Question 7 (2 MARKS)

The structures of amylose and cellulose are given.



cellulose



amylose (starch)

A science student, Dylan, notes that these structures are relatively similar, and so concludes that both will be digested in the same way in the body. However, after conducting a study, Dylan notes that cellulose had minimal effect on blood glucose levels compared to that of amylose. Provide an explanation as to why Dylan's prediction does not match observations.

Question 8 (6 MARKS)

A food chemist is interested in the GI of different types of bread. A sample is taken from wholemeal and white bread in the supermarket, and the amylose and amylopectin content in 1.0 gram of carbohydrate calculated.

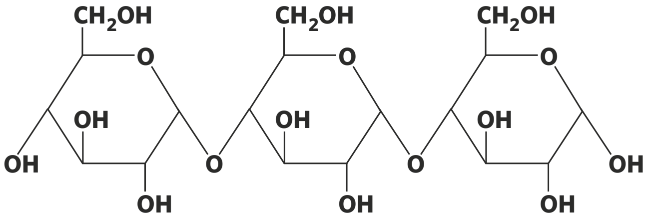
Starch type	White bread	Wholemeal bread
Amylose	0.22 g	0.63 g
Amylopectin	0.78 g	0.33 g

- **a** According to the data above, which bread would you expect to have a lower GI? (1 MARK)
- **b** The white bread is found to have a GI of 76, and the wholemeal bread a GI of 57.
  - **i** What is the unit for measuring GI? Explain your answer. (2 MARKS)
  - **ii** Using your knowledge of amylose and amylopectin, explain why the white bread has a higher GI than the wholemeal bread. (3 MARKS)

Question 9 (2 MARKS)

In a laboratory, chemical scientist Bridie discovers an organic compound in a sample she is analysing. The structure of this molecule is provided.

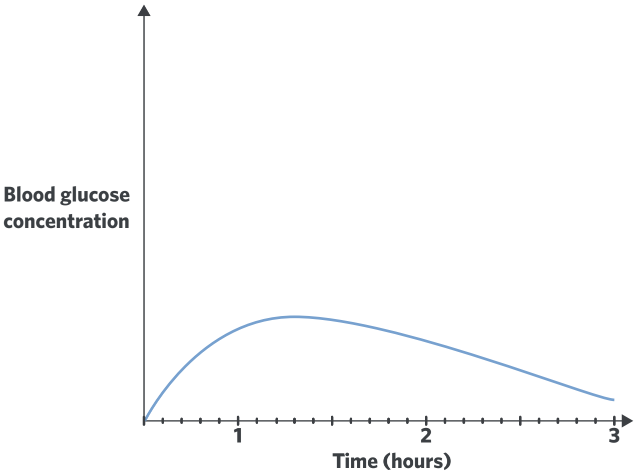
Bridie decides to investigate the molecule's properties by adding water to the sample, initiating a hydrolysis reaction.



- **a** How many water molecules would be required for this reaction? (1 MARK)
- **b** Circle on the diagram above the locations water would be added. (1 MARK)

Question 10 (3 MARKS)

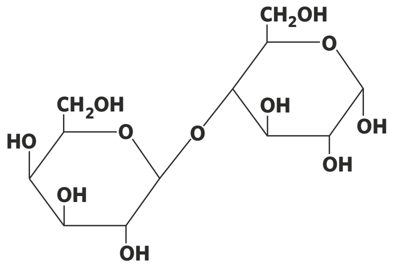
The effect of the consumption of an oat-based porridge on the blood glucose level over time is provided.



- **a** Based on the graph above, is the porridge a high GI or low GI food? Explain your answer. (2 MARKS)
- **b** A brand of salt and vinegar potato chips is compared to the porridge. If the packet of chips is classed as higher GI than the porridge, draw on the graph above the effect you would expect consumption of the chips to have on the blood sugar level. (1 MARK)

Question 11 (4 MARKS)

The structural formula for lactose is provided.



α-lactose

a Circle on the diagram above the glycosidic bond. (1 MARK)

b Lactose is composed of a glucose monomer (180 g mol^{-1}) and a galactose monomer (180 g mol^{-1}). Using your knowledge of hydrolysis reactions, calculate the molar mass of lactose. (2 MARKS)

c Sally notices she has digestive discomfort after consuming high-lactose foods and drinks, but has no issue after consuming high-sucrose foods. Give an explanation for this observation. (1 MARK)

Multiple lessons

Question 12 (1 MARK)

Consider the following statements.

I Glycogen has a highly branched structure.

II Cellulose is a high GI source of energy.

III Aspartame has a much lower energy content per gram compared to sucrose.

IV Excess energy is stored as glycerol in humans.

V α-glucose and β-glucose differ only in the orientation of the hydroxyl group on carbon 1.

Which of the above statements are true?

A I, II, V

B I, V

C II, III, V

D I, III

Question 13 (6 MARKS)

The equation for a reaction occurring in a skin cell is given below.

$$C_6H_{12}O_{6\,(aq)} + 6O_{2(g)} \rightarrow 6H_2O_{(l)} + 6CO_{2(g)} \qquad \Delta H = -2803 \text{ kJ mol}^{-1}$$

a Name the process occurring and its purpose. (2 MARKS)

b Is this reaction endothermic or exothermic? (1 MARK)

$$\textbf{sucrose} + \textbf{Compound } \boldsymbol{X} \xrightarrow{\text{sucrase}} \textbf{glucose} + \textbf{Compound } \boldsymbol{Y}$$

c The reactant for the reaction in part a can be produced via the process shown above.

- **i** What is the molecular formula of compound X? (1 MARK)
- **ii** Draw the structure of compound Y and name one key difference between its structure and that of glucose. (2 MARKS)

Question 14 (5 MARKS)

A new type of biscuit is analysed to determine its starch content. The biscuit is found to contain 23% amylopectin and 77% amylose.

a Describe the difference in structure between amylose and amylopectin. (2 MARKS)

b Use these structural differences to explain which is more soluble in water. (2 MARKS)

c Using your answer to part b, conclude whether this biscuit will be high GI or low GI. (1 MARK)

10C STRUCTURE OF FATS AND OILS

In this lesson, we will learn about the general structure of fats and oils.

10A Structure of carbohydrates	10B Breakdown and importance of carbohydrates	10C Structure of fats and oils	10D Breakdown of fats and oils	10E Properties of fats and oils	10F Calorimetry	10G Energy in food

Study design dot point

- fats and oils (triglycerides): common structural features including ester links; distinction between fats and oils with reference to melting points; explanation of different melting points of triglycerides with reference to the structures of their fatty acid tails and the strength of intermolecular forces; chemical structures of saturated and unsaturated (monounsaturated and polyunsaturated) fatty acids; distinction between essential and non-essential fatty acids; and structural differences between omega-3 fatty acids and omega-6 fatty acids

Key knowledge units

Fats and oils	4.2.3.1
Structure of triglycerides	4.2.3.2
Fatty acids	4.2.3.3

Key terms and definitions

- **Essential fatty acid** fatty acid that cannot be produced by the human body
- **Fats** lipid molecules that are solid at room temperature
- **Fatty acid** carboxylic acid with a long hydrocarbon chain
- **Fatty acid residue** part of a triglyceride molecule
- **Glycerol** organic compound with three hydroxyl (OH) groups which forms the backbone of lipids
- **Lipid** biomolecule commonly found in food which has two main types, fats and oils
- **Monounsaturated fatty acid** fatty acid which contains only one carbon-carbon double bond
- **Non-essential fatty acid** fatty acid that can be produced by the human body
- **Oils** lipid molecules which are liquid at room temperature
- **Omega carbon** carbon atom of the methyl group at the end of the carbon chain (opposite end to the carboxyl group) in a fatty acid
- **Omega-3 fatty acid** fatty acid that has a carbon-carbon double bond on the third carbon from the omega carbon
- **Omega-6 fatty acid** fatty acid that has a carbon-carbon double bond on the sixth carbon from the omega carbon
- **Polyunsaturated fatty acid** fatty acid which contains more than one carbon-carbon double bond in the molecule
- **Saturated fatty acid** fatty acid which contains only carbon-carbon single bonds in the molecule
- **Triglycerides** large and mostly non-polar lipid molecules made from glycerol and three fatty acid residues

Lesson links

This lesson builds on:

- 9A – Structure of organic compounds

Ester functional groups (COO) are present in the structure of fats and oils.

- 9F– Types of organic reactions

The idea of condensation reactions is important in the formation of triglycerides.

Fats and oils 4.2.3.1

OVERVIEW

Fats and oils are two common types of triglycerides with different physical and chemical properties.

THEORY DETAILS

Carbohydrates, proteins and lipids are the three main sources of nutrition that we obtain from the food we eat. **Lipids** are commonly found in meat, fish, butter, seeds and some vegetables. Similar to carbohydrates, lipids provide energy to the body. However, lipids contain more than double the energy content of carbohydrates per gram.

One of the common types of lipids found in food are triglycerides. **Triglycerides** are large and mostly non-polar molecules. There are two main types of triglycerides: **fats** and **oils**. The reason why triglycerides are classified as either fats or oils is that they have different physical states at room temperature. While fats exist as solids at room temperature, oils exist as liquids. The reason for this difference between fats and oils will be explained later in the chapter.

Image: colnihko/Shutterstock.com

Image: MaraZe/Shutterstock.com

Figure 1 Sources of triglycerides in our diet

Structure of triglycerides 4.2.3.2

OVERVIEW

A triglyceride consists of a glycerol molecule and three **fatty acid residues** joined together by three ester linkages (COO).

THEORY DETAILS

We learned about the structure of proteins in 9A and the structure of carbohydrates in 10A. We will learn about the structure of triglycerides in this lesson. A triglyceride is formed from a condensation reaction between one **glycerol** and three separate **fatty acids** as shown in figure 2. As can be observed in figure 2, glycerol is an organic molecule with three hydroxyl (OH) groups and fatty acids are organic molecules with a carboxyl (COOH) group on the end of a long hydrocarbon chain (R, R' and R" represent three alkyl groups). It is important to note that R, R' and R" can be the same or different in a triglyceride. Therefore, the condensation reaction between glycerol and three fatty acids is similar to the condensation reaction between alcohols and carboxylic acids that we learned in lesson 7F. In figure 2, three OH groups are taken from glycerol and three H atoms are taken from three fatty acids. As a result, the products of the reaction are one triglyceride molecule, with three ester (COO) groups linking the glycerol and three fatty acid residues together, and three water molecules.

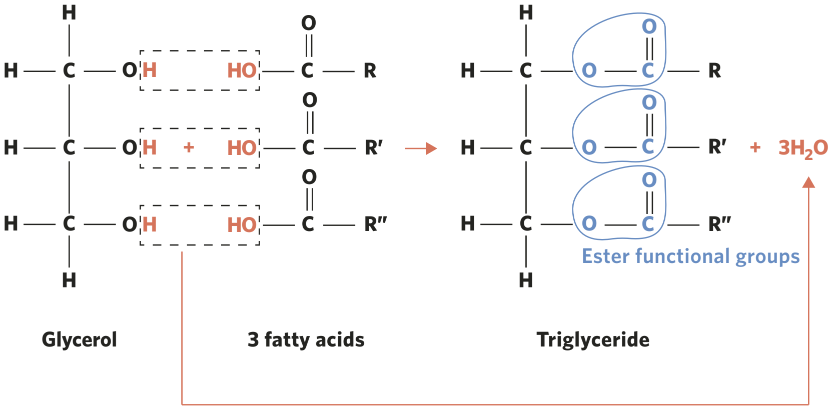


Figure 2 Condensation reaction between one glycerol and three fatty acids to form a triglyceride and three water molecules

Figure 3 shows examples of a triglyceride with three identical fatty acids and a triglyceride with three different fatty acids.

Tip Common fatty acids with their molecular formulas and semi-structural formulas can be found in the chemistry data book

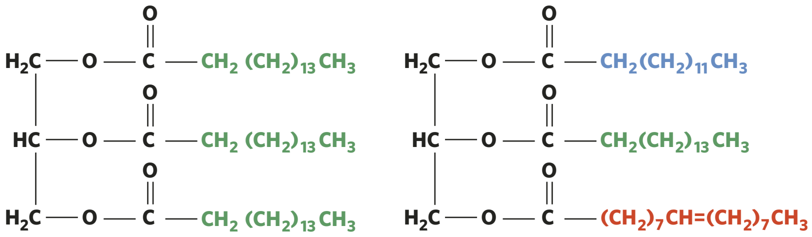


Figure 3 Examples of a triglyceride with three identical fatty acids and a triglyceride with three different fatty acids

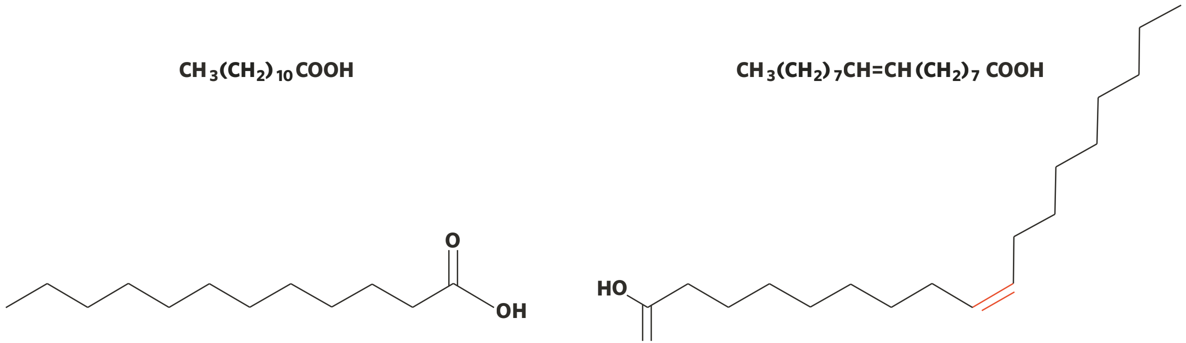
Fatty acids 4.2.3.3

OVERVIEW

Fatty acids are classified based on the types of carbon-carbon bonds present, the position of carbon-carbon double bonds and the ability of the human body to synthesise them.

THEORY DETAILS

In triglycerides, the glycerol backbone is always present but the types of fatty acids it is connected to vary. Based on the carbon-carbon bonds present, fatty acids can be classified into two main types, **saturated** and **unsaturated fatty acids**. As shown in figure 4, a saturated fatty acid contains only carbon-carbon single bonds, whereas an unsaturated fatty acid contains at least one carbon-carbon double bond.

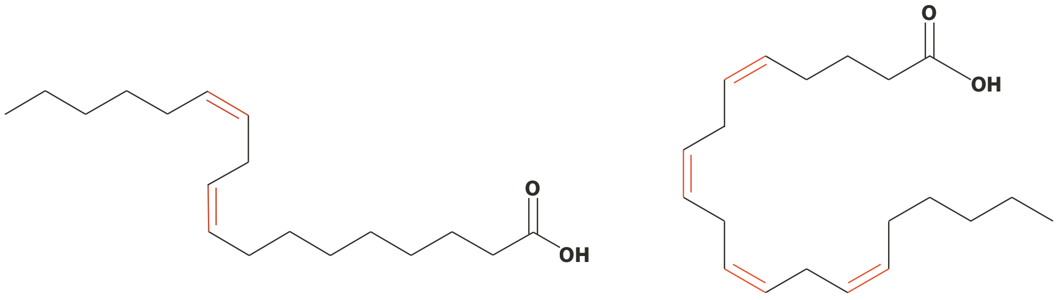


Lauric acid (saturated fatty acid)

Oleic acid (unsaturated fatty acid)

Figure 4 Structures of a saturated fatty acid (lauric acid) and an unsaturated fatty acid (oleic acid)

Interestingly, unsaturated fatty acids can have one or more carbon-carbon double bonds in their structure. If an unsaturated fatty acid has only one carbon-carbon double bond, it is called a **monounsaturated fatty acid** where 'mono' stands for one. If an unsaturated fatty acid has more than one carbon-carbon double bond, it is called a **polyunsaturated fatty acid** where 'poly' refers to many. For example, in figure 5, linoleic acid has two carbon-carbon double bonds and arachidonic acid has four carbon-carbon double bonds. Therefore, they are both classified as polyunsaturated fatty acids. Oleic acid in figure 4 is a monounsaturated fatty acid because it only has one carbon-carbon double bond.

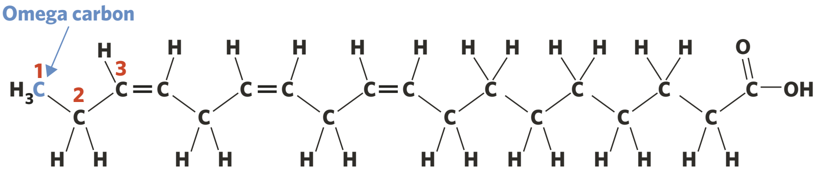


Linoleic acid

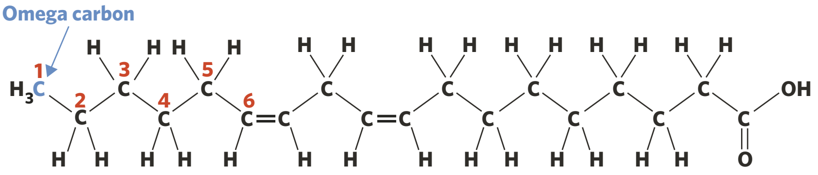
Arachidonic acid

Figure 5 Linoleic acid and arachidonic acid are examples of polyunsaturated fatty acids

Unsaturated fatty acids can also be classified into two different categories with reference to the position of the first carbon-carbon double bond relative to the **omega carbon.** In figure 6, the omega carbon is the carbon atom of the methyl group at the end of the carbon chain in a fatty acid. An unsaturated fatty acid is called an **omega-3 fatty acid** if it has a carbon-carbon double bond on the third carbon atom counting from the omega carbon. Therefore, linolenic acid is an omega-3 fatty acid. Similarly, if an unsaturated fatty acid has a carbon-carbon double bond on the sixth carbon counting from the omega carbon, it is called an omega-6 fatty acid. According to this, linoleic acid is an **omega-6 fatty acid**.



Linolenic acid (omega-3 fatty acid)



Linoleic acid (omega-6 fatty acid)

Figure 6 Examples of an omega-3 fatty acid and an omega-6 fatty acid

The human body is capable of synthesizing most, but not all fatty acids. Those that can be synthesised by the human body are called **non-essential fatty acids**. It is important to note that 'non-essential' does not mean that they are not important. It only means that it is not necessary to consume them in our diet because our bodies are able to synthesize them from small components broken down from the food we eat. Conversely, **essential fatty acids** are fatty acids that the human body is not capable of synthesising. Therefore, we have to directly consume them from the food we eat or from nutritional supplements. For the most part, essential fatty acids are those that are unsaturated because the human body is unable to synthesise double bonds. Three examples of essential fatty acids are linolenic acid, linoleic acid and arachidonic acid.

1 Worked example

Explain why palmitoleic acid is classified as a monounsaturated fatty acid.

What information is presented in the question?

The name of the fatty acid.

What is the question asking us to do?

Explain why it is a monounsaturated fatty acid.

What strategy(ies) do we need in order to answer the question?

1. Look for the semi-structural formula of the given fatty acid in the data book.
2. Determine the number of carbon-carbon double bonds present in the structure of the given fatty acid.

Answer

Palmitoleic acid is classified as a monounsaturated fatty acid because it has one carbon-carbon double bond in the structure.

2 Worked example

Identify whether arachidonic acid is classified as an omega-3 fatty acid or an omega-6 fatty acid. Justify your answer.

What information is presented in the question?

The name of the fatty acid.

What is the question asking us to do?

Identify if the fatty acid is an omega-3 fatty acid or an omega-6 fatty acid and justify your answer.

What strategy(ies) do we need in order to answer the question?

1. Look for the semi-structural formula of the given fatty acid in the data book.
2. Determine where the carbon-carbon double bonds are located in the structure of the given fatty acid.

Answer

Arachidonic acid has the semi-structural formula

$CH_3(CH_2)_4(CH{=}CHCH_2)_3CH{=}CH(CH_2)_3COOH$

Arachidonic acid is an omega-6 fatty acid because it has a carbon-carbon double bond on the sixth carbon, counting from the omega carbon.

Theory summary

- Fats and oils are two common types of triglycerides.
- At room temperature, fats appear as solids while oils appear as liquids.
- The structure of a triglyceride consists of glycerol and three fatty acid tails joined by three ester links.
- A triglyceride is formed by a condensation reaction between a glycerol and three fatty acids with three water molecules as the by-product.
- Based on the carbon-carbon bonds present in the structure, fatty acids are classified into three types: saturated fatty acids, monounsaturated fatty acids and polyunsaturated fatty acids.
- Omega-3 and omega-6 fatty acids are determined based on the position of the carbon-carbon double bond relative to the omega carbon.
- There are two types of fatty acids depending on whether the human body can synthesise them: essential fatty acids and non-essential fatty acids.

10C QUESTIONS

Theory review questions

Question 1

Which of the following statements is true?

A Fats are triglycerides whereas oils are not triglycerides.

B At room temperature, fats appear as liquids and oils appear as solids.

C At room temperature, fats appear as solids and oils appear as liquids.

D Oils are important to the human body whereas fats are not.

Question 2

Which of the following statements is **not** true about the structure of triglycerides?

A A triglyceride molecule is composed of one glycerol and three fatty acid tails joined by three ester links.

B The three fatty acid tails in triglycerides are always identical.

C The three fatty acid tails in triglycerides can be identical or different.

D In terms of types of organic compounds, triglycerides are classified as esters.

Question 3

Consider the following statements.

I A triglyceride is formed via a condensation reaction between one glycerol and three fatty acids.
II There are peptide links in triglycerides.
III Three water molecules are formed from the condensation reaction between one glycerol and three fatty acids.
IV There are ester links in triglycerides.
V The three fatty acids that react with glycerol to form a triglyceride are always identical.

Which of the above are true about the formation of triglycerides?

A I, III and IV
B I only
C I, II and III
D III and V only

Question 4

Type of fatty acid	Number of carbon-carbon double bonds present
Saturated	*X*
Y	more than one
Z	one

What words are *X*, *Y*, and *Z* respectively?

A Two, essential, monounsaturated
B None, polyunsaturated, monounsaturated
C None, monounsaturated, polyunsaturated
D One, non-essential, omega-3

Question 5

Fill in the blanks to describe omega-3 and omega-6 fatty acids. More than one word may be required in each space.

The omega carbon is the carbon atom of the methyl group at the end of the carbon chain in a fatty acid. An unsaturated fatty acid is called an omega-3 fatty acid if it has a ___________ on the ___________ carbon atom counting from the omega carbon. Similarly, if an unsaturated fatty acid has a carbon-carbon double bond on the sixth carbon counting from the omega carbon, it is called an ___________.

Question 6

Which of the following statements is true about both essential and non-essential fatty acids?

A Essential fatty acids are fatty acids that the human body can synthesise.
B Non-essential acids are not important to the human body.
C Non-essential fatty acids are fatty acids that the human body cannot synthesise.
D Essential fatty acids are fatty acids that the human body cannot synthesise.

Exam style-questions

Within lesson

Question 7 (1 MARK)

Linolenic acid is a

A monounsaturated omega-3 non-essential fatty acid.
B monounsaturated omega-6 non-essential fatty acid.
C polyunsaturated omega-3 essential fatty acid.
D polyunsaturated omega-3 non-essential fatty acid.

Question 8 (1 MARK)

Which of the following lists only polyunsaturated fatty acids?

A Palmitoleic, linoleic, palmitic

B Linoleic, linolenic, arachidonic

C Linolenic, arachidonic, oleic

D Arachidic, linoleic, linolenic

Question 9 (2 MARKS)

Is arachidonic acid classified as an omega-3 fatty acid or as an omega-6 fatty acid? Justify your answer.

Question 10 (6 MARKS)

Determine whether the following fatty acids are saturated, monounsaturated or polyunsaturated. Explain your answer.

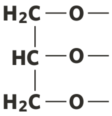
a Oleic acid (2 MARKS)

b Palmitic acid (2 MARKS)

c Linoleic acid (2 MARKS)

Question 11 (6 MARKS)

Macadamia nuts are one of the healthiest sources of lipids. One of the fatty acids found in macadamia nuts is palmitoleic acid. The triglyceride formed from three palmitoleic acids is glycerol tripalmitate $C_{51}H_{92}O_6$ with its incomplete semi-structural formula given below.



$$\begin{array}{l} H_2C-O- \\ \;\,| \\ HC-O- \\ \;\,| \\ H_2C-O- \end{array}$$

a Complete the semi-structural formula of glycerol tripalmitate. (1 MARK)

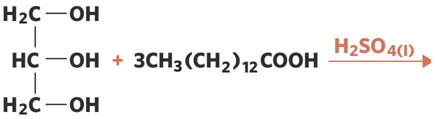
b Is palmitoleic acid a saturated fatty acid or an unsaturated fatty acid? Justify your answer. (2 MARKS)

c A food scientist wants to synthesize 30.0 g of glycerol tripalmitate. What is the mass of glycerol required to produce 30.0 g of glycerol tripalmitate? (3 MARKS)

Multiple lessons

Question 12 (5 MARKS)

A chemistry student performed a reaction between glycerol and three myristic fatty acids.



$$\begin{array}{l} H_2C-OH \\ \;\,| \\ HC-OH \\ \;\,| \\ H_2C-OH \end{array} + 3CH_3(CH_2)_{12}COOH \xrightarrow{H_2SO_{4(l)}}$$

a Name the type of organic reaction that the student performs between glycerol and three myristic acids. (1 MARK)

b Write the structural formula of the organic product of the reaction above. Circle and name any functional group(s) present. (3 MARKS)

c To which class of biomolecules does the organic product of the reaction above belong? (1 MARK)

10D BREAKDOWN OF FATS AND OILS

In this lesson we will learn how the body breaks down fats and oils into smaller molecules in order to be absorbed and transported throughout the body.

10A Structure of carbohydrates	10B Breakdown and importance of carbohydrates	10C Structure of fats and oils	10D Breakdown of fats and oils	10E Properties of fats and oils	10F Calorimetry	10G Energy in food

Study design dot points

- metabolism of food as a source of energy and raw materials: general principles of metabolism of food involving enzyme-catalysed chemical reactions with reference to the breakdown of large biomolecules in food by hydrolytic reactions to produce smaller molecules, and the subsequent synthesis of large biologically important molecules by condensation reactions of smaller molecules
- hydrolysis of fats and oils from foods to produce glycerol and fatty acids; oxidative rancidity with reference to chemical reactions and processes, and the role of antioxidants in slowing the rate of oxidative rancidity

Key knowledge units

Hydrolysis of fats and oils	4.2.5.1.2 & 4.2.9.1.1
Oxidative rancidity	4.2.9.1.2

Key terms and definitions

- **Bile** fluid secreted by the liver that aids digestion
- **Emulsion** mixture of liquids where one liquid is usually not soluble in the other
- **Oxidative rancidity** series of chemical reactions involving the deterioration of fats and oils resulting in food with an unpleasant odour and taste
- **Autoxidation** spontaneous oxidation of a compound in the presence of oxygen
- **Antioxidant** compound that prevents oxidative rancidity of fats and oils

Lesson links

This lesson builds on:

▶ 10C – Structure of fats and oils

Hydrolysis of fats and oils involves the breakdown of the structure of fats and oils.

Hydrolysis of fats and oils 4.2.5.1.2 & 4.2.9.1.1

OVERVIEW

Triglycerides are broken down by the process of hydrolysis, in the presence of enzymes, so that the body can obtain energy from the food we eat.

THEORY DETAILS

As we learned in 10C, fats and oils are two common types of triglycerides found in the food we eat. They consist of three fatty acid residues and a glycerol molecule. The glycerol molecule is bonded to each fatty acid residue by an ester link.

Triglycerides are hydrolysed during digestion by enzymes. However, they are insoluble in water, which means they need help in order for enzymes and water to access the triglyceride molecules. **Bile** is a chemical secreted from the liver into the small intestine which converts large groups of triglycerides into smaller droplets, in a process called emulsification. This is similar to the operation of dishwashing detergent when cleaning pots and pans with oil on them. As shown in figure 1, the fat globules are broken into tiny droplets, providing a larger surface area on which enzymes can act to break down fats into fatty acids and glycerol for digestion.

After emulsification, the enzyme lipase catalyses the hydrolysis of fats, which results in the breaking of the three ester bonds between the fatty acid tails and the glycerol backbone, as shown in figure 2. The products of this reaction are a glycerol molecule and three fatty acids.

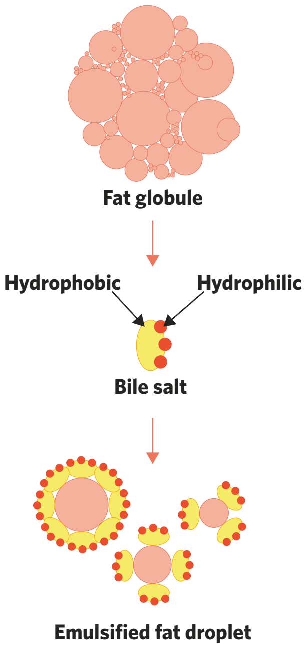


Figure 1 Emulsification of fats by bile salts

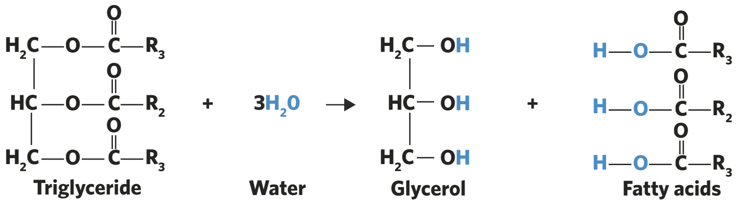


Figure 2 Hydrolysis of triglycerides to form glycerol and fatty acids, where the letter R represents different hydrocarbon chains of fatty acids

The emulsification of triglycerides by bile increases the surface area exposed, and so increases the rate at which lipase can hydrolyse triglycerides. After lipase breaks down the triglycerides, the glycerol and fatty acid molecules are absorbed into the bloodstream where they are transported to the liver to be reformed into triglycerides.

When we eat more fat than our body requires, excess triglycerides are stored in adipose tissues. This tissue is found under the skin and around muscles or organs, serving as a long-term energy reserve. When energy is required by the body, triglycerides from the fatty tissue are hydrolysed and transported through the body to muscle cells. Fatty acids are then oxidised to produce carbon dioxide and water, as shown in the following equation involving the oxidation of palmitic acid.

$C_{16}H_{32}O_{2(aq)} + 23O_{2(g)} \rightarrow 16CO_{2(g)} + 16H_2O_{(l)}$

An overall diagram of the many processes involved in the digestion of fats is shown in figure 3.

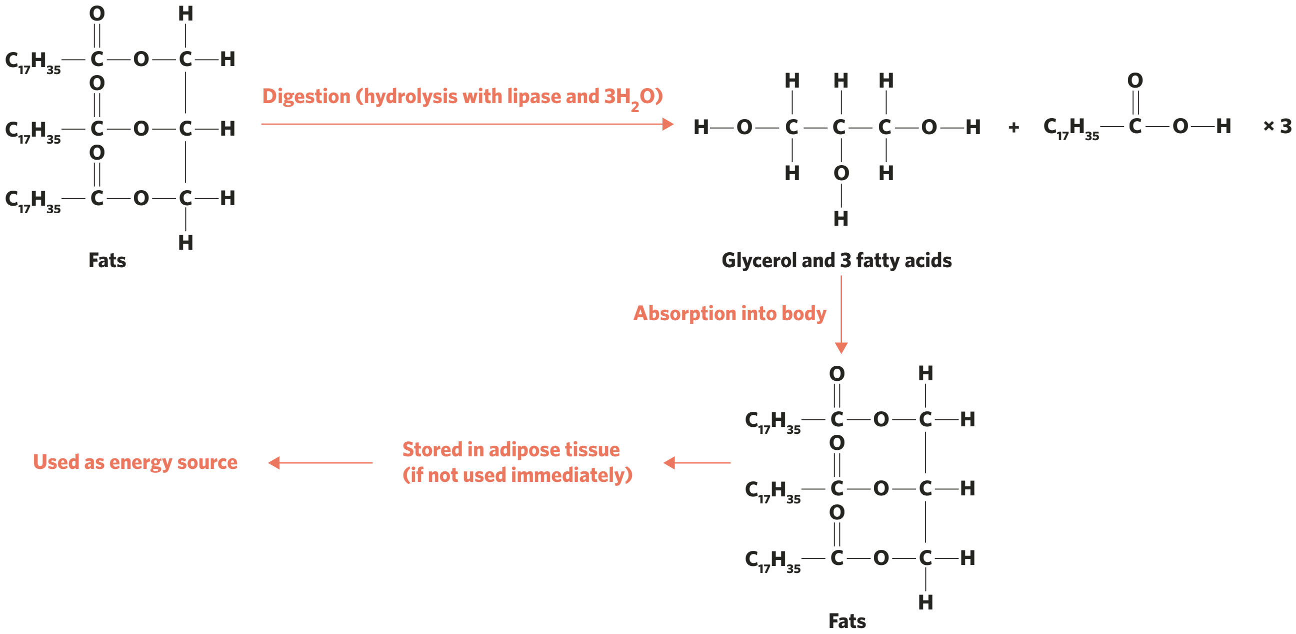


Figure 3 Flow chart of the digestion of fats

Oxidative rancidity 4.2.9.1.2

OVERVIEW

The odour and bad taste that accompanies the decay of fats is developed in a process known as oxidative rancidity.

THEORY DETAILS

Rancidity

Most components of food decay and deteriorate over time and therefore they cannot be stored indefinitely. Some foods deteriorate quicker than others. When a triglyceride reacts with oxygen, the carbon-carbon double bond(s) in the unsaturated fatty acids are broken, as shown in figure 4, to reform single bonds with the oxygen atoms. This causes the production of highly volatile aldehydes and ketones, which give off unpleasant smells and flavours. This process is known as **oxidative rancidity.**

Unsaturated fats are more reactive than saturated fats due to their carbon-carbon double bonds, allowing them to react in multiple ways to temperature, light, water and enzymes. This is due to the fact that carbon-carbon double bonds are more susceptible to the process of oxidative rancidity than single bonds. Therefore, unsaturated fats can break down to form smaller molecules. The more carbon-carbon double bonds there are in unsaturated fats, the easier it is for oxidative rancidity to occur. Lower temperatures reduce the rate of reaction of fats with oxygen, reducing the rate of oxidation of fats and so foods can be stored in the refrigerator to delay rancidity.

An important type of oxidative rancidity is **autoxidation**, which is the spontaneous oxidation of a compound in the presence of oxygen. It occurs when free radicals (molecules or atoms with unpaired electrons) which are unstable and highly reactive, react with the carbon-carbon double bonds in unsaturated fats. This can be seen in the smell and flavour that is produced when meat is left out in the open. Due to the formation of aldehydes and ketones, an unpleasant odour occurs.

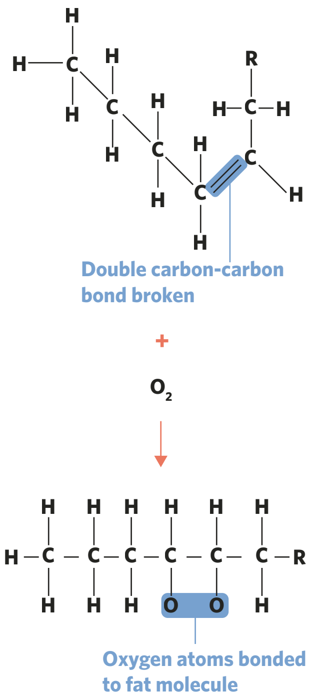


Figure 4 Example of the oxidative rancidity of a triglyceride, where R represents the rest of the fatty acid chain

Antioxidants

As well as refrigeration, the decay of food can be slowed by antioxidants. **Antioxidants** interrupt the propagation of free radicals by being oxidised in preference to triglycerides, as shown in figure 5. The presence of antioxidants thus delays the oxidation of triglycerides in the compound.

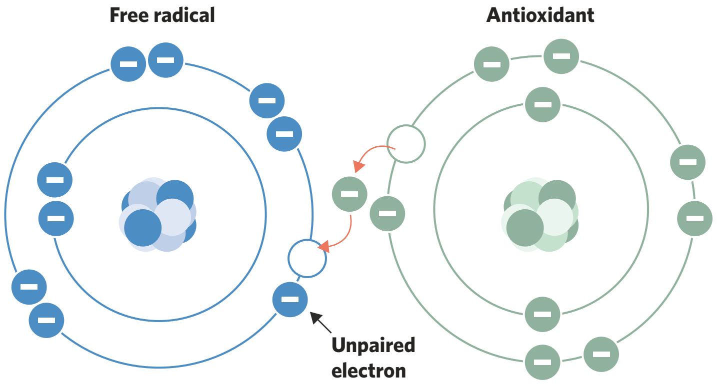


Figure 5 Antioxidants donate an electron, usually from a hydroxyl group, to stabilise free radicals

This occurs as antioxidants donate an electron, often from their hydroxyl group, to the free radicals which means that the triglycerides do not undergo oxidation, interrupting the propagation of free radicals that leads to increased rancidity. Antioxidants are found naturally in foods like berries, fish and citrus fruits, but can also be made synthetically and added as a preservative to foods. A list of common natural and synthetic antioxidants are listed in table 1, along with their molecular formulas.

Table 1 List of common natural and synthetic antioxidants

Antioxidant	Notes
Natural	
Ascorbic acid (vitamin C) ($C_6H_8O_6$)	Berries, leafy green vegetables, citrus fruits, kiwi fruit
Vitamin E ($C_{29}H_{50}O_2$)	Canola, seeds, whole grains, soybeans
α-Carotene ($C_{40}H_{56}$)	Carrots, tomatoes, apricots, mangoes, sweet potatoes
Selenium (Se^{6+})	Fish, red meat, eggs, whole grains, nuts, garlic
Synthetic	
PG (Propyl gallate) ($C_{10}H_{12}O_5$)	Used in cosmetics, adhesives and food
BHT (Butylated hydroxytoluene)($C_{15}H_{24}O$)	Fat-soluble and helps delay oxidative rancidity of fats
BHA (Butylated hydroxyanisole)($C_{11}H_{16}O_2$)	Fat-soluble and helps delay oxidative rancidity of fats

Theory summary

- Digestion of triglycerides occurs through hydrolysis by enzymes like lipase, to produce glycerol and fatty acids. This occurs in the small intestine where bile emulsifies fat.
- Triglycerides can be stored in adipose tissue, then oxidised in muscles to release energy.
- Triglycerides can undergo oxidative rancidity when exposed to heat, light or oxygen, leading to an unpleasant smell or taste.
- Antioxidants can delay the deterioration of fats by restricting the generation of free radicals.

10D QUESTIONS

Theory review questions

Question 1

Below are three definitions of concepts discussed in this lesson. Identify the option with the terms that correctly matches the respective definitions.

I The chemical breakdown of a substance when reacted with water.
II Degradation of a compound due to reaction with oxygen in air.
III A dispersion of droplets of a liquid in another liquid in which it is not soluble.

A I oxidative rancidity, II emulsion, III hydrolysis
B I condensation, II oxidative rancidity, III emulsion
C I hydrolysis, II condensation, III oxidative rancidity
D I hydrolysis, II oxidative rancidity, III emulsion

Question 2

Identify the option that correctly completes the following sentences.

Triglycerides are ___________ by bile. Following this, the fats are then broken down by the ___________ lipase via hydrolysis into fatty ___________ and ___________. The products are then absorbed into the ___________ to be transported to cells.

A emulsified, enzyme, acids, glycerol, bloodstream
B hydrolysed, endopeptidase, oils, glycogen, fat
C emulsified, endopeptidase, oils, glycerol, fat
D oxidised, enzyme, acids, glucose, bloodstream

Question 3

Identify which statement applies to triglycerides.

A Digestion begins with saliva.
B Hydrolysis involves enzymes.
C They are not related to oxidative rancidity.
D They are stored as glucose when in excess.

Question 4

Which of the following lists the correct order of events in the digestion of fats.

A Emulsification by bile → degradation by lipases → absorption of fatty acids and glycerol into bloodstream → conversion into triglycerides
B Emulsification by bile → absorption of fatty acids and glycerol → degradation by lipases → conversion into triglycerides
C Degradation by lipases → emulsification by bile → absorption of fatty acids and glycerol into bloodstream → conversion into triglycerides
D Degradation by lipases → emulsification by bile → conversion into triglycerides → absorption of fatty acids and glycerol into bloodstream

Exam-style questions

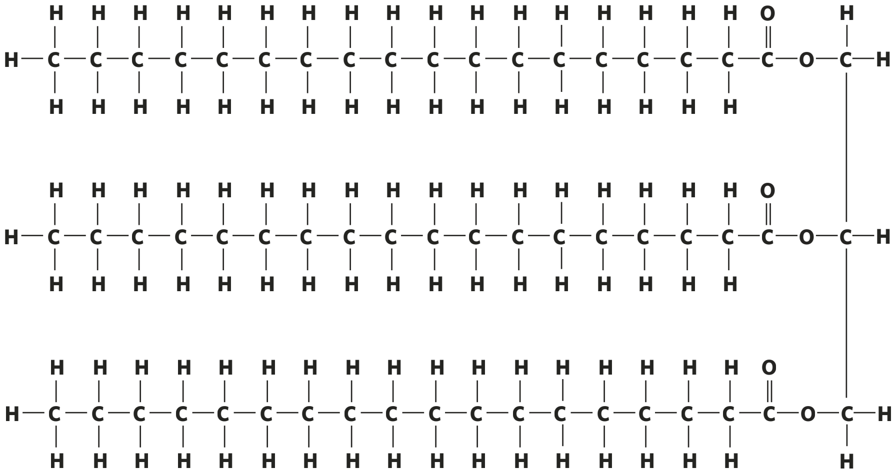
Within lesson

Question 5 (1 MARK)

Name the functional group(s) that is/are formed in the reaction of 3 linoleic acid molecules and glycerol.

Question 6 (1 MARK)

Glycerol tristearate is the primary fat component of beef. When it is hydrolysed, it produces stearic acid as the only fatty acid. Circle the functional group that is hydrolysed in this process.



Question 7 (4 MARKS)

The following fatty acids are analysed: Linoleic acid ($C_{18}H_{32}O_2$), oleic acid ($C_{18}H_{34}O_2$), stearic acid ($C_{18}H_{36}O_2$) and linolenic acid ($C_{18}H_{30}O_2$).

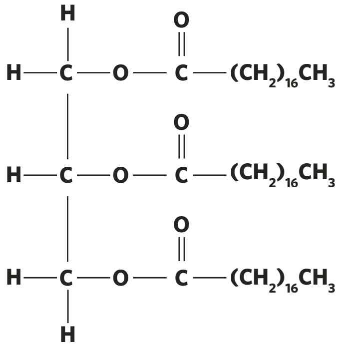
a When stored under identical conditions, which of the following fatty acids is likely to undergo oxidative rancidity in the shortest time? Explain your answer. (2 MARKS)

b Explain the difference between oxidative rancidity and hydrolysis of fats. (2 MARKS)

Question 8 (2 MARKS)

The provided structural formula represents a triglyceride.

When this fat is hydrolysed in the presence of the enzyme lipase and water, two types of products are formed. Write the structural formulas of these two products.



Question 9 (4 MARKS)

Vitamin C is important for the growth and repair of tissue but can also act as an antioxidant for the human body.

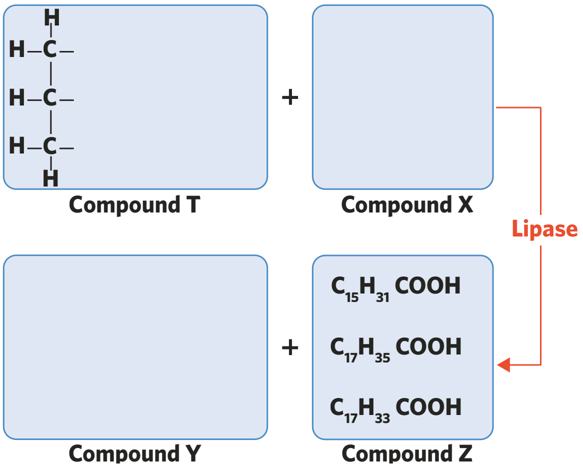
a Explain how vitamin C functions as an antioxidant, identifying the functional group that is important for its action. (2 MARKS)

b Explain why vitamin C in berries is considered a natural antioxidant, as opposed to a synthetic one. (2 MARKS)

Multiple lessons

Question 10 (4 MARKS)

Red meats, such as beef, contain a particular triglyceride, labelled Compound T in the reaction pathway provided. It is composed of three different fatty acid chains: palmitic, stearic and oleic acid. This compound undergoes hydrolysis during digestion, as represented in the reaction pathway provided.



a Complete the structure of Compound T in the box provided. (1 MARK)

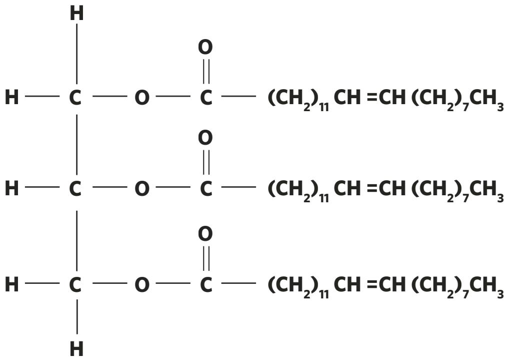
b Write the formula for Compound X, with its correct stoichiometric ratio in the box provided. (1 MARK)

c Draw the structural formula of Compound Y, one of the products of the reaction, in the box provided. (1 MARK)

d Lipase is the enzyme that catalyses the reaction provided. How does this enzyme work with a coenzyme to catalyse the reaction? (1 MARK)

Question 11 (4 MARKS)

The diagram provided represents a particular biomolecule.



a State the class of organic biomolecules to which the provided molecule belongs. (1 MARK)

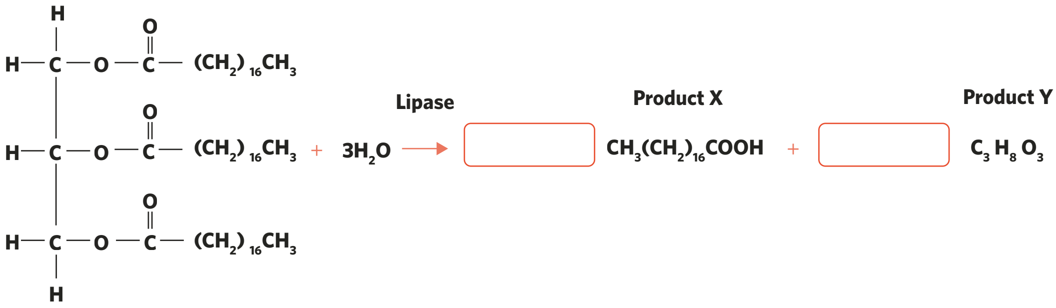
b This molecule can be hydrolysed, forming the products glycerol and euricic acid. Euricic acid is considered a monounsaturated fatty acid. Explain what is meant by the term monounsaturated fatty acid. (1 MARK)

c Euricic acid is derived from plants and reacts with methanol to form a biodiesel, methyl erucate. Write the semi-structural formula of methyl erucate. (1 MARK)

d Biodiesel is considered a renewable energy source. What is meant by the term renewable energy? (1 MARK)

Question 12 (6 MARKS)

An incomplete reaction between a triglyceride and water molecules is shown below.



a Rewrite the above equation by adding appropriate coefficients for Product X and Product Y, so that the equation is balanced. (2 MARKS)

b Name the fatty acid Product X. (1 MARK)

c The fatty acid produced in this reaction is oxidised to produce carbon dioxide and water. Write a balanced equation for this reaction. States are not required. (2 MARKS)

d Given the structure of this triglyceride, explain why it exists as a solid at room temperature. (2 MARKS)

10E PROPERTIES OF FATS AND OILS

In this lesson, we will learn how the chemical properties of fats and oils are dependent upon their structures.

10A Structure of carbohydrates	10B Breakdown and importance of carbohydrates	10C Structure of fats and oils	10D Breakdown of fats and oils	10E Properties of fats and oils	10F Calorimetry	10G Energy in food

Study design dot point

- fats and oils (triglycerides): common structural features including ester links; distinction between fats and oils with reference to melting points; explanation of different melting points of triglycerides with reference to the structures of their fatty acid tails and the strength of intermolecular forces; chemical structures of saturated and unsaturated (monounsaturated and polyunsaturated) fatty acids; distinction between essential and non- essential fatty acids; and structural differences between omega-3 fatty acids and omega-6 fatty acids

Key knowledge units

Properties of fats and oils	4.2.3.4

Key terms and definitions

- **Melting point** temperature at which a substance changes from solid to liquid

Lesson links

This lesson builds on:

- ▶ 10C – Structure of fats and oils

Structure of fats and oils determine their properties.

- ▶ 7E – Properties of organic compounds

Intermolecular forces between molecules determine the melting points of organic compounds, which is also applied to the melting points of fats and oils.

Properties of fats and oils 4.2.3.4

OVERVIEW

Different types of fats and oils have different **melting points** due to differences in structure.

THEORY DETAILS

As we learned in 10C, a triglyceride consists of one glycerol and three fatty acid tails. The properties of triglycerides are determined by the structure of these fatty acid tails. In this lesson, we will only focus on the melting points of triglycerides. As shown in figure 1, saturated fats only have carbon-carbon single bonds in the structure of their fatty acids, which allows the fatty acid tails to be packed tightly together. This means the intermolecular forces between saturated fat molecules are strong. However, the intermolecular forces between unsaturated fat molecules (also known as oils) are weaker due to the presence of carbon-carbon double bonds in the structure of their fatty acid tails. The double bonds generate 'kinks' which prevent fatty acid tails from being packed tightly together. As intermolecular forces between saturated fat molecules are strong, it requires more energy to break these bonds. Hence, with the same number of carbon atoms, a saturated fat will have a higher melting point than an unsaturated fat. This trend is shown in table 1.

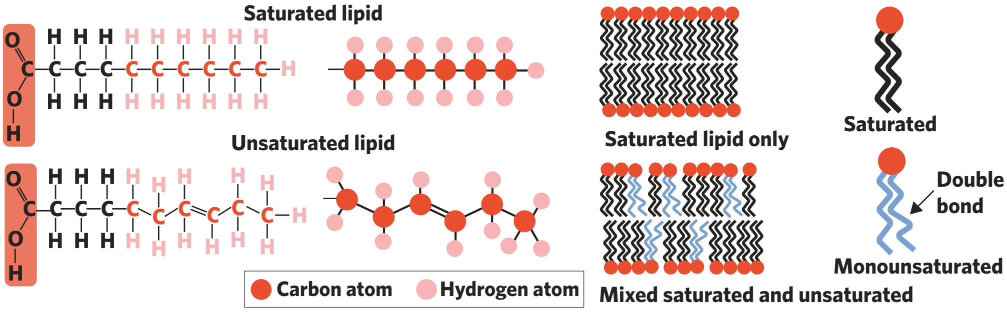


Figure 1 Tightly packed fatty acid tails in saturated fat and loosely packed in unsaturated fat (oil)

Table 1 Some saturated and unsaturated fats with the corresponding semi-structural formulas and melting points

Name	Semi-structural formula	Melting points (°C)
Saturated fats		
lauric acid	$CH_3(CH_2)_{10}COOH$	45
palmitic acid	$CH_3(CH_2)_{14}COOH$	63
stearic acid	$CH_3(CH_2)_{16}COOH$	69
Unsaturated fats		
oleic acid	$CH_3(CH_2)_7CH{=}CH(CH_2)_7COOH$	13
linolenic acid	$CH_3CH_2(CH{=}CHCH_2)_3(CH_2)_6COOH$	–11
arachidonic acid	$CH_3(CH_2)_4(CH{=}CHCH_2)_3CH{=}CH(CH_2)_3COOH$	–49

As can be observed in table 1, melting points can also be different between different types of saturated fats. As the number of carbon atoms present in the structure of fatty acids in saturated fats increases, the melting points increase. This is because the strength of intermolecular dispersion forces between molecules increase as the size of molecules increases. Melting points also vary between different types of unsaturated fats. As the number of carbon-carbon double bonds in the structure of fatty acids of unsaturated fats increases, the melting point decreases due to more 'kinks' in the chain preventing molecules from stacking together well. To compare the melting points between different types of saturated or unsaturated fats, we need to consider the semi-structural formulas shown in table 2. For example, linolenic acid has three carbon-carbon double bonds and therefore requires less energy to break the intermolecular forces holding it together, as compared to linoleic acid which has only two carbon-carbon double bonds. Hence, a triglyceride with three linolenic fatty acids has a lower melting point than a triglyceride with three linoleic fatty acids.

Table 2 Some saturated and unsaturated fats with their corresponding formulas and semi-structural formulas

Name	Formula	Semi-structural formula
lauric	$C_{11}H_{23}COOH$	$CH_3(CH_2)_{10}COOH$
myristic	$C_{13}H_{27}COOH$	$CH_3(CH_2)_{12}COOH$
palmitic	$C_{15}H_{31}COOH$	$CH_3(CH_2)_{14}COOH$
palmitoleic	$C_{15}H_{29}COOH$	$CH_3(CH_2)_4CH_2CH{=}CHCH_2\ (CH_2)_5CH_2COOH$
stearic	$C_{17}H_{35}COOH$	$CH_3(CH_2)_{16}COOH$
oleic	$C_{17}H_{33}COOH$	$CH_3(CH_2)_7CH{=}CH(CH_2)_7COOH$
linoleic	$C_{17}H_{31}COOH$	$CH_3(CH_2)_4(CH{=}CHCH_2)_2(CH_2)_6COOH$
linolenic	$C_{17}H_{29}COOH$	$CH_3CH_2(CH{=}CHCH_2)_3(CH_2)_6COOH$
arachidic	$C_{19}H_{39}COOH$	$CH_3(CH_2)_{17}CH_2COOH$
arachidonic	$C_{19}H_{31}COOH$	$CH_3(CH_2)_4(CH{=}CHCH_2)_3CH{=}CH(CH_2)_3COOH$

Source: VCAA data book

1 Worked example

Consider a triglyceride M that contains three palmitic acid tails and another triglyceride P that contains three palmitoleic acid tails. Predict which triglyceride has a higher melting point. Explain your answer with reference to structure and bonding.

What information is presented in the question?

Triglyceride M contains three palmitic acid tails and triglyceride P contains three palmitoleic acid tails.

What is the question asking us to do?

Predict which triglyceride has a higher melting point. Explain your answer with reference to the structure and bonding of each triglyceride.

What strategy(ies) do we need in order to answer the question?

1. Compare the number of carbon atoms present in the triglycerides.
2. Determine the types of carbon-carbon bonds present.
3. Predict which triglyceride has a higher melting point based on the differences in steps 1 and 2.

Answer

Both triglycerides have the same number of carbon atoms because palmitic acid and palmitoleic acid both have 16 carbon atoms. Based on table 2, palmitic acid is a saturated fatty acid, so the fatty acids tails in M are packed closely together. However, palmitoleic acid is an unsaturated fatty acid, so the presence of a carbon-carbon double bond creates ‘kinks’ in the fatty acid tails, preventing molecules of P from packing closely together. Therefore, M has stronger intermolecular dispersion forces, and a higher melting point.

Theory summary

- For triglycerides with the same number of carbon atoms, saturated fats have higher melting points than unsaturated fats.
- Fatty acid tails in saturated fats only have carbon-carbon single bonds. This makes the saturated fat molecules pack tightly together and therefore the intermolecular dispersion forces are strong.
- Fatty acid tails in unsaturated fats have carbon-carbon double bonds. This prevents the unsaturated fat molecules from being tightly packed together due to ‘kinks’ in the chains and therefore the intermolecular dispersion forces are weak.
- As the number of carbon atoms present in the structure of fatty acids of saturated fats increases, the melting point increases.
- As the number of carbon-carbon double bonds in the structure of fatty acids of unsaturated fats increases, the melting point decreases.

10E QUESTIONS

Theory review questions

Question 1

Which of the following statements is correct about fats and oil?

A Intermolecular forces between fat molecules are weaker than those between oil molecules.

B Oil has a lower melting point than fat because oil molecules are not closely packed together.

C Fat has a lower melting point than oil because the fatty acid tails only have carbon-carbon single bonds, meaning that it requires less energy to break down fat.

D Fat has a higher melting point than oil because the fatty acid tails contain carbon-carbon double bonds, meaning that it requires more energy to break down fat.

Question 2

Fill in the blanks to explain the different melting points in different types of saturated fats.

The strength of intermolecular forces between molecules ___________ as the size of the molecules increases. Therefore, as the number of carbon atoms present in the structure of fatty acids in saturated fats increases, the melting points ___________.

Question 3

Fill in the blanks to explain the different melting points in different types of unsaturated fats.

As the number of carbon-carbon double bonds present in the fatty acids increases, the strength of intermolecular forces between unsaturated fats ___________. This means we need ___________ energy to disturb the intermolecular forces between unsaturated fats. Hence, melting points ___________ when there are more carbon-carbon double bonds in the fatty acids.

Question 4

Fill in the blanks to explain why saturated fats have much higher melting points than unsaturated fats. More than one word may be required for each space.

Fatty acid tails in saturated fats have only carbon-carbon ___________ bonds and therefore they can pack closely together. This means ___________ between saturated fat molecules are ___________. However, in unsaturated fats, the carbon-carbon ___________ bonds present in fatty acids tails prevent fat molecules from packing tightly together due to 'kinks' in their hydrocarbon chains. As a result, the intermolecular forces between unsaturated fats are much ___________ than between saturated fats. Therefore, it requires ___________ energy to disturb the intermolecular forces between saturated fats, giving them much higher melting points than unsaturated fats.

Exam-style questions

Within lesson

Question 5 (1 MARK)

Which of the following lists the fatty acids in the correct order of increasing melting point?

A Lauric, linolenic, palmitic, stearic, oleic
B Oleic, linolenic, lauric, palmitic, stearic
C Linolenic, oleic, lauric, palmitic, stearic
D Linolenic, oleic, palmitic, stearic, lauric

Question 6 (1 MARK)

Which of the following is **not** correct?

I Oils have a lower boiling point than fats because they have weaker intermolecular forces.
II Oleic acid has a higher melting point than lauric acid because oleic acid has more carbon atoms than lauric acid.
III Linoleic acid has a lower melting point than myristic acid because carbon-carbon double bonds prevent linoleic acid tails from being packed closely together.
IV Stearic acid and oleic acid have the same melting point because they have the same number of carbon atoms.
V Palmitoleic acid and oleic acid have the same melting point because they have the same number of carbon-carbon double bonds.

A I, II, III
B V only
C IV and V
D II, IV, V

Question 7 (6 MARKS)

There are four meals A, B, C, D provided at a conference. Each meal contains only one type of fatty acid, myristic acid, arachidic acid, linoleic acid, or arachidonic acid. A few of the attendees are allergic to some of these fatty acids. However, there is no information provided on which type of fatty acid is present in each meal. As a food scientist, you tested the melting points of the fat component in each meal and produced the provided table of results.

Meal	Melting point (°C)
A	76
B	-11
C	-49
D	55

a Put the given fatty acids in the order of increasing melting points. Justify your answer with reference to the structure of fatty acids and intermolecular forces. (4 MARKS)

b Identify the fatty acid present in each meal and fill in the table given. (2 MARKS)

Meal	Fatty acid
A	
B	
C	
D	

Question 8 (6 MARKS)

A table of fatty acids and their melting points is shown.

With reference to their structure and bonding, explain the difference in melting point between

a lauric acid and oleic acid. (2 MARKS)

b stearic acid and lauric acid. (2 MARKS)

c arachidonic acid and palmitoleic acid. (2 MARKS)

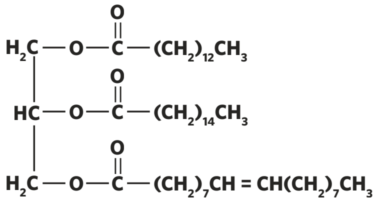
Fatty acid	Melting point (°C)
Stearic	69
Lauric	45
Oleic	13
Arachidonic	-49
Palmitoleic	0

Multiple lessons

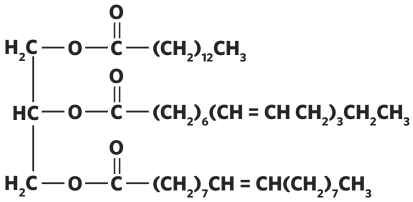
Question 9 (5 MARKS)

Two triglycerides A and B have the following structures.

A)



B)

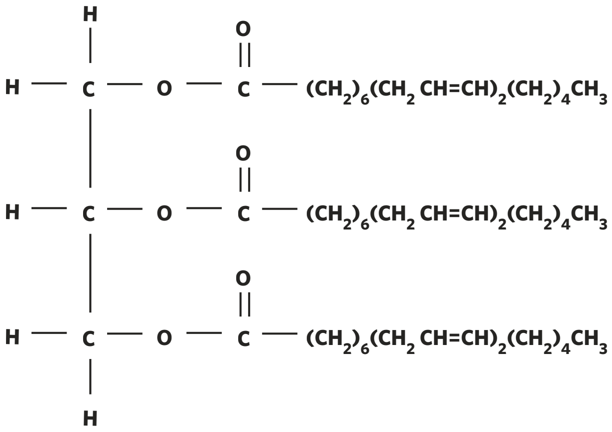


a Which triglyceride has a lower melting point? Justify your answer with reference to structure and bonding. (3 MARKS)

b Draw a hydrolysis reaction for the breakdown of the triglyceride with the lower melting point. Give correct names to all products. (2 MARKS)

Question 10 (13 MARKS)

The structure of a biomolecule is shown.



a Circle the functional group(s) present in the biomolecule given and identify the class of organic biomolecules to which this compound belongs. (3 MARKS)

b The biomolecule can be formed from glycerol and linoleic fatty acids. Is linoleic acid classified as a saturated fatty acid, a monounsaturated fatty acid or a polyunsaturated fatty acid? Justify your answer. (2 MARKS)

c Is linoleic acid classified as an omega-3 fatty acid or an omega-6 fatty acid? Justify your answer. (2 MARKS)

d Will the melting point of the biomolecule increase or decrease if we replace the three linoleic tails with three lauric acid tails? Explain your answer. (3 MARKS)

e The given biomolecule can react with methanol to form biodiesel and glycerol in the presence of potassium hydroxide. Write the semi-structural formula of the biodiesel, circle and name the functional group(s) present. (3 MARKS)

10F CALORIMETRY

In this lesson, we will learn about a technique that can be used to calculate energy changes in a chemical reaction, as well as the potential issues with the calorimetry technique.

10A Structure of carbohydrates	**10B Breakdown and importance of carbohydrates**	**10C Structure of fats and oils**	**10D Breakdown of fats and oils**	**10E Properties of fats and oils**	**10F Calorimetry**	**10G Energy in food**

Study design dot point

- the principles of calorimetry; solution and bomb calorimetry, including determination of calibration factor and consideration of the effects of heat loss; and analysis of temperature-time graphs obtained from solution calorimetry.

Key knowledge units

Principles of calorimetry	4.2.13.1
Bomb calorimetry	4.2.13.2.1
Solution calorimetry	4.2.13.2.2

Key terms and definitions

- **Calorimetry** method used to determine the amount of heat energy transferred in a system
- **Calibration factor** joules of energy required to raise the temperature of the calorimeter by one degree celsius
- **Calibration graph** plot of temperature as a function of time

Lesson links

This lesson builds on:

- 3A – Combustion reactions

Combustion reactions in calorimeters are used to determine calibration factors.

- 3B – Energy changes during combustion

Energy released during combustion of food can be used for calorimeter calculations.

Principles of calorimetry 4.2.13.1

OVERVIEW

The heat energy absorbed or released by a chemical reaction can be measured using a process called calorimetry.

THEORY DETAILS

Calorimetry can often be used in the laboratory to determine the energy content in food. In calorimetry, the heat energy released by a chemical reaction is transferred to water in a separate container. This heat energy raises the temperature of the water, which we can then use to calculate the quantity of energy transferred.

To do this, the initial temperature, the volume of water and the final temperature of the water need to be measured. Once we have these values we can use the specific heat capacity of water to calculate the energy transferred.

$q = m \times c \times \Delta T$

where q is the energy that is transferred (joules)

m is the mass of water (grams)

c is the specific heat capacity of water (4.18 J g^{-1} K^{-1})

ΔT is the change in temperature of the water.

As we are only measuring the change in temperature of water, we can use either celsius or kelvin as our unit of temperature.

The change in temperature is measured as:

$\Delta T = T_{final} - T_{initial}$

1 Worked example

When a sample of food is burned to heat 200 mL of water, the temperature rises from 24 °C to 42 °C. Calculate the heat energy, in kJ, that has been transferred.

What information is presented in the question?

Mass of water = 200 mL × 0.997 g mL^{-1}
= 199 g (1 mL of water = 0.997 g)

Initial temperature = 24 °C

Final temperature = 42 °C

What is the question asking us to do?

Calculate the energy transferred in the chemical reaction.

What strategy(ies) do we need in order to answer the question?

The specific heat capacity of water.

Answer

$q = m \times c \times \Delta T$
$= 199 \times 4.18 \times (42 - 24) = 14973 \text{ J}$

To express in kJ:

$q = \frac{14973}{1000} = 15 \text{ kJ}$

In order for calorimetry measurements to have more accuracy, they need to be measured in a closed system so that when the energy is transferred, heat loss to the surrounding environment is minimised. In an open system, where there is no lid or cover, heat will be lost from the surface of the water and transferred to the surrounding air so the temperature of the water does not increase as much. The comparison to a closed system where most of the energy is used to heat the water is shown in figure 1.

Tip The specific heat capacity of water can be found in the data book.

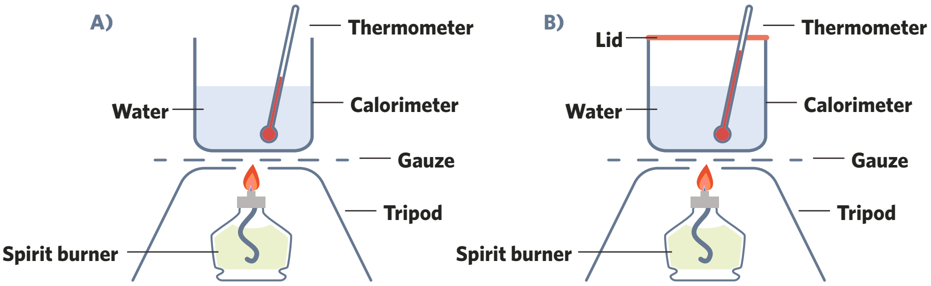


Figure 1 Comparison of calorimetry in **a)** an open system, versus **b)** a closed system

To create a closed system calorimeter and reduce heat loss to the surrounding environment:

- A lid could be placed on a container.
- The container of water could be insulated.
- The container where the food is being combusted can also be insulated.

We know that heat can be lost to the surroundings in an open system, causing the measured temperature difference of the water to be inaccurate. Whilst lids and insulation can help minimise the inaccurate measurements of temperature change, there will always be some heat lost to the surrounding environment. In order to account for the lost heat, calorimeters can be calibrated to further minimise the effect of lost heat as well as ensuring that the data from the calorimeter is more accurate.

To calibrate a calorimeter, the energy required to change the temperature of the water by 1 °C in that particular calorimeter is calculated. This is known as the **calibration factor** (CF) and it is measured in J $°\text{C}^{-1}$. The value will be unique for each calorimeter due to its physical composition. To calculate this, a known amount of energy is delivered to the water, then the resultant rise in temperature is measured. This can be done by electrical calibration which uses an electric heater where the following formula is used to calculate the thermal energy released into the water by an electric current:

$E = V \times I \times t$

Where E is the energy released (joules)

V is the voltage (volts)

I is the current (amps)

t is the time (seconds) that the heater was turned on for.

Once the change in temperature is measured, the calibration factor can be calculated by the following formula:

$$\text{CF} = \frac{E}{\Delta T} = \frac{V \times I \times t}{\Delta T}$$

Another type of calibration is chemical calibration which involves performing a chemical reaction in the calorimeter that will similarly release a known quantity of energy so that the rise in temperature can be measured. For chemical calibration, the following formula is used to calculate the heat released.

$$E = n \times \Delta H_C$$

Where E is the energy released during calibration (joules)

n is the amount of reactant and

ΔH_C is the enthalpy of combustion for the reaction (J mol^{-1}).

As a calorimeter is not perfectly insulated, calculating the temperature change in the water is not the most accurate method. A more accurate way of determining the temperature change is by a calibration graph, in which the temperature against time before, during and after calibration is plotted on a graph.

Figure 2a is a **calibration graph** for a perfectly insulated calorimeter, where the temperature change can be easily seen. However, calorimeters that don't have perfect insulation produce graphs that may need to be extrapolated to get the temperature change or that may show anomalies, as shown in figure 2b. Therefore, it is important to know that this method is still limited and will not always yield perfect results.

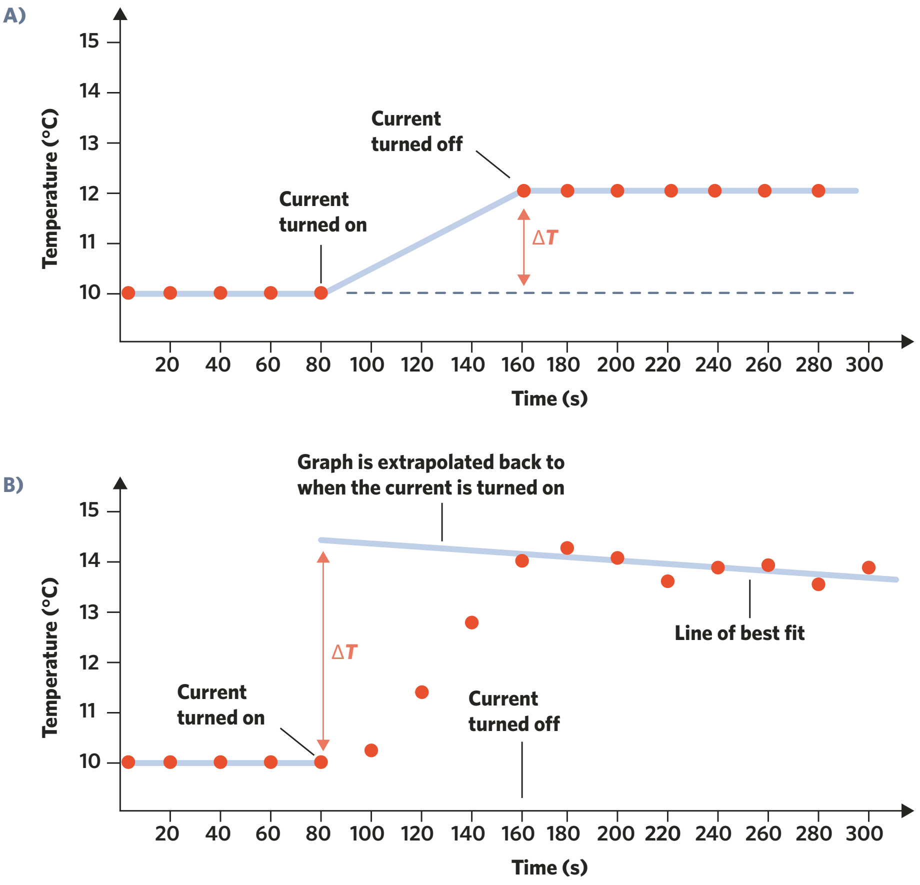


Figure 2 Calibration graph for different calorimeters

2 Worked example

A bomb calorimeter was calibrated by the complete combustion of 1.5 g of benzoic acid ($M(C_6H_5COOH) = 122.0$ g mol^{-1}; $\Delta H_C = -3227$ kJ mol^{-1}). The temperature of the water in the calorimeter started at 16 °C and rose to 23 °C during the calibration. Determine the calibration factor.

What information is presented in the question?

Mass = 1.5 g

$M = 122.0$ g mol^{-1}

$\Delta H_C = -3227$ kJ mol^{-1}

Initial temperature = 16 °C

Final temperature = 23 °C

What is the question asking us to do?

Calculate the energy transferred in the chemical reaction.

What strategy(ies) do we need in order to answer the question?

1. Calculate n.
2. Calculate E, using the equation $E = n \times \Delta H_C$.
3. Calculate change in temperature.
4. Calculate calibration factor.

Answer

$$n = \frac{m}{M} = \frac{1.5}{122} = 0.0123 \text{ mol}$$

$$E = n \times \Delta H_C = 0.0123 \times 3227 = 39.69 \text{ kJ}$$

$$\Delta T = T_{final} - T_{initial} = 23 - 16 = 7\ °\text{C}$$

$$\text{CF} = \frac{E}{\Delta T} = \frac{39.69}{7} = 5.7 \text{ kJ °C}^{-1}$$

Using the above techniques and formulas, the energy content of food can be determined by the following formula:

$$\text{Energy content of food} = \frac{E}{m}$$

where E is the energy responsible for the temperature change (kJ), and m is the mass (g) of the food that was burned (or combusted) and the units of the energy content is kJ g^{-1}.

The enthalpy of combustion (ΔH_C) or the heat of solution (ΔH) can also be calculated using the formulas that have been discussed in this lesson.

Bomb calorimetry 4.2.13.2.1

OVERVIEW

Bomb calorimetry is used to measure the heat of combustion of chemical reactions that involve gaseous reactants or products.

THEORY DETAILS

The name for the devices that measure the energy changes using heat are calorimeters. There are two specific types: bomb calorimeters and solution calorimeters. As suggested by their names, for bomb calorimeters, the reaction takes place in a sealed 'bomb' vessel, whilst for solution calorimeters, the reaction occurs in a solution.

Figure 3 shows an example of a bomb calorimeter where combustion reactions occur. The reaction occurs in a reaction chamber that is usually made to withstand high pressures and high temperatures whilst maintaining a constant volume. The reaction chamber is wired to an electrical circuit so that the contents can be electrically ignited to start combustion. For this to occur, there needs to be sufficient oxygen in the chamber to do so. The reaction chamber is surrounded by a vessel of water so that the heat energy that is transferred can be measured. Insulation around the calorimeter prevents heat being released into the surrounding environment and the stirrer ensures that heat is evenly distributed in the water.

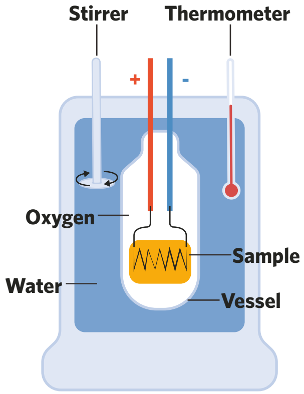


Figure 3 Set up of a standard bomb calorimeter

3 Worked example

8.6 g of glucose (molar mass is 180.0 g mol^{-1}) was completely burned in a bomb calorimeter, causing the temperature of the water in the calorimeter to increase by 13 °C. Given a calibration factor of 10.2 kJ °C^{-1}, calculate the enthalpy of combustion of glucose.

What information is presented in the question?

CF = 10.2 kJ °C^{-1}

Mass = 8.6 g

$M = 180.0$ g mol^{-1}

$\Delta T = 13$ °C

What is the question asking us to do?

Calculate the enthalpy of combustion.

What strategy(ies) do we need in order to answer the question?

1. Calculate *n*.
2. Calculate *E*, using the equation $E = \text{CF} \times \Delta T$.
3. Calculate the energy released per mole.
4. State the enthalpy of combustion, ΔH_C with the correct sign (remember combustion is an exothermic reaction).

Answer

$n = \frac{m}{M} = \frac{8.6}{180} = 0.0478$ mol

$E = \text{CF} \times \Delta T = 10.2 \times 13 = 132.6$ kJ

Energy released per mole

$= \frac{E}{n} = \frac{132.6}{0.0478} = 2774 = 2.8 \times 10^3$ kJ mol^{-1}

ΔH_C (glucose) = -2.8×10^3 kJ mol^{-1}

Solution calorimetry 4.2.13.2.2

OVERVIEW

Energy changes of chemical reactions occurring in a solution can be measured using solution calorimetry.

THEORY DETAILS

A solution calorimeter, like a bomb calorimeter, calculates the energy transferred in a chemical reaction, but uses a much simpler instrument. As shown in figure 4, solution calorimeters can be made with a polystyrene cup which means the reaction occurs at a constant pressure.

In a solution calorimeter, an insulated container holds a known volume of water in which a reaction in solution occurs, like the dissolution of a solid. From a solution calorimeter we can assess whether the reaction occurring is exothermic or endothermic. If the temperature of the surrounding water increases, then it is an exothermic reaction as the reaction has released heat energy into the water. If the temperature of the surrounding water decreases, then it is an endothermic reaction as the reaction has absorbed heat energy from the water.

A limitation with using polystyrene is that it absorbs some of the heat from the water. Therefore, the change in temperature will be slightly lower than it should be. Another limitation is that solution calorimeters cannot measure the energy content of food as in this case, combustion cannot occur in an aqueous solution. However, they are useful to measure the energy changes of dissolving substances like sugar in water, as well as the enthalpy changes from acids/bases reacting with solids in water.

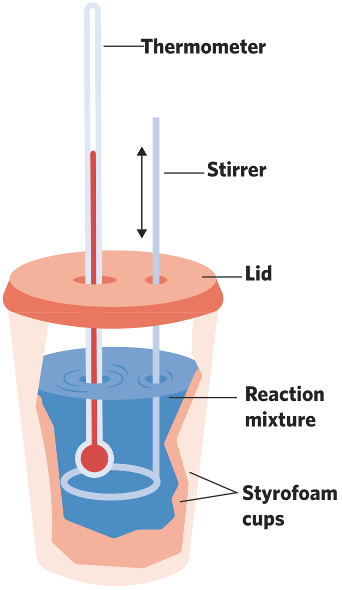


Figure 4 Set up of a polystyrene coffee cup solution calorimeter

Theory summary

- Calorimetry is the method by which chemists measure the heat released or absorbed in a chemical reaction, such as combustion.
- The specific heat formula calculates the energy that is transferred to a fixed volume of water in the system.
- Calorimeters can be calibrated to determine the relationship between the temperature change in the water and the heat energy transferred to the water.
- The calibration factor is a measure of the energy required to raise the temperature of the water by 1 °C.
- The energy required to raise the temperature of the water can be calculated by electrical calibrators using the formula $E = VIt$, or by a chemical calibrator using the formula $E = n \times \Delta H_c$ where the $CF = \frac{E}{\Delta T}$.
- The energy content of food can be calculated with the formula: energy content $(\text{kJ g}^{-1}) = \frac{E}{m}$, where E is measured in kJ and mass in grams.
- Bomb calorimeters are insulated instruments where combustion reactions occur in a sealed, oxygen-filled reaction vessel.
- A solution calorimeter measures the enthalpy change of a substance dissolved in a solution.

10F QUESTIONS

Theory review questions

Question 1

When 120 g of water at 92 °C was added to a calorimeter containing 100 g of water at 22 °C, the temperature increased to 44 °C. Assuming no energy was lost to the environment outside of the calorimeter, the energy absorbed by the calorimeter is equal to the

A difference between the energy lost by the hot water and the energy gained by the cold water.

B energy gained by the cold water.

C zero, no energy was transferred.

D energy lost by the cold water.

Question 2

A calorimeter was calibrated using electric heating. A current of 1.700 A with a potential difference of 3.500 V was applied for three minutes. There was a temperature rise of 7.200 °C. Therefore, the calibration factor in J °C^{-1} is

A 120.5

B 107.1

C 60.2

D 148.8

Question 3

Which option describes a scenario where a bomb calorimeter would be more useful than a polystyrene cup calorimeter?

A Measuring the enthalpy change of the dissolution of a solid

B Measuring the enthalpy change of an acid-base reaction

C Measuring the energy content of a piece of food

D None of the above

Exam-style questions

Within lesson

Question 4 (1 MARK)

How much heat is needed to raise 7.00 g of a sample of food, with a specific heat capacity (C) of 0.900 J g^{-1} °C^{-1}, by 17.0 °C?

Question 5 (3 MARKS)

A 3.4 g sample of methyl stearate ($C_{19}H_{38}O_2$) was burnt in excess oxygen in a bomb calorimeter, with the temperature rising by 2.17 °C. The calibration factor was calculated to be 4.42 kJ °C^{-1}.

Given $M(C_{19}H_{38}O_2)$ = 298.0 g mol^{-1}, calculate the molar enthalpy of combustion of methyl stearate.

Question 6 (5 MARKS)

A sample of tetradecanoic acid ($C_{14}H_{28}O_2$) was burnt in a bomb calorimeter in excess oxygen. The experimental results are as follows:

Mass of tetradecanoic acid	1.72 g
$M(C_{14}H_{28}O_2)$	228.0 g mol^{-1}
Temperature rise	13.2 °C
Calibration factor	4.85 kJ °C^{-1}

a Use the data provided to calculate the molar enthalpy of combustion of the tetradecanoic acid. (3 MARKS)

b Write a balanced thermochemical equation for the complete combustion reaction. (2 MARKS)

Question 7 (6 MARKS)

An experiment was performed by a student to determine whether ethanol is suitable as a fuel. The student first burnt a 1.5 g sample of ethanol in a bomb calorimeter, so that the sample underwent a complete combustion reaction according to the following equation:

$C_2H_5OH_{(l)} + 3O_{2(g)} \rightarrow 2CO_{2(g)} + 3H_2O_{(g)}$

The calorimeter was first calibrated by passing a current through an electric heater placed in the water surrounding the reaction vessel. A 1.5 A current and a potential difference of 5.5 V was applied for two and a half minutes. The temperature rose by 1.7 °C.

a Determine the calibration factor for the calorimeter. (2 MARKS)

b Determine Δ*H* if the sample of ethanol increased the temperature of the water by 10.0 °C. Include appropriate units in your answer. (3 MARKS)

c The value calculated in b is different to the value provided in the data book. Provide a reason for this difference. (1 MARK)

Multiple lessons

Question 8 (3 MARKS)

5.6 g of food was burned in a bomb calorimeter, with the temperature rising 18 °C.

Provided is the nutritional details for this sample of food.

Serving Size	56 g
Fat	9.3 g
Protein	1.7 g
Carbohydrate	12.0 g

a Calculate the theoretical total amount of energy released from the complete combustion of this 5.6 g sample of food. (2 MARKS)

b Calculate the calibration factor for this bomb calorimeter. (1 MARK)

Question 9 (5 MARKS)

Napthalene ($C_{10}H_8$) was burned in a bomb calorimeter as a first step to determine the calibration factor. The combustion reaction for napthalene is shown below:

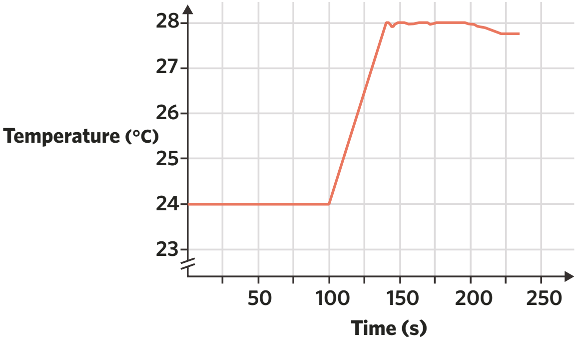
$C_{10}H_{8(s)} + 12O_{2(g)} \rightarrow 10CO_{2(g)} + 4H_2O_{(g)}$ $\Delta H = -5133$ kJ mol^{-1}

The data for the calibration of the bomb calorimeter is as follows:

Mass of $C_{10}H_8$ = 0.212 g

Mass of water = 300 g

The graph given was produced in the bomb calorimeter.



a Using the graph above, calculate the calibration factor for the bomb calorimeter. (3 MARKS)

b Comment on the reliability of the data collected. (2 MARKS)

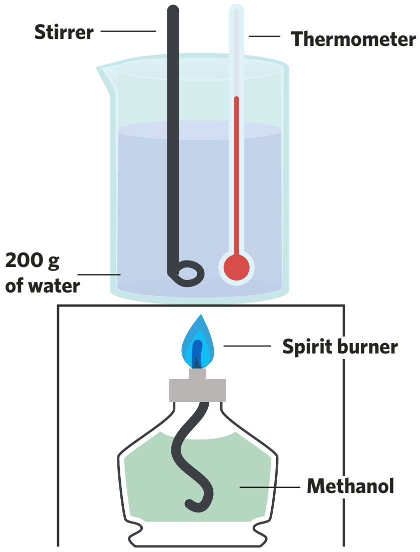
Question 10 (9 MARKS)

The complete combustion of methanol is shown in the following equation.

$2CH_3OH_{(l)} + 3O_{2(g)} \rightarrow 2CO_{2(g)} + 4H_2O_{(g)}$

The heat of combustion of methanol is found in your data book.

A scientist used a spirit burner to burn 2.3 g of methanol, raising the temperature of 200.0 g of water from 16.0 °C.



a If all the energy released by the complete combustion of methanol is transferred to the water, calculate the final temperature of the water. (3 MARKS)

b Identify one way to limit heat loss to the environment. (1 MARK)

c Canola oil can be reacted with methanol, in the presence of a strong base, to produce glycerol and a mixture of biodiesel molecules. A typical biodiesel molecule produced in this reaction has the following formula $C_{15}H_{30}O_2$.

i Write the structural formula of this molecule, then name and circle the functional group present. (3 MARKS)

ii If the methanol in the spirit burner was replaced with canola oil, the heat content would be 18 kJ g^{-1}. Suggest why the heat content of canola oil is measured in kJ g^{-1} and not kJ mol^{-1}. (2 MARKS)

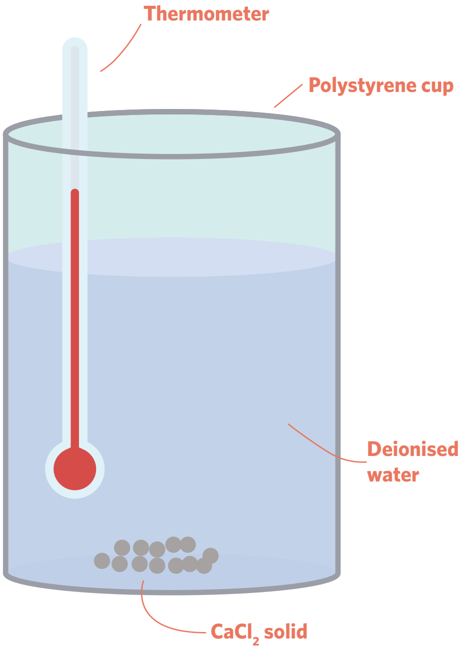
Question 11 (11 MARKS)

Chris has set up a solution calorimeter experiment as shown in the diagram provided. He is measuring the enthalpy change of the following chemical reaction.

$CaCl_{2(s)} \rightarrow Ca^{2+}_{(aq)} + 2Cl^{-}_{(aq)}$

After placing 25 g of $CaCl_{2(s)}$ in the calorimeter with 100 ml of water, he measured the initial and final temperature of the water after he believed all $CaCl_{2(s)}$ had dissolved. He recorded his results in the table below.

Initial temperature	27 °C
Final temperature	54 °C



a Calculate the experimental value for the enthalpy change in kJ mol^{-1}. Is this reaction endothermic or exothermic? (5 MARKS)

b However, his teacher soon told him that the literature value of the enthalpy of dissolution of calcium chloride was –83 kJ mol^{-1}. Is the experimental value the same as the literature value? If not, suggest a reason for this disparity. (2 MARKS)

c Calculate the percentage heat loss to the environment (2 MARKS)

d Identify 2 improvements to the experimental set-up. (2 MARKS)

10G ENERGY IN FOOD

In this lesson, we will learn about the energy content of different macromolecules.

10A Structure of carbohydrates	10B Breakdown and importance of carbohydrates	10C Structure of fats and oils	10D Breakdown of fats and oils	10E Properties of fats and oils	10F Calorimetry	10G Energy in food

Study design dot point

- the comparison of energy values of carbohydrates, proteins and fats and oils

Key knowledge units

Comparison of energy in different macromolecules	4.2.11.1

Key terms and definitions

- **Energy content** amount of heat energy (in joules or kilojoules) produced upon burning 1 g or 1 mol (for pure substances) of the substance

Lesson links

This lesson builds on:

- ▶ 9B – Breakdown of proteins

The breakdown of proteins provides energy.

- ▶ 10B – Importance and breakdown of carbohydrates

The breakdown of carbohydrates provides energy.

- ▶ 10D – Breakdown of fats and oils

The breakdown of fats and oils provides energy.

Comparison of energy in different macromolecules 4.2.11.1

OVERVIEW

The breakdown of protein, fats and carbohydrates all produce different amounts of energy.

THEORY DETAILS

Food plays an integral role in our survival. Metabolism of food not only gives us the building blocks of important molecules critical to our biological functioning, it also provides us with energy to sustain all of the reactions that are required for us to survive. Proteins, carbohydrates and fats all have a different **energy content**; that is they provide us with a different amount of energy for every gram metabolised. As outlined in table 1, fats and oils provide the greatest amount of energy per gram, followed by proteins and lastly carbohydrates.

Table 1 Energy content of each food type

Food	Heat of combustion (kJ g^{-1})
Fats and oils	37
Protein	17
Carbohydrate	16

Tip This information can be found in the data book.

Due to the fact that food is a mixture of different substances, the energy content is expressed in per grams rather than per mole.

As we know, foods contain more than just fats, proteins and carbohydrates. For example, many cereals contain fibre, which is known to be important in digestion. However, fibre is mostly indigestible and therefore does not really provide the body with much energy. As a result, when calculating the energy content of food, we mainly focus on the three main food groups highlighted in table 1.

1 Worked example

The nutritional value of a homemade muesli is shown.

	Amount (g) per 100 g
Fats	23
Carbohydrates	12
Proteins	9
Fibre	11

Calculate the energy, in kJ, of energy provided by the consumption of 100 g of the muesli.

What information is presented in the question?

The mass of different food groups in a muesli

What is the question asking us to do?

Calculate the amount of energy in 100 g of the muesli.

What strategy(ies) do we need in order to answer the question?

1. Calculate the energy provided by each major food group.
2. Add the values together to determine the overall amount of energy in 100 g of the muesli.

Answer

Energy provided by fats = 23 g × 37 kJ g^{-1} = 851 kJ

Energy provided by carbohydrates = 12 g × 16 kJ g^{-1} = 192 kJ

Energy provided by proteins = 9 g × 17 kJ g^{-1} = 153 kJ

Total energy provided = 851 + 192 + 153 = 1196 kJ

Theory summary

- Fats, proteins and carbohydrates all supply different amounts of energy.
- Although there are other ingredients in food, the main sources of energy come from fats, proteins and carbohydrates.

10G QUESTIONS

Theory review questions

Question 1

Compared to fats, oils and carbohydrates, proteins provide

A the most amount of energy per gram.
B more energy than fats but less energy than carbohydrates per gram.
C more energy than carbohydrates but less energy than fats per gram.
D the least amount of energy per gram.

Question 2

The energy content in food is expressed

A per mole as this is most accurate.
B per molecule due to the different food types.
C per particle as this is most accurate.
D per gram as it is a mixture of different types of compounds.

Exam-style questions

Question 3 (1 MARK)

A popular chocolate bar has a nutritional value seen in the table provided.

Ingredients	**Amount (g) per serving*.** ***serving size 50 g**
Protein	3.3
Fat (total)	12.9
Carbohydrates (total)	9.2
Sodium	0.14

Given that Rajesh ate 100 g of the chocolate bar, this would be the equivalent of

A 1000.6 kJ

B 500.5 kJ

C 1361.2 kJ

D 1500.1 kJ

Question 4 (3 MARKS)

A granola bar was advertised to contain 1022.7 kJ of energy per serving (42 g). As part of its advertising, the company claimed that the bar contained more than 5 g of protein.

a Given that the bar contained 21.3 g of carbohydrates and 16.5 g of fat per serve, determine the accuracy of the statement made by the company. (2 MARKS)

b What is the unit used to express the energy content in food? (1 MARK)

Question 5 (4 MARKS)

Penny wanted to develop a new high protein low carbohydrate snack bar that contained less than 800 kJ of energy.

a For her first batch of snack bars, she included the following ingredients per bar:

Ingredients	**Amount (g)**
Protein powder	9.8
Flour	20.0
Fibre mix	3.2
Butter	7.0

i Determine whether or not this mixture of ingredients would allow the bar to meet her energy requirements. (2 MARKS)

ii According to food regulations, all food products need to have their energy content expressed as kJ/100 g. Determine the energy value of the bar that would satisfy this rule. (1 MARK)

b What percentage of the bar's energy is provided by the butter? (1 MARK)

Multiple lessons

Question 6 (3 MARKS)

Due to the availability of raw ingredients, many regions in the world have a diet that is high in carbohydrates.

a During the digestion of carbohydrates, identify the bond that is broken. (1 MARK)

b Maltose is often found in foods made from fermented starch. Identify the monomer(s) that make up maltose. (1 MARK)

c A fruitcake claimed to contain 45.0% carbohydrates per 100 g serving. Determine the total energy provided by carbohydrates in a 100 g serving. (1 MARK)

Question 7 (3 MARKS)

Cellular respiration is an important process that supplies energy for the body.

a Give the balanced equation for cellular respiration. (1 MARK)

b We tend to consume more carbohydrates than necessary to fuel the body. Name the molecule used to store excess energy derived from carboydrates. (1 MARK)

c If 4.30 g of glucose was consumed through food, how much energy would be produced during cellular respiration? (1 MARK)

Question 8 (4 MARKS)

Two different savoury biscuits claim to be low GI. The composition of the biscuits is shown in the table.

	Biscuit 1 (per 50 g)	**Biscuit 2 (per 50 g)**
Carbohydrates (total) Amylopectin Amylose	22.0 g 15.0 g 7.0 g	22.0 g 12.0 g 10.0 g
Protein	6.8 g	7.3 g
Fats	18.7 g	19.1 g
Dietary fibre	2.5 g	1.6 g

a Which of the two biscuits contain more energy per serving? Assume each serving size is 50 g. (2 MARKS)

b Which of the two biscuits would have a lower GI value? Explain. (2 MARKS)

Question 9 (4 MARKS)

Athletes are often recommended to consume a high energy meal a few hours prior to competing.

a Given a choice between a high-fat or a high-protein meal, which would be the better option for an athlete prior to a competition? Explain. (Assume the time taken to digest both food types is similar) (2 MARKS)

b Fats that are digested are absorbed into the body to produce energy. Name the type of reaction occurring during the initial digestion of a triglyceride. (1 MARK)

c Name the products formed as a result of the digestion of a triglyceride. (1 MARK)

EXPERIMENT

ENERGY CONTENT IN FOOD

Calorimetry

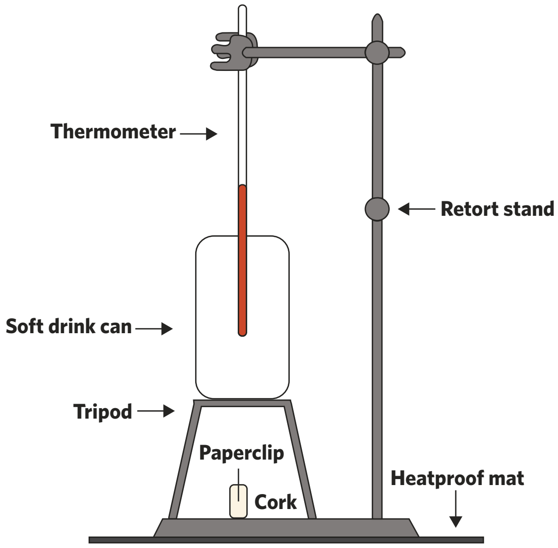
In an era of calorie-counting, it is useful to know the energy content of the foods we eat. We can compare the energy content of various types of bread by bomb calorimetry.

Materials

- 3 varieties of bread (1 slice each)
- A soft drink can
- Tripod
- Cork
- Paperclip
- Retort stand
- Heatproof mat
- 100 mL measuring cylinder
- Lighter
- Thermometer
- Timer
- Set of scales

Method

1 Set up a calorimeter as shown in the diagram.
2 Cut a 1.0 g cube of bread from a bread sample.
3 Place the bread sample on the paperclip below the soft drink can.
4 Use the measuring cylinder to fill the can with 100 mL of water.
5 Record the temperature of the water and ensure it is constant.
6 Ignite the bread and start timing.
7 Every 10 seconds note the temperature reading on the thermometer until the bread has entirely combusted.
8 Repeat steps 2–6 for each bread type.



Results

	Bread sample 1	Bread sample 2	Bread sample 3
Initial temperature of water (°C)			
Final temperature of water (°C)			
Temperature change (°C)			

QUESTIONS

Question 1 (2 MARKS)

Identify the independent and dependent variables in this experiment.

Question 2 (2 MARKS)

If one were to graph the temperature vs time for each sample, what data from the graph do we use to calculate the energy released by the bread when it combusts? Explain your answer.

Question 3 (2 MARKS)

Would you expect the energy content of the bread samples determined in this experiment to be higher or lower than the actual energy content? Justify your response.

Question 4 (1 MARK)

This experiment is repeated with the same conditions with aluminium foil around the whole setup. What effect would you expect this to have on the results?

Question 5 (2 MARKS)

Could the energy content of the bread be expressed in kJ/mol? Explain.

Question 6 (8 MARKS)

a The experiment above was carried out on a 1.0 g sample of white bread with the following results obtained.

	Water
Volume (mL)	100
Initial temperature (°C)	24.5 °C
Final temperature (°C)	24.9 °C

Use the data from these results to calculate the energy content of the bread in kJ/g. (2 MARKS)

b Using the experimental data collected in your experiment, calculate the energy content for each bread sample. (6 MARKS)

ANSWERS

1 The independent variable is the type of bread and the dependent variable is the temperature change of the water.

2 [The overall change in temperature of the water over time.^{1}][This temperature change is used to calculate the heat transferred to the water from the combustion of the bread.^{2}][Since the mass of the bread sample is 1.0 g, the energy content is the same as the heat energy transferred to the water in kJ/g.^{3}]

✓ ✗ I have identified the element of the graph that will be used .^{1}

✓ ✗ I have explained how this element is used.^{2}

✓ ✗ I have linked the energy transferred to the water to the energy content of the bread.^{3}

3 [The energy content is likely to be lower.^{1}][Heat energy is lost to the environment, as the system is not insulated.^{2}]

✓ ✗ I have concluded that the energy content is likely to be lower.^{1}

✓ ✗ I have justified my answer with evidence from the experiment.^{2}

4 [Less energy is lost to the environment as the foil prevents the heat from leaving the setup^{1}][so it is expected that the calculated energy content of the bread sample will be higher.^{2}]

✓ ✗ I have explained the effect of the foil on the experiment.^{1}

✓ ✗ I have linked this effect on the experiment to the results.^{2}

5 [The energy content of the bread cannot be calculated in kJ/mol because the bread is a mixture of substances, not a pure chemical compound^{1}][and therefore we are not able to accurately calculate the mol of bread.^{2}]

✓ ✗ I have explained why the energy content of the bread cannot be measured in kJ/mol.^{1}

✓ ✗ I have identified that the mol of the substance cannot be calculated.^{2}

6 **a** The energy released by the combustion of the bread is equal to the energy gained by the water.

$$\begin{aligned} \text{So } q(\text{bread}) &= q(\text{water}) \\ &= m(\text{water}) \times c(\text{water}) \times \Delta T \\ &= (100 \times 0.997) \times 4.18 \times (24.9 - 24.5) \\ &= 0.167 \text{ kJ} \end{aligned}$$

The energy content of the bread is 0.167 kJ/ 1 g = 0.167 kJ/g

b Please have your answer checked by your teacher.

CHAPTER 10 QUESTIONS

MULTIPLE CHOICE (10 MARKS)

Question 1 (1 MARK)

Which of the following options best categorises the organic molecules listed?

	polysaccharide	disaccharide	monosaccharide
A	amylopectin	amylose	fructose
B	glycerol	cellulose	glucose
C	cellulose	sucrose	glucose
D	amylose	amylopectin	sucrose

Question 2 (1 MARK)

Julia is attempting to create a triglyceride in her laboratory. What types of molecules are required to create this molecule?

A Carbohydrates
B Glycerol and fatty acids
C Amino acids
D Aldehydes and glycerol

Question 3 (1 MARK)

Which of the following molecules is/are used to store energy in the human body?

I Glucose
II Cellulose
III Glycogen
IV Fat

A IV only
B III, IV only
C I, III, IV only
D I, III only

Question 4 (1 MARK)

Hannah returns from the supermarket on a hot summer's day and accidentally leaves her groceries on the kitchen bench. Among her shopping is a piece of fish high in a particular fatty acid, *M*.

Which of the following identities of fatty acid *M* would account for the strong odour coming from the fish?

A Lauric acid
B Palmitic acid
C Stearic acid
D Arachidonic acid

Question 5 (1 MARK)

A saturated fat undergoes a hydrolysis reaction. The product of this reaction is glycerol and an unknown compound X. Which of the following is a possible molecular formula for X?

A $C_{14}H_{29}COOH$
B $C_{15}H_{29}COOH$
C $C_{14}H_{30}COOH$
D $C_{14}H_{28}COOH$

Question 6 (1 MARK)

Fatty acids

A release water when undergoing a hydrolysis reaction.

B are polyunsaturated if they contain many single bonds.

C are composed of three glycerol molecules.

D contain a terminal carboxyl group.

Question 7 (1 MARK)

A low GI wholemeal bread is found to contain a particular linear starch molecule of 346 monomers. How many water molecules are required to break down the starch, and what is the molar mass of the molecule?

A 346 water molecules, 56 052 g mol^{-1}

B 345 water molecules, 68 490 g mol^{-1}

C 346 water molecules, 62 280 g mol^{-1}

D 345 water molecules, 56 070 g mol^{-1}

Question 8 (1 MARK)

Jesse and Finn are discussing the properties of aspartame and sucrose. From the table they construct below, which comparison is true?

	Aspartame	**Sucrose**
A	More sweet	Less sweet
B	Significantly higher energy content	Significantly lower energy content
C	Lipid	Carbohydrate
D	Composed of glucose	Composed of fructose

Question 9 (1 MARK)

A bomb calorimeter is set up to examine the energy content of a brown rice cracker. A sample of methanol is used to calculate the calibration factor. If 50.0 g of methanol raised the water temperature from 23.2 °C to 26.8 °C, and one cracker of 30.3 g raised the temperature of the same mass of water from 24.5 °C to 24.9 °C, what is the energy content per gram of the brown rice crackers?

A 5.46 kJ g^{-1}

B 4.16 kJ g^{-1}

C 6.32 kJ g^{-1}

D 2.19 kJ g^{-1}

Question 10 (1 MARK)

Food chemist Lucas is interested in the composition of various foods. The results of his investigation are shown below.

Food	**% fat**	**% protein**	**% carbohydrate**	**% fibre**
Bread	9	4	49	28
Egg	11	16	1	37
Tuna	3	22	2	12
Potatoes	4	2	20	9

Which of the following samples will release the greatest amount of energy when digested?

A 80 g of egg

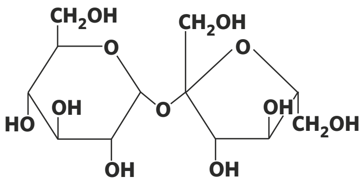
B 150 g of tuna

C 100 g of potato

D 50 g of bread

SHORT ANSWER (30 MARKS)

Question 11 (5 MARKS)



sucrose

The structure of sucrose, a disaccharide, is given. 50 g of powdered sucrose is dissolved in a solution with the enzyme sucrase, and stirred until thoroughly mixed.

a Circle on the diagram above the glycosidic link between the monomers of sucrose. (1 MARK)

b What type of reaction is occurring when the powdered sucrose is stirred in the solution of sucrase? (1 MARK)

c Draw the structure of the molecules produced after the powdered sucrose is dissolved in the enzyme solution and fully reacted. (2 MARKS)

d Name one difference in structure between alpha glucose and beta glucose. (1 MARK)

Question 12 (5 MARKS)

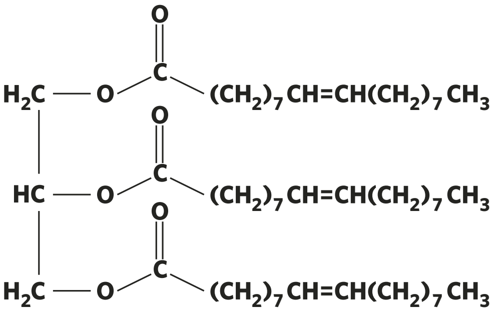
A triglyceride found in avocado has its structure shown and it contains oleic acid as the only fatty acid. 15.0 g of a pure sample of the triglyceride is completely broken down into glycerol and oleic acid.

M(triglyceride) = 884.0 g mol^{-1}

M(glycerol) = 92.0 g mol^{-1}

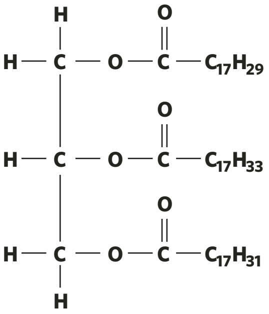
a Circle the ester functional groups present in the structure of the triglyceride. (1 MARK)

b Calculate the mass of glycerol and oleic acid produced from the breakdown of the triglyceride. (4 MARKS)



Question 13 (9 MARKS)

Chris is an aspiring young researcher, and is interested in the possible health effects of a particular compound in linseed oil. The structure of the compound is given below.



Chris adds water and an enzyme to a sample of the compound to mimic the breakdown of the given compound in the body.

a What class of biomolecules does this compound belong to? (1 MARK)

b What enzyme did Chris add, and what is the name of this type of reaction? (2 MARKS)

c Chris now adds bromine gas to the sample of the compound, and measures the amount consumed. How many bromine molecules would you expect to react with one molecule of the sample? Explain your answer. (2 MARKS)

d The triglyceride is broken down into glycerol and three other molecules. Identify the names of all three molecules and determine which of the three molecules produced will have the highest boiling point. (2 MARKS)

e Chris now combines an excess amount of aqueous lipase in 1.756×10^3 grams of the given compound. What mass of water is required for this reaction? (3 MARKS)

Question 14 (5 MARKS)

A new line of high-protein cereals are under scrutiny for their energy content after an array of failed weight-loss attempts from consumers. A food chemist investigates this claim by using a bomb calorimeter. The results of the experiment are summarised below.

Control of methanol

Initial temperature of water	22.3°C
Final temperature of water	25.7°C
Mass of methanol combusted	50.6 g

Sample

Initial temperature of water	24.8°C
Final temperature of water	28.9°C
Mass of cereal combusted	47.7 g

a What is the calibration factor of this calorimeter? (2 MARKS)

b Calculate the energy content per gram for the cereal. (2 MARKS)

c Why is a calibration factor used in this experiment? (1 MARK)

Question 15 (6 MARKS)

Andrew the baker is interested in the properties of his new sourdough spelt bread and discovers it has a low GI of only 51.

a Of the starch content in the bread, would you expect a higher proportion of amylose or amylopectin? Explain your answer. (2 MARKS)

b In addition to starch, the bread also contains lactose from the milk powder used as an ingredient. Lucy notes discomfort in her stomach after consumption of the bread, however Jessie does not.
Explain one key difference in their digestive systems that allows Jessie to digest the lactose in the bread but not Lucy. (1 MARK)

Andrew is looking for a triglyceride to incorporate into his recipe to replace the lactose, and can choose between olive oil and sunflower oil. The triglyceride composition of these two oils is compared below.

	Sunflower oil	**Olive oil**
Saturated triglycerides	82%	13%
Unsaturated triglycerides	18%	87%

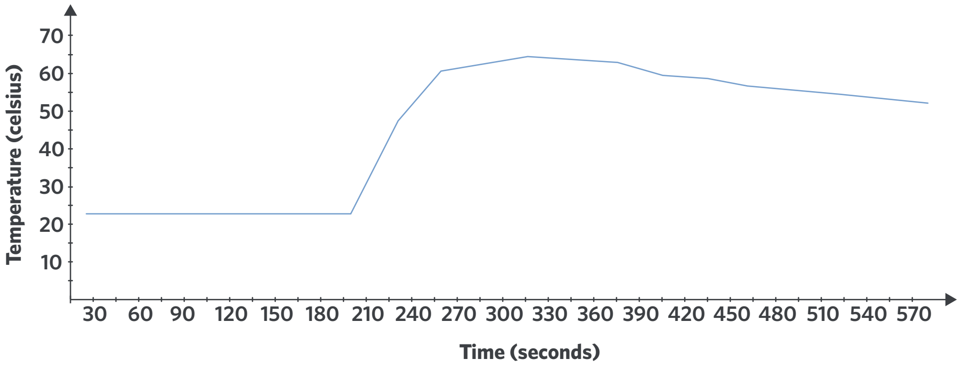
c Andrew is looking for a triglyceride that will be more viscous at room temperature to make his bread more firm. Use an explanation of intermolecular bonding to evaluate which of the two options is more likely to satisfy this requirement. (3 MARKS)

KEY SCIENCE SKILL QUESTION

Question 16 (6 MARKS)

James and his partner Kael wanted to find how much energy can be produced if 1.50 g of glucose is consumed. To do this, the pair conducted a bomb calorimetry experiment to measure the energy change that occurs during the combustion of this quantity of glucose.

a James calibrated the bomb calorimeter for 100 seconds and from the results, drew the following graph.



i Given that 100 mL of water was calibrated using a current of 1.50 amps at 2.00 V for 100 seconds, calculate the calibration factor. (2 MARKS)

ii Based on this graph, Kael believes that this calorimeter is well insulated. Comment on the accuracy of his statement. (2 MARKS)

b During the experiment, instead of using water in the bomb calorimeter, the students accidentally used an unknown liquid with a heat capacity of 2.10 J g^{-1} K^{-1}. Identify how this would affect their final result if they assumed they had been using a water solution. (2 MARKS)

1A Planning your investigation question

Theory review questions

1 D **2** B **3** D

Exam-style questions

Within lesson

4 C

5 a [The amount of salt is the independent variable,^{1}][because it is the variable that is changed to test the effects of the dependent variable,^{2}][time,^{3}][as it is the variable that is being measured.^{4}]

✓ ✗ I have identified what type of variable salt is.^{1}

✓ ✗ I have justified this with the definition of that type of variable.^{2}

✓ ✗ I have identified what type of variable time is.^{3}

✓ ✗ I have justified this with the definition of that type of variable.^{4}

b To ensure that salt is the only variable that is affecting the time it takes for the water to boil

6 a Type of milk used

b [If the mass of the clump depends on the protein content in milk,^{1}] [then the mass of the clump formed will increase with an increase in protein content in the milk.^{2}]

✓ ✗ I have referred to the dependent variable in my hypothesis.^{1}

✓ ✗ I have referred to the independent variable in my hypothesis.^{2}

c Controlled variable(s)

7 a The time taken for the cookies to cook

b [In this experiment, Barukh changed two variables; the temperature in which the cookies were cooked and the mass of dough used per cookie.^{1}][As a result, there is not one independent variable.^{2}]

✓ ✗ I have identified the variables changed.^{1}

✓ ✗ I have explained why a single independent variable does not exist.^{2}

c [To determine whether an increase in temperature^{1}][would result in cookies being cooked faster.^{2}]

✓ ✗ I have referred to the independent variable in my aim.^{1}

✓ ✗ I have referred to the dependent variable in my aim.^{2}

8 a The mass of iron ore used, the concentration of HCl used, the volume of HCl used, the temperature of the HCl solution

b [As iron is used in many different materials, it's important for us to identify a process that is highly efficient^{1}][so that we can minimize the amount of resources lost and maximise the amount of iron we can extract.^{2}][We can then identify an optimal process that can be used by industry to extract iron.^{3}]

✓ ✗ I have identified efficiency as an important attribute.^{1}

✓ ✗ I have explained why it is important for us to be efficient with this process.^{2}

✓ ✗ I have identified the industry implications for this experiment.^{3}

9 a To determine the hottest chilli type

b [By controlling the other variables in her experiment,^{1}][Mohini can be sure that she can make a sound conclusion from her results.^{2}]

✓ ✗ I have linked my answer to the question.^{1}

✓ ✗ I have linked the purpose of the control variables to the conclusion made from the experiment.^{2}

c [The experimenter could wear gloves^{1}][and safety goggles.^{2}]

✓ ✗ I have identified a safety precaution to protect the skin.^{1}

✓ ✗ I have identified a safety precaution to protect the eyes.^{2}

d Whether or not the experimenter involved wanted to consume the chilli

1B Conducting your experiment

Theory review questions

1 D **2** C

Exam-style questions

Within lesson

3 a Quantitative analysis

b Qualitative data

4 a Bubbling & coating on the *P* rod

b [Weigh the mass of rod *P* before and after the experiment (once rod has been dried).^{1}][This enables the student to determine the mass of substance deposited on rod *P*.^{2}]

✓ ✗ I have identified a technique to collect quantitative data.^{1}

✓ ✗ I have explained how this technique could give quantitative data.^{2}

Multiple lessons

5 a [To determine the colour changes occurring at different pH levels^{1}] [for various indicators.^{2}]

✓ ✗ I have identified the dependent variable as part of the aim.^{1}

✓ ✗ I have identified the independent variable as part of the aim.^{2}

b Qualitative data

c [The dependent variable in this experiment is the colour change[1]] [and the independent variable is the pH level.[2]] [The colour change observed for each indicator will vary based on the pH of the solution, therefore the change in colour is considered as the dependent variable. Subsequently, the pH level causing the change in colour is considered as the independent variable.[3]]

✓ ✗ I have identified the dependent variable.[1]

✓ ✗ I have identified the independent variable.[2]

✓ ✗ I have explained the categorisation of each variable.[3]

6 **a** The liquid

b [As the conclusion was dealing with the amount of a substance,[1]] [this can be considered as a quantitative analytical technique.[2]]

✓ ✗ I have identified the data being collected.[1]

✓ ✗ I have linked my answer to the question.[2]

1C Collecting data

Theory review questions

1 D **2** B

Exam-style questions

Within lesson

3 A

4 **a** pH of 2.1

b [As the pH increases from 0 to about 2.1, the enzyme activity increased.[1]] [Any point after 2.1, the enzyme activity decreased until was at a pH of about 6.8 where the enzyme was no longer active.[2]]

✓ ✗ I have identified an increase in enzyme activity using experimental data.[1]

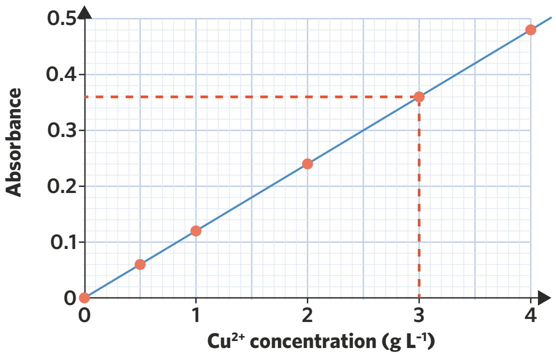
✓ ✗ I have identified a decrease in enzyme activity using experimental data.[2]

5 **a** Magnesium

b The supplement contains mostly chlorine, followed by sodium, magnesium, sulfur and calcium. The remainder of the supplement is composed of other materials.

6 **a** As the concentration of copper ions is increased (independent variable) the absorbance increases (dependent variable).

b 3 g L^{-1}



7 **a** As the concentration of H^+ ions increases with a decrease in pH, the temperature with the most H^+ ions is 200 degrees.

b As temperature is increased, the pH decreases.

c [According to the results in the experiment, it is evident that the change in temperature, the independent variable, results in a decrease in pH, the dependent variable, of the reaction.[1]] [However, we can't conclude that the change in pH was solely caused by the change in temperature. There may have been other variables involved that may have contributed to this result.[2]] [As a consequence, we are unable to conclude that temperature is the only variable that causes a change in pH and therefore the statement is inaccurate.[3]]

✓ ✗ I have identified the relationship demonstrated by the graph.[1]

✓ ✗ I have explained why the relationship identified cannot be considered as causal.[2]

✓ ✗ I have linked my answer back to the question.[3]

Multiple lessons

8 **a** 200 atmospheres

b [The yield is a measurement of how much product is made as a result of the experiment,[1]] [therefore would be considered as quantitative data.[2]]

✓ ✗ I have described the implication of the data collected.[1]

✓ ✗ I have identified the type of data collected.[2]

c As the pressure is increased the yield of *Z* increases.

9 **a** Independent variable – temperature change; Dependent variable – concentration of sulfur trioxide

b *y* axis – concentration of sulfur trioxide; *x* axis – temperature.

c [As the temperature increased the concentration of sulfur trioxide increased,[1]] [but then levelled out (i.e. there was no change in concentration).[2]]

✓ ✗ I have identified the initial trend of sulfur trioxide concentration.[1]

✓ ✗ I have identified the point of no change in concetration.[2]

1D Ensuring quality data

Theory review questions

1 D **2** B **3** B **4** A

Exam-style questions

Within lesson

5 **a** [Precision refers to how close measured values are to each other.[1]] [Based on the results, there is a large range between each of the values measured, with a total range total of 40 mg,[2]] [Due to this large difference, the measurements cannot be considered as being precise.[3]]

✓ ✗ I have defined the word precision.[1]

✓ ✗ I have referred to the range between the data measured.[2]

✓ ✗ I have linked my answer to the question.[3]

b As the values vary in an unpredictable way, this would be considered a random error.

6 **a** [Dorothy used the total mass of the beaker and water in her calculations,[1]][which reflects an experimenter mistake. Consequently, this would be considered as a personal error.[2]]

✓ ✗ I have identified the nature of the data used.[1]

✓ ✗ I have identified the type of error.[2]

b [The 330.1 g used in her calculations includes the beaker and not just the water,[1]][therefore the energy calculated would result in a value higher than the true value.[2]]

✓ ✗ I have identified the nature of the data used in Dorothy's calculations.[1]

✓ ✗ I have identified the effect on the true value.[2]

c [By concluding that 1.22 g of fuel contains 66.9 kJ, Dorothy assumed that 100% of the energy from the fuel source was used to heat the water.[1]][Some of the heat energy may have been lost into the environment during the experiment, which would not have been accounted for.[2]]

✓ ✗ I have used data to demonstrate the assumption made.[1]

✓ ✗ I have identified the concept that was overlooked in the assumption.[2]

7 **a** [A personal error occurs as a result of a mistake by the experimenter.[1]][Given that the student tore the filter paper by mistake,[2]][this can be considered as a personal error.[3]]

✓ ✗ I have defined personal errors.[1]

✓ ✗ I have identified the error made in the experiment.[2]

✓ ✗ I have linked my answer to the question.[3]

b **i** [The constant, and relatively large, decrease in mass of the three measurements taken suggests that the sample was not completely dry.[1]][To ensure that no water is left in the sample, the student needed to dry the sample to a constant mass.[2]][As a result, the student likely stopped weighing too early, and the sample may have still contained traces of water.[3]]

✓ ✗ I have used data to explain why the sample may not have been dry.[1]

✓ ✗ I have identified a characteristic that would signal when to stop measuring.[2]

✓ ✗ I have linked my answer to the question.[3]

ii 4 significant figures

c [Precision describes the closeness between replicated values.[1]] [The student could repeat the experiment multiple times to improve the precision of results.[2]]

✓ ✗ I have defined precision.[1]

✓ ✗ I have described ways in which precision can be improved.[2]

d [The scales used to measure the filtered sample may not have been calibrated correctly,[1]][therefore the value measured would be consistently over/under the true value.[2]][As a result, the amount of sulfate calculated using these results would be inaccurate.[3]]

✓ ✗ I have identified a systematic error relevant to the experiment.[1]

✓ ✗ I have described the effect of this error on the values measured.[2]

✓ ✗ I have identified the effect of this error on the accuracy of the results.[3]

Multiple lessons

8 **a** Qualitative data

b [As the data collected in the experiment is based on colour change, this can be quite subjective[1]][and therefore each experimenters judgement of colour can differ.[2]][As a result, the measurements taken in repeated experiments conducted by different experimenters may differ and therefore affect the reliability of results.[3]]

✓ ✗ I have identified the subjectivity of the data collected.[1]

✓ ✗ I have identified how the data collected can vary.[2]

✓ ✗ I have linked my answer to the question.[3]

9 **a** [Precision indicates the closeness of repeated measurements.[1]][As the values measured in stream 2 are the closest, these would be the most precise.[2]]

✓ ✗ I have defined precision.[1]

✓ ✗ I have identified the most precise stream by linking my answer to the results obtained.[2]

b 2,3,1

c [A systematic error is an error in measurement that is constant.[1]] [Therefore, the constant error of 0.002 units would be considered as a systematic error.[2]]

✓ ✗ I have defined systematic errors.[1]

✓ ✗ I have identified the type of error.[2]

1E Presenting your findings

Theory review questions

1 D **2** A **3** C

Exam-style questions

Within lesson

4 D

5 **a** The boiling point of molecules increases as the size of the molecule increases.

b [The results suggest that larger molecules have higher boiling points.[1]][This is supported by the theory, due to the fact that larger molecules exhibit stronger dispersion forces, resulting in more energy required to break the bonds during a phase change,[2]] [leading to an increase in boiling point.[3]]

✓ ✗ I have identified the key findings from the results.[1]

✓ ✗ I have used the given theory to explain the key idea.[2]

✓ ✗ I have linked my answer to the question.[3]

6 **a** [The main reason for the decrease in the rate of browning as a result of the experiment is due to the disruptions in the bonding structure of PPO[1]][as a result of pH levels, particularly due to acidic conditions (due to the use of HCl).[2]]

✓ ✗ I have identified the disruption of enzyme structure as a reason.[1]

✓ ✗ I have related the change in enzyme structure to the conditions of the experiment.[2]

b [Accuracy describes how closely the measured value is to the true value[1]][and precision describes how closely together the measured values are from each other within the same experiment.[2]][Both of these concepts do not require whole experiments being repeated but rather changes in the experimental method itself.[3]][In contrast, repeatability describes the closeness of results obtained from experiments conducted under the same conditions,[4]][and therefore relies on repeating the experiment multiple times.[5]]

✓ ✗ I have defined accuracy.[1]

✓ ✗ I have defined precision.[2]

✓ ✗ I have identified the requirements of increasing accuracy and precision.[3]

✓ ✗ I have defined repeatability.[4]

✓ ✗ I have linked my answer to the question.[5]

Multiple lessons

7 **a** [Based on the experimental results, where the total mass of the system remains at 184.34g before and after the experiment, it can be seen that there is no loss in mass as a result of a chemical reaction in a closed system.[1]][Therefore, it can be deduced that, based on the law of conservation of mass, no mass is created nor destroyed as a result of an experiment in a closed system.[2]]

✓ ✗ I have used experimental data in my explanation.[1]

✓ ✗ I have described the law of conservation of mass.[2]

b **i** [Due to the absence of the stopper,[1]][there was a decrease in mass as a result of the chemical reaction.[2]][This suggests that the law of conservation of mass developed in part a occurs only in a closed system.[3]]

✓ ✗ I have identified the key difference between both experiments.[1]

✓ ✗ I have identified the effect of the change on the experimental result.[2]

✓ ✗ I have described the implication of this difference on the law of conservation of mass.[3]

ii [Given that the law states that no mass is created or destroyed, it's possible that the difference in mass seen in experiment 2 was due to the escape of gas into the atmosphere.[1]][If the gas was collected and measured, the total mass of gas lost would equate to the difference measured in experiments 1 & 2.[2]][Therefore, the conclusion made in question b.i, stating that the law only occurs in closed systems, may not be accurate.[3]]

✓ ✗ I have described the implication of the law on the results seen in experiment 2.[1]

✓ ✗ I have linked the results measured and its relationship to the law.[2]

✓ ✗ I have identified the relationship between the conclusion of question b.i and the law.[3]

iii Quantitative data

c [Based on the law of conservation of mass, there would be no change in mass[1]][as a result of a reaction between hydrochloric acid and sodium bicarbonate.[2]]

✓ ✗ I have used the law of conservation of mass to justify my answer.[1]

✓ ✗ I have linked my answer to the question.[2]

8 **a** 44 °C

c IV – temperature (°C), DV – solubility (mg L^{-1})

d [Based on the experimental results, it is evident that an increase in temperature results in a decrease in solubility.[1]][As a result, the data refutes the hypothesis made.[2]]

✓ ✗ I have identified the key finding based on the experimental results.[1]

✓ ✗ I have linked my answer to the question.[2]

d [As the divers dive deeper into the sea, the temperature decreases.[1]] [Based on the experimental results, oxygen is more soluble at lower temperatures.[2]][As a result, this would be more beneficial for the divers as more oxygen would be soluble in the blood to be distributed to the body's tissues.[3]]

✓ ✗ I have identified the temperature change with respect to changes in depth.[1]

✓ ✗ I have described the implications on oxygen solubility using experimental data.[2]

✓ ✗ I have identified an implication for deep sea divers.[3]

Chapter 1 review

Multiple choice

1	D	**2**	D	**3**	C	**4**	C	**5**	A
6	C	**7**	A	**8**	C	**9**	B	**10**	C

Short answer

11 **a** The concentration of HCl

b Instead of using HCl, water would be used instead

c Wear gloves and a lab coat

d Systematic error

12 **a** To determine the difference in energy of butan-1-ol and propan-1-ol

b That butan-1-ol contains more energy per gram than propan-1-ol

c **i** Random error

ii Take more readings

13 **a** Mass of barium sulfate

b **i** [If water was still remaining when the barium sulfate sample (and filter paper) was weighed, this would mean that the mass measured would be greater than the true value.[1]][As a result, the mass of sulfur dioxide calculated would be higher than expected.[2]]

✓ ✗ I have identified the effect of water on the mass of barium sulfate measured.[1]

✓ ✗ I have identified the effect of a higher than expected mass of barium sulfate on the amount of sulfur dioxide calculated.[2]

ii [Precision describes how close two or more measured values are to each other, and a scale which is more sensitive would enable experimenters to assess the precision of their results, however would not reduce the range of the results.[1]][Accuracy refers to the distance of the results from the actual value, and smaller increments on the scales reduce this distance.[2]][Therefore, the new scales improve the accuracy of results but not necessarily their precision.[3]]

✓ ✗ I have explained the effect on precision.[1]

✓ ✗ I have explained the effect on accuracy.[2]

✓ ✗ I have stated how the scales have affected the precision and accuracy.[3]

14 **a** Temperature, concentration of $HCl_{(aq)}$, volume of $HCl_{(aq)}$, mass of $CaCO_3$

b $CaCO_{3(s)} + 2HCl_{(aq)} \rightarrow CO_{2(g)} + CaCl_{2(aq)} + H_2O_{(l)}$

c **i** The mass of the beaker before and after the experiment

ii [To measure how quickly a reaction is proceeding, we can measure how quickly products are being formed.[1]][Of the products formed, the carbon dioxide produced would leave the beaker into the air and as a result, the mass of the beaker and its contents would decrease.[2]][Measured over the one minute, this will indicate the rate of the reaction.[3]]

✓ ✗ I have identified a way in which the rate of a reaction can be measured.[1]

✓ ✗ I have described how the loss of carbon dioxide would affect the experiment.[2]

✓ ✗ I have linked my answer back to the question.[3]

2A Fossil fuels

Theory review questions

1 B **2** C **3** A **4** B

Exam-style questions

Within lesson

5 C

6 **a** [Peat is found much closer to the surface than black coal, therefore has a lower carbon content and higher water content compared to black coal.[1]][As a result, black coal would have a higher energy content than peat.[2]]

✓ ✗ I have compared the composition of peat and black coal.[1]

✓ ✗ I have linked my answer to the results in the question.[2]

b The main use of coal is to produce electricity.

7 **a** Crude oil/petroleum

b [Aside from producing carbon dioxide when burned, petrodiesel that is contaminated with sulfur and nitrogen can result in the formation of sulfuric acid and nitric oxide.[1]][All of these compounds have negative impacts on the environment due to effects such as acid rain.[2]]

✓ ✗ I have identified the potential products formed as a result of the burning of petrodiesel.[1]

✓ ✗ I have linked my answer to the question.[2]

8 [Methane is a non-renewable energy source when it is obtained from coal,[1]][as non-renewable resources are those that cannot be readily replenished as quickly as they are being consumed.[2]][Methane from coal deposits has formed over a long period of time so once natural gas supplies are used up, they are not readily replenished as they take millions of years to form.[3]][So, methane produced via coal is considered a non-renewable energy source.[4]]

✓ ✗ I have identified in which situation methane is a non-renewable resource.[1]

✓ ✗ I have stated what a non-renewable resource is.[2]

✓ ✗ I have explained why this option is non-renewable.[3]

✓ ✗ I have linked my answer to the question.[4]

9 **a** [Coal is a fossil fuel [1]][because deposits are formed from organic matter decaying in sediments that are turned into coal over millions of years.[2]][Natural gas is also a fossil fuel,[3]][as it is extracted from fractures in the Earth's surface that release this gas from deposits formed in the same way as coal.[4]]

✓ ✗ I have identified coal as a fossil fuel.[1]

✓ ✗ I have explained why coal is a fossil fuel.[2]

✓ ✗ I have identified natural gas as a fossil fuel.[3]

✓ ✗ I have explained why natural gas is a fossil fuel.[4]

b [Fossil fuels have been formed from the remains of living organisms.[1]][Therefore, ethanol produced from coal is a fossil fuel as coal has been formed from the remains of plants over millions of years.[2]][As a result, ethanol produced from this method cannot be considered as renewable as it will not be able to be replenished as quickly as it is being consumed.[3]]

✓ ✗ I have stated what a fossil fuel is.[1]

✓ ✗ I have linked the production of ethanol and the formation of fossil fuels.[2]

✓ ✗ I have linked my answer to the question.[3]

10 **a** [Wood is a product of a recently living organism and grows relatively quickly,[1]][whilst fossil fuels are formed from the decomposition of plant and animal material over millions of years.[2]][Based on the rate at which wood can be generated, wood would not be considered as a fossil fuel.[3]]

✓ ✗ I have identified how wood is produced.[1]

✓ ✗ I have identified how fossil fuels are produced.[2]

✓ ✗ I have linked my answer to the question.[3]

b Wood is not a sustainable energy source as it is burned quicker than the trees can grow.

Multiple lessons

11 [Hydrogen formed through methane, a fossil fuel, produces carbon dioxide, a greenhouse gas. As a result, there is an increase in the amount of greenhouse gas emissions contributing to climate change.[1]][Electrolysis of water powered by solar energy, a renewable source, only uses water to produce hydrogen fuel. Hence, neither the electrolytic process nor the energy powering it has a negative impact on the environment.[2]][Oxygen is the by-product of this reaction and it is beneficial for life on Earth,[3]][therefore electrolysis of water does not have much of an impact on the environment.[4]]

✓ ✗ I have explained the effect of methane on the environment.[1]

✓ ✗ I have explained the effect of water and solar energy on the environment.[2]

✓ ✗ I have explained the effect of oxygen on the environment.[3]

✓ ✗ I have stated the impact of electrolysis of water on the environment.[4]

2B Biofuels

Theory review questions

1 D **2** B **3** C **4** B

Exam-style questions

Within lesson

5 C **6** C

7 **a** [Yes.[1]][The sunflower crops used to produce the fuel can be replenished at a rate faster than they are consumed. [2]]

✓ ✗ I have identified biodiesel as a renewable energy source.[1]

✓ ✗ I have explained why with reference to the origin of the fuel.[2]

b A large amount of water is required to cultivate the sunflower crops.

c Transesterification reaction

d Glycerol

Multiple lessons

8 **a** X = (Bio)ethanol and Y = carbon dioxide

b Bioethanol is considered a renewable fuel because it is derived from crops that can be replenished at a rate faster than or equal to the rate at which they are consumed.

c Carbon dioxide acts as a greenhouse gas which contributes to climate change.

d [Yes.[1]][Potatoes can be grown and cultivated in a relatively short period of time and at a rate faster than or equal to the rate at which the bioethanol is consumed.[2]]

✓ ✗ I have identified bioethanol from potatoes as renewable.[1]

✓ ✗ I have explained why the origin of this bioethanol is regarded as renewable.[2]

9 **a** Biodiesel

b [Coal is derived from the fossilisation of organic matter over the course of millions of years, and so is not easily replenished by natural sources, making it non-renewable.[1]][Biodiesel is quickly produced by canola crops and so can be replenished by natural processes at a rate faster than it is consumed which means it is considered renewable.[2]]

✓ ✗ I have explained how coal is a fossil fuel, and therefore non-renewable.[1]

✓ ✗ I have explained how biodiesel is a biofuel and therefore renewable.[2]

2C Comparison of fuels

Theory review questions

1 D **2** B **3** C

Exam-style questions

Within lesson

4 A **5** C **6** C

7 **a** [Biodiesel has a higher viscosity than petrodiesel[1]][meaning that it is harder for biodiesel to flow than petrodiesel under the same conditions.[2]]

✓ ✗ I have compared the viscosity of biodiesel and petrodiesel.[1]

✓ ✗ I have used the difference in the viscosity of the two types of diesel to compare their ability to flow.[2]

b [The combustion of biodiesel produces a lower net amount of carbon dioxide than petrodiesel due to the partial carbon dioxide offset resulting from the production of biodiesel crops,[1]][meaning that biodiesel has less negative impacts on the environment than petrodiesel.[2]]

✓ ✗ I have compared the amount of carbon dioxide produced by biodiesel and petrodiesel.[1]

✓ ✗ I have used the difference in the amount of carbon dioxide produced by the two types of diesel to compare their environmental impacts.[2]

8 **a** [Biofuels are renewable, whereas fossil fuels are not.[1]][This is because organic matter used to produce biofuels can be grown faster than or equal to the rate at which it is consumed, while fossil fuels are formed from the decomposition of plant and animal matter over a very long period of time.[2]]

✓ ✗ I have compared the renewability of the fuels.[1]

✓ ✗ I have explained my answer based on the time required to produce the fuels.[2]

b [Biofuels and fossil fuels both have advantages and disadvantages with respect to their environmental impact from sourcing and combustion.[1]][The sourcing of fossil fuels can lead to land degradation and water pollution,[2]][whereas the production of biofuels requires intensive farming practices which can use up water supplies, erode the land and take up land once available for food production.[3]][With respect to combustion, petrodiesel releases more particulate matter and has a higher net greenhouse gas emission than biodiesel.[4]][Even though biodiesel still releases carbon dioxide when undergoing combustion, this is partially offset by the production of plant matter which absorbs carbon dioxide from the atmosphere via the process of photosynthesis.[5]]

✓ ✗ I have stated that both fossil fuels and biofuels have environmental impacts.[1]

✓ ✗ I have explained the environmental impacts resulting from the sourcing of fossil fuels.[2]

✓ ✗ I have explained the environmental impacts resulting from the sourcing of biofuels.[3]

✓ ✗ I have explained the environmental impacts resulting from the combustion of fossil fuels.[4]

✓ ✗ I have explained the environmental impacts resulting from the combustion of biofuels.[5]

Multiple lessons

9 [The diesel in cylinder A moved a shorter distance than the diesel in cylinder B.[1]][This indicates that the diesel in cylinder A is more viscous than the diesel in cylinder B.[2]][Biodiesel molecules are held tightly by permanent dipole-dipole bonds due to the presence of polar COO groups whereas non-polar petrodiesel molecules are held loosely by dispersion forces, leading to its lower viscosity.[3]][Therefore, cylinder A contains biodiesel and cylinder B contains petrodiesel.[4]]

✓ ✗ I have compared the distance travelled by each type of diesel.^{1}

✓ ✗ I have linked the distance travelled to the viscosity of each type of diesel.^{2}

✓ ✗ I have used the intermolecular forces present in each diesel to explain the difference in viscosity.^{3}

✓ ✗ I have determined the diesel contained in each cylinder.^{4}

10 **a** Petrodiesel

b [Petrodiesel is less hygroscopic than biodiesel so it can be stored for a longer period of time without losing its quality due to water being absorbed into the fuel supply.^{1}][This is because the polar COO groups present in biodiesel can form hydrogen bonds with water, making it absorb water more easily.^{2}][Petrodiesel has a lower viscosity than biodiesel, meaning that it can flow more readily in cold weather.^{3}][This is because the polar ester COO groups allow biodiesel molecules to be held tightly by permanent dipole-dipole bonds.^{4}]

✓ ✗ I have compared the hygroscopicity between the two types of diesel.^{1}

✓ ✗ I have explained the difference in hygroscopicity.^{2}

✓ ✗ I have compared the viscosity between the two types of diesel.^{3}

✓ ✗ I have explained the difference in viscosity.^{4}

Chapter 2 review

Multiple choice

1	B	**2**	A	**3**	B	**4**	D	**5**	C
6	D	**7**	C	**8**	C	**9**	A	**10**	A

Short answer

11 **a** [For a fuel to be considered renewable it must be easily replenished by natural processes as fast or more rapidly than it is consumed.^{1}] [Ethanol sourced from coal is not easily replenishable as fossilisation of organic matter occurs over millions of years, however ethanol sourced from sweet potato crops can be replenished at a rate equal to or faster than its consumption.^{2}]

✓ ✗ I have defined a renewable fuel source.^{1}

✓ ✗ I have used my definition to describe why ethanol can be both renewable and non-renewable depending on its source.^{2}

b $C_6H_{12}O_{6(aq)} \rightarrow 2C_2H_5OH_{(l)} + 2CO_{2(g)}$

c [The production of sweet potato crops would absorb carbon dioxide to offset the amount released when combusted,^{1}][whereas ethanol sourced from coal deposits would not.^{2}]

✓ ✗ I have identified carbon offsetting as an advantage of farming sweet potatoes.^{1}

✓ ✗ I have compared this to coal deposit sourcing.^{2}

d The clearing of land to produce sweet potato crops may damage animal habitats.

12 **a** [A renewable fuel is easily replenished by natural processes within a relatively short period of time.^{1}][The petrodiesel product is obtained from underground coal deposits formed over millions of years, and so it is not considered renewable.^{2}]

✓ ✗ I have defined a renewable fuel.^{1}

✓ ✗ I have used this definition to explain why petrodiesel is not renewable.^{2}

b [Petrodiesel is a long non-polar hydrocarbon chain, with no functional groups.^{1}][Therefore, the intermolecular bonds between petrodiesel molecules are only dispersion forces.^{2}]

✓ ✗ I have identified the structure of petrodiesel.^{1}

✓ ✗ I have used the structure to identify the intermolecular force that is present.^{2}

c [Biodiesel contains a polar ester linkage, which allows it to form permanent dipole-dipole intermolecular bonds.^{1}][These polar bonds are significantly stronger than the dispersion forces present in petrodiesel.^{2}][As a result, more energy will be required to break the bonds, leading to a higher boiling point for the mixture.^{3}]

✓ ✗ I have identified the primary intermolecular bond present in biodiesel.^{1}

✓ ✗ I have related the strength of these bonds to those of petrodiesel.^{2}

✓ ✗ I have explained how this difference will affect the mixture's boiling point.^{3}

d Combustion of petrodiesel releases the greenhouse gas carbon dioxide into the atmosphere, which contributes to global warming.

13 **a** [A renewable energy source is one replenished by natural processes as fast or more rapidly than it is consumed.^{1}][Natural gas is obtained from coal deposits which are formed over millions of years and are rapidly depleted, making it non-renewable.^{2}]

✓ ✗ I have defined a renewable fuel.^{1}

✓ ✗ I have used this definition to explain why electricity sourced from natural gas is not renewable.^{2}

b [The decreased temperature of the environment decreases the average kinetic energy of the fuel and decreases bond length between atoms and between molecules of biodiesel, resulting in an increase in density.^{1}][As a result, there is an increase in the viscosity of the biodiesel.^{2}]

✓ ✗ I have described the effect of a decrease in temperature on the bonding of biodiesel.^{1}

✓ ✗ I have stated how this change in temperature will affect the biodiesel's viscosity.^{2}

c $m(CO_2)$ per 75 km $= \frac{m(CO_2)}{L} \times \frac{L}{100\text{ km}} \times 0.75$

Car 1 = 1750 × 21.3 × 0.75 = 27 956 g

Car 2 = 2479 × 17.6 × 0.75 = 32 723 g

Car 3 = 2453 × 17.3 × 0.75 = 31 828 g

Car 4 = 2871 × 11.4 × 0.75 = 24 547 g

Therefore car 4 has the lowest amount of carbon dioxide released per 75 km.

d [Bioethanol is primarily produced from the fermentation of glucose sourced from crops.^{1}][These crops absorb carbon dioxide during growth, so when combusted the net release of carbon dioxide into the atmosphere is minimal.^{2}][Petrodiesel is sourced from both plant and animal matter and so has a smaller amount of carbon offsetting, leading to a significantly higher net amount of carbon dioxide released into the atmosphere compared to bioethanol.^{3}]

✓ ✗ I have stated the origin of bioethanol.^{1}

✓ ✗ I have used the origin to explain the net carbon dioxide impact of bioethanol.^{2}

✓ ✗ I have compared the net environmental impact of bioethanol and petrodiesel.^{3}

14 a i [Petrodiesel is a hydrocarbon with no functional groups, and so can only form weak dispersion forces.^{1}][Biodiesel contains a polar ester group and so can form much stronger intermolecular dipole-dipole bonds.^{2}][Because petrodiesel has weaker intermolecular forces, it is held less tightly together and so has a lower viscosity than biodiesel.^{3}]

✓ ✗ I have identified the structure and intermolecular forces of petrodiesel.^{1}

✓ ✗ I have identified the structure and intermolecular forces of biodiesel.^{2}

✓ ✗ I have related these properties to the viscosity and determined which fuel has a lower viscosity.^{3}

ii Lower viscosity allows easier flow through fuel lines.

b i [Petrodiesel consists of non-polar hydrocarbons with no functional groups, meaning they are non-polar molecules.^{1}] [Biodiesel molecules contain a polar ester group and so are comparatively more polar molecules.^{2}][As water is also a polar molecule, biodiesel will attract water more, making petrodiesel less hygroscopic.^{3}]

✓ ✗ I have described the structure of petrodiesel.^{1}

✓ ✗ I have described the structure of biodiesel.^{2}

✓ ✗ I have used the differences in structure to explain why petrodiesel is less hygroscopic than biodiesel.^{3}

ii [Hygroscopic fuels attract water, and so can cause rust,^{1}][make the combustion reaction less efficient and foster the growth of microorganisms in fuel lines.^{2}]

✓ ✗ I have identified a property of hygroscopic fuels.^{1}

✓ ✗ I have identified an inefficiency of hygroscopic fuels.^{2}

Key science skill question

15 a Independent variable: type of fuel.

Dependent variable: boiling point.

b [While the hydrogen bonds of ethanol are significantly stronger than dispersion forces,^{1}][petrodiesel molecules have hydrocarbon chains that are long enough to generate an overall intermolecular dispersion force that is actually greater than these hydrogen bonds.^{2}]

✓ ✗ I have made a reference to the different intermolecular forces present in ethanol and petrodiesel.^{1}

✓ ✗ I have suggested a reason for the differences in each fuel's boiling point.^{2}

c [To improve the precision of the results, the engineer could repeat the experiment multiple times under the same experimental conditions.^{1}][He could then take the average of all the results obtained in order to reduce the effects of any random errors.^{2}]

✓ ✗ I have identified how the engineer could improve the accuracy of his results.^{1}

✓ ✗ I have described why this method will improve the accuracy of the results.^{2}

3A Combustion reactions

Theory review questions

1 B **2** C **3** C

Exam-style questions

Within lesson

4 C

5 **a** X – 12, Y – 8, Z – 9

b $\Delta H = H_p - H_r$

6 **a** [Equation 1 is not a combustion reaction because a fuel is not being combusted in the presence of oxygen.^{1}][Equation 2 is a combustion reaction because butane, C_4H_{10}, is a fuel and is being combusted in the presence of oxygen.^{2}]

✓ ✗ I have identified equation 1 as not a combustion reaction.^{1}

✓ ✗ I have identified equation 2 as a combustion reaction.^{2}

b The enthalpy change of this reaction will have a negative sign because all combustion reactions are exothermic.

7 **a** [The ΔH of the reaction is stated as being positive, indicating that this reaction is endothermic.^{1}][However, all combustion reactions are exothermic,^{2}][therefore the value of the ΔH should be negative instead of positive.^{3}]

✓ ✗ I have identified the ΔH of the reaction given.^{1}

✓ ✗ I have described the nature of combustion reactions with respect to the energy change.^{2}

✓ ✗ I have identified the appropriate sign of the ΔH based on the reaction.^{3}

b [The presence of soot suggests that this reaction is an incomplete combustion reaction.^{1}][As a result, soot (and carbon monoxide) is produced instead of carbon dioxide.^{2}]

✓ ✗ I have identified the implication of soot.^{1}

✓ ✗ I have described the effect of this observation on the overall reaction.^{2}

8 **a** $2C_4H_{10(l)} + 13O_{2(g)} \rightarrow 8CO_{2(g)} + 10H_2O_{(g)}$

b [Due to the lack of carbon dioxide produced in this reaction, this would indicate that incomplete combustion has occurred to produce carbon monoxide and water.^{1}][As a result, it is possible to deduce that there was a limited supply of oxygen present in the surrounding environment.^{2}]

✓ ✗ I have identified the type of combustion reaction that occurred.^{1}

✓ ✗ I have linked this fact to the limited supply of oxygen in the external environment.^{2}

c [The conversion of liquid water to steam is an endothermic reaction^{1}][as energy is absorbed by the water molecules in order to break the intermolecular forces that keep water molecules as a liquid, rather than a gas.^{2}]

✓ ✗ I have identified whether it is an endothermic or exothermic process.^{1}

✓ ✗ I have justified my answer by referring to the process involved in state changes.^{2}

Multiple lessons

9 **a** $2C_{17}H_{34}O_{2\,(l)} + 49O_{2\,(g)} \rightarrow 34CO_{2\,(g)} + 34H_2O_{(g)}$

b [The temperature of the water will increase. ^{1}][This is because all combustion reactions are exothermic and release energy to the surrounding environment, causing the temperature of the water to increase.^{2}]

✓ ✗ I have identified the effect of the temperature on the water.^{1}

✓ ✗ I have explained why the temperature of the water will increase.^{2}

c [The production of carbon monoxide indicates that incomplete combustion has occurred.^{1}][This means that the fuel only has access to a limited supply of oxygen.^{2}]

✓ ✗ I have identified that incomplete combustion has occurred.^{1}

✓ ✗ I have linked the occurrence of the incomplete combustion to the availability of oxygen.^{2}

c In order to ensure a supply of oxygen in excess, she could pump oxygen near the burning fuel.

d [Biodiesel is a renewable source of energy.^{1}][This is because it can be replenished by natural processes at a rate equal to or faster than the rate at which it is consumed.^{2}]

✓ ✗ I have stated whether it is a renewable source of energy.^{1}

✓ ✗ I have stated the definition of a renewable source of energy.^{2}

3B Energy changes during combustion

Theory review questions

1 A **2** B **3** D **4** D

Exam-style questions

Within lesson

5 C **6** A

7 $E = n \times \Delta H_c = 0.65 \times 1360 = 884 \text{ kJ} = 8.8 \times 10^2 \text{ kJ}$

8 $\Delta H = H(\text{products}) - H(\text{reactants}) = 70 - 150 = -80 \text{ kJ mol}^{-1}$

9 $n(\text{Mg}) = \frac{6.7}{24.3} = 0.2757 \text{ mol}$

$E = 0.2757 \times \left(\frac{1200}{2}\right) = 165.42 \text{ kJ} = 1.7 \times 10^2 \text{ kJ}$

10 $n(C_6H_{12}O_6) = \frac{65}{180} = 0.361 \text{ mol}$

Energy released per mol $= \frac{1.126 \times 10^3}{0.361} = 3.2 \times 10^3 \text{ kJ mol}^{-1}$

$\Delta H = 3.2 \times 10^3 \text{ kJ mol}^{-1}$

11 There are two moles of methanol in the given reaction, therefore the molar heat of combustion is half the given enthalpy change.

$\Delta H = \frac{-1452}{2} = -726 \text{ kJ mol}^{-1}$

Heat of combustion = 726 kJ mol^{-1}

12 $m = 200 \times 0.997 = 199.4$ g

$\Delta T = 22$ °C

$c = 4.18\ \text{J g}^{-1}\,°\text{C}^{-1}$

$q = m \times c \times \Delta T = 199.4 \times 4.18 \times 22 = 18337\ \text{J} = 18\ \text{kJ}$

13 **I** activation energy of the forward reaction

II energy released, enthalpy of the reaction

III activation energy for the reverse reaction

Multiple lessons

14 **a** $2C_4H_{10(g)} + 13O_{2(g)} \rightarrow 8CO_{2(g)} + 10H_2O_{(g)}\ \Delta H = -5760\ \text{kJ mol}^{-1}$

b $m(\text{water}) = 100 \times 0.997 = 99.7$ g

$\Delta T = 28 - 15 = 13$ °C

Energy $= 99.7 \times 4.18 \times 13 = 5418\ \text{J} = 5.4\ \text{kJ}$

c % energy loss $= \dfrac{(-2880 - (-1500))}{-2880} \times 100 = 48\%$

15 **a** $C_6H_{12}O_{6\,(l)} + 6O_{2\,(g)} \rightarrow 6CO_{2\,(g)} + 6H_2O_{(g)}\ \ \Delta H = -2816\ \text{kJ mol}^{-1}$

b Energy released per mole = 2816 kJ

$M(\text{glucose}) = 180.0\ \text{g mol}^{-1}$

Energy released per gram $= \dfrac{2816}{180.0} = 15.64\ \text{kJ g}^{-1}$

c Energy(bar) $= 25.0 \times 15.64 = 391$ kJ

Km travelled $= \dfrac{\text{total kJ}}{75} = \dfrac{390}{75} = 5.2$ km

3C Gases

Theory review questions

1 A **2** C **3** B **4** B

Exam-style questions

Within lesson

5 A **6** C

7 **a** Volume = 250 mL = 0.250 L

Temperature = 65 °C = (65 + 273) K = 338 K

Number of moles $= \dfrac{4.6}{28} = 0.16$ mol

$PV = nRT$

$P = \dfrac{nRT}{V} = \dfrac{0.16 \times 8.31 \times 338}{0.250} = 1.8 \times 10^3$ kPa

b $= 1846 \times \dfrac{0.987}{100} = 18$ atm

8 **a** $= \dfrac{12 \times 100}{750} = 1.6$ kPa

$= 1.6 \times 1000 = 1600$ Pa

b Pressure $= 1.6 \times 10^3$Pa = 1.6 kPa

Volume = 10 L

Temperature = 32 °C = (32 + 273) K = 305 K

$PV = nRT$

$n = \dfrac{PV}{RT}$

$n = \dfrac{1.6 \times 10}{8.31 \times 305} = 6.3 \times 10^{-3}$ mol

c [When under the same conditions, all gases (assumed ideal) in a set volume contain the same number of moles.[1]] [Therefore, we cannot determine the identity of the gas without further analysis.[2]]

✓ ✗ I have explained the universal nature of gases.[1]

✓ ✗ I have identified that more information is required.[2]

d $m(CO_2) = n(CO_2) \times M(CO_2)$

$M(CO_2) = 44.0\ \text{g mol}^{-1}$

$m(CO_2) = 6.31 \times 10^{-3} \times 44.0$

= 0.28 grams

9 Volume = 50 L

Temperature = 25 °C = (25 + 273) K = 298 K

Number of moles $= \dfrac{m(N_2O)}{M(N_2O)} = \dfrac{2.0}{44.0} = 4.55 \times 10^{-2}$ mol

$PV = nRT$

$P = \dfrac{nRT}{V} = \dfrac{4.55 \times 10^{-2} \times 8.31 \times 298}{50} = 2.3$ kPa

10 **a** $n\,(CO_2) = \dfrac{5.0}{44} = 0.11$ mol

$V = n \times V_m = 0.11 \times 24.8 = 2.8$ L

$n(SO_2) = \dfrac{5.0}{64} = 0.078$ mol

$V = n \times V_m = 0.078 \times 24.8 = 1.9$ L

$n(N_2) = \dfrac{5.0}{28} = 0.18$ mol

$V = n \times V_m = 0.18 \times 24.8 = 4.4$ L

Therefore the gases all occupy different volumes.

b [The universal gas law is $PV = nRT$. Rearranging for pressure, $P = \dfrac{nRT}{V}$.[1]] [We can see that as temperature increases, so too does the pressure, indicating that a temperature increase to 40°C would increase the pressure.[2]]

✓ ✗ I have given the relevant form of the universal gas law.[1]

✓ ✗ I have explained how this demonstrates the relationship between temperature and pressure.[2]

Multiple lessons

11 **a** $C_3H_{8\,(g)} + 5O_{2(g)} \rightarrow 3CO_{2\,(g)} + 4H_2O_{(g)}\quad \Delta H = -\,2220\ \text{kJ mol}^{-1}$

b Pressure = 1 atm = 101.3 kPa

Volume = 0.100 L

Temperature = 25 °C = (25 + 273) K = 298 K

$PV = nRT$

$n = \dfrac{PV}{RT}$

$n(C_3H_8) = \dfrac{101.3 \times 0.100}{8.31 \times 298} = 4.09 \times 10^{-3}$ mol

$3 \times n(C_3H_8) = n(CO_2)$

$n(CO_2) = 1.23 \times 10^{-2}$ mol

$V = \dfrac{nRT}{P} = \dfrac{1.23 \times 10^{-2} \times 8.31 \times (48 + 273)}{101.3} = 0.3$ L

c $n(CO_2) = 1.23 \times 10^{-2}$ mol

$m(CO_2) = 1.23 \times 10^{-2} \times 44 = 0.54$ grams

d Energy $= \Delta H \times n(C_3H_8) = 2220 \times 4.09 \times 10^{-3} = 9.08$ kJ

e Carbon dioxide acts as a greenhouse gas, and so contributes to climate change.

3D Calculating energy changes from combustion reactions

Theory review questions

1 B **2** D

Exam-style questions

Within lesson

3 D **4** C

5 $2 \times (\frac{1}{2}N_{2(g)} + O_{2(g)} \rightarrow NO_{2(g)}) = N_{2(g)} + 2O_{2(g)} \rightarrow 2NO_{2(g)}$
$\Delta H = +60 \text{ kJ mol}^{-1}$

$-1 \times (N_{2(g)} + 2O_{2(g)} \rightarrow N_2O_{4(g)}) = N_2O_{4(g)} \rightarrow N_{2(g)} + 2O_{2(g)}$
$\Delta H = -10 \text{ kJ mol}^{-1}$

$N_2O_{4(g)} \rightarrow 2NO_{2(g)}$ $\Delta H = +50 \text{ kJ mol}^{-1}$

6 **a** $n(C_8H_{18}) = \frac{3.65}{8 \times 12 + 18 \times 1} = 0.032 \text{ mol}$

$n(CO_2) = \frac{16}{2} \times n(C_8H_{18}) = 8 \times 0.032 = 0.256 \text{ mol}$

$V(CO_2) = n \times V_m = 0.256 \times 24.8 = 6.35 \text{ L}$

b $n(O_2) = \frac{9.05 \times 10^4}{2 \times 16} = 2828.1 \text{ mol}$

$n(H_2O) = \frac{18}{25} \times n(O_2) = \frac{18}{25} \times 2828.1 = 2036 \text{ mol}$

$m(H_2O) = n \times M = 2036 \times 18.0 = 3.67 \times 10^4 \text{ g}$

c $V(O_2) = \frac{25}{16} \times V(CO_2) = \frac{25}{16} \times 12.0$

$= 18.8 \text{ L}$

7 **a** **i** $n(C_3H_8) = \frac{2.3}{3 \times 12 + 8 \times 1} = 0.0523 \text{ mol}$

$n(CO_2) = \frac{3}{1} \times n(C_3H_8) = 3 \times 0.0523 = 0.157 \text{ mol}$

$V(CO_2) = n \times V_m = 0.157 \times 24.8 = 3.89 \text{ L}$

ii $n(CO_2) = 0.157 \text{ mol}$

$T = 76 + 273 = 349 \text{ K}$

$895 \text{ mm Hg} = \frac{895}{750} \times 100 = 119.3 \text{ kPa}$

$PV = nRT$

$119.3 \text{ x } V = 0.157 \text{ x } 8.31 \text{ x } 349$

$V = 3.81 \text{ L}$

b [Burning propane in its liquid form would produce less energy than if it were burnt in its gaseous form.[1]][This is because the phase change from liquid to gas requires a certain amount of energy to first be put into the system in order to break the intermolecular bonds, decreasing the net energy released.[2]]

✓ ✗ I have determined whether the combustion of the liquid would produce more or less energy.[1]

✓ ✗ I have justified my answer with reference to the enthalpy of the state change from liquid to gas.[2]

8 $-1 \times (N_{2(g)} + 2O_{2(g)} \rightarrow 2NO_{2(g)}) = 2NO_{2(g)} \rightarrow N_{2(g)} + 2O_{2(g)}$
$\Delta H = -68 \text{ kJ mol}^{-1}$

$N_{2(g)} + 2O_{2(g)} \rightarrow N_2O_{4(g)}$ $\Delta H = +10 \text{ kJ mol}^{-1}$

$2NO_{2(g)} \rightarrow N_2O_{4(g)}$ $\Delta H = -58 \text{ kJ mol}^{-1}$

$\frac{3}{2} \times (2NO_{2(g)} \rightarrow N_2O_{4(g)}) = 3NO_{2(g)} \rightarrow \frac{3}{2} N_2O_{4(g)}$ $\Delta H = -87 \text{ kJ mol}^{-1}$

9 $V(\text{produced}) = V(CO_2) + V(H_2O) = 37.0 \text{ L}$

V(produced) is proportional to V(consumed) as volumes react according to the molar ratio.

$(2 + 15) \rightarrow (10 + 12)$

$V(C_5H_{11}OH) = \frac{2}{10 + 12} = \frac{2}{22} \times 37.0 = 3.36 \text{ L}$

Multiple lessons

10 **a** $n(C_2H_6) = 4.56 \text{ mol}$

$n(CO_2) = \frac{4}{2} \times n(C_2H_6) = 2 \times 4.56 = 9.12 \text{ mol}$

$V = 20.0 \text{ L}$

$T = 31 + 273 = 304 \text{ K}$

$PV = nRT$

$P \times 20.0 = 9.12 \times 8.31 \times 304$

$P = 1152 \text{ kPa}$

$P = 1.15 \times 10^3 \text{ kPa}$ (3 sig. fig.)

b $n(C_2H_6) = \frac{3.60}{2 \times 12 + 6 \times 1} = 0.12 \text{ mol}$

Energy released = $0.12 \times 1560 = 187.2 \text{ kJ} = 1.872 \times 10^5 \text{ J}$

$q = mc\Delta T$

Energy absorbed = $q = 750 \times 0.997 \times 4.18 \times (47 - 13) = 1.063 \times 10^5 \text{ J}$

Percentage heat absorbed = $\frac{1.063 \times 10^5}{1.872 \times 10^5} \times 100 = 56.8\ \%$

Percentage heat lost = $100 - 56.8 = 43.2\ \%$

c $V(CO_2) = 12.0 \text{ L}$

$n(CO_2) = \frac{12.0}{24.8} = 0.4839 \text{ mol}$

From the reaction coefficients:

4 mol of CO_2: 3120 kJ

$\rightarrow 0.4839 \text{ mol}: \frac{3120}{4} \times 0.4839 = 377.4 \text{ kJ}$

$q = mc\Delta T$

$q = 3.774 \times 10^5 \text{ J}$

$m = 960 \text{ g}$

$\Delta T = 39\ °\text{C}$

$3.774 \times 10^5 = 960 \times c \times 39$

$c = 10.1 \text{ J g}^{-1} \text{ K}^{-1}$

11 B **12** D

13 **a** 1 mol of octane produces $\frac{10920}{2} = 5460 \text{ kJ}$

$1 \text{ MJ} = 1.0 \times 10^3 \text{ kJ}$

$n(C_8H_{18}) = \frac{1.0 \times 10^3}{5460} = 0.18 \text{ mol}$

1 mol of ethanol produces 1360 kJ

$n(C_2H_5OH) = \frac{1.0 \times 10^3}{1360} = 0.74 \text{ mol}$

b Octane

$n(CO_2) = \frac{16}{2} \times n(C_8H_{18}) = 8 \times 0.183 = 1.5 \text{ mol}$

$n(H_2O) = \frac{18}{2} \times n(C_8H_{18}) = 9 \times 0.183 = 1.6 \text{ mol}$

Ethanol

$n(CO_2) = \frac{2}{1} \times n(C_8H_{18}) = 2 \times 0.735 = 1.5 \text{ mol}$

$n(H_2O) = \frac{3}{1} \times n(C_8H_{18}) = 3 \times 0.735 = 2.2 \text{ mol}$

c Greenhouse gases here are CO_2 and H_2O

Octane

$V(CO_2) + V(H_2O) = n \times V_m = (1.464 + 1.647) \times 24.8 = 77 \text{ L}$

Ethanol

$V(CO_2) + V(H_2O) = n \times V_m = (1.47 + 2.205) \times 24.8 = 91 \text{ L}$

d This difference would suggest that octane is more environmentally friendly than ethanol as it produces a smaller volume of greenhouse gases (approximately 15 L less than ethanol) for every MJ of energy that it provides.

e [If the ethanol used were bioethanol, this would mean that the net greenhouse gas emissions involved in the fuel's production would be essentially zero as CO_2 and H_2O are consumed by plants through photosynthesis in its creation.[1]][This would mean that the ethanol would instead be more environmentally friendly than the octane, changing the answer given in part d.[2]]

✓ ✗ I have described the environmental impact of bioethanol.[1]

✓ ✗ I have explained how this change affects the answer given in part d.[2]

Chapter 3 review

Multiple choice

1	B	**2**	D	**3**	B	**4**	A	**5**	D
6	D	**7**	D	**8**	B	**9**	B	**10**	C

Short answer

11 $n = 5.00$ mol

$T = 26\ °C = 26 + 273 = 299$ K

$P = 520$ kPa

$V = \frac{nRT}{P}$

$= \frac{(5.00 \times 8.31 \times 299)}{520}$

$= 23.9$ L

12 a [Methane obtained from biomass is renewable.[1]][As natural gas is a fossil fuel, it is not replenished as quickly as it is consumed, making it non-renewable.[2]][Methane obtained from biomass is considered renewable, as it is replenished as quickly as it is consumed by natural processes.[3]]

✓ ✗ I have identified which option is renewable.[1]

✓ ✗ I have explained why methane produced from fossil fuels is non-renewable.[2]

✓ ✗ I have explained why methane produced from biomass is renewable.[3]

b $CH_{4(l)} + 2O_{2(g)} \rightarrow CO_{2(g)} + 2H_2O_{(g)}$

c $E = 2.0 \times 55.6$

$= 1.1 \times 10^2$ kJ

13 a $2C_3H_{8(l)} + 7O_{2(g)} \rightarrow 6CO_{(g)} + 8H_2O_{(g)}$, carbon monoxide

b Soot (solid carbon)

14 a $C_4H_9OH_{(l)} + 6O_{2(g)} \rightarrow 4CO_{2(g)} + 5H_2O_{(g)}$

b $M(C_4H_9OH) = 74\ g\ mol^{-1}$

Conversion for

T: 45 x 74 = 3330 kJ mol^{-1}

X: 35 x 74 = 2590 kJ mol^{-1}

Y: 25 x 74 = 1850 kJ mol^{-1}

Z: 15 x 74 = 1110 kJ mol^{-1}

[Fuel X is most likely butan-1-ol [1]][as its value is the closest to the published value.[2]]

✓ ✗ I have stated which fuel is most likely to be butan-1-ol.[1]

✓ ✗ I have compared the calculated values to those given in the question.[2]

✓ ✗ I have included calculations in my answer.[3]

c Heat loss

15 a Loss of carbon dioxide into the environment

b $m(CO_2) = 1375 - 1350$

$= 25$ g

$n(CO_2) = \frac{25}{44}$

$= 0.568$ mol

$V = n \times V_m$

$V = 0.568 \times 24.8$

$= 14$ L

c $14 \times 400 = n \times 8.31 \times (30 + 273)$

$n = \frac{14 \times 400}{8.31 \times 303}$

$= 2.2$ mol

16 a $q = m \times C \times \Delta T$

$= 200 \times 4.18 \times 55$

$= 45980$

$= 45.98$ kJ

Therefore, $n_{(C_2H_5OH)} = \frac{q}{\Delta H}$

$= \frac{45.98}{29.6}$

$= 1.55$ g

50% of heat has been lost to the surroundings, therefore,

Initial $m_{(C_2H_5OH)} = 2 \times 1.55$

$= 3.1$ g

b [Insulate the beaker of water[1]][and use an appropriate lid to cover the beaker of water.[2]]

✓ ✗ I have identified a way to insulate the immediate environment.[1]

✓ ✗ I have identified a way to insulate the whole experiment.[2]

c q (energy released) $= m \times$ heat of combustion of ethanol in kJ/g

$= 3.1 \times 29.6$

$= 91.96$ kJ

60% was transferred to the water, therefore

$q = 0.60 \times 91.96$

$= 5.5 \times 10^4$ J

$\Delta T = \frac{q}{(m \times C)}$

$= \frac{5.5 \times 10^4}{(200 \times 4.18)}$

$= 66\ °C$

Key science skill question

17 a If the candle flame goes out it indicates that the candle has used up all of the oxygen in the jar, showing that hydrocarbons need oxygen to undergo combustion.

b There could have been a gap under the jar which would have allowed the gas to escape, resulting in weak test results. Furthermore, carbon monoxide could have been produced instead of carbon dioxide.

c The experiment could have been replicated multiple times to ensure that the results are consistent.

✓ ✗ I have identified a factor that would contribute to increased reliability of results.[1]

✓ ✗ I have linked my answer to the question.[2]

4A Redox reactions

Theory review questions

1 C **2** B **3** A

Exam-style questions

Within lesson

4 A

5 No, because there is no change in oxidation numbers.

6 **a** [As a reactant, $Zn_{(s)}$ has an oxidation number of 0 compared to Zn in $ZnO_{2\,(s)}$ that has an oxidation number of +2.^{1}][Therefore, $Zn_{(s)}$ has lost electrons and undergone oxidation.^{2}]

✓ ✗ I have identified which element undergoes oxidation using oxidation numbers.^{1}

✓ ✗ I have supported my answer, referencing the loss of electrons.^{2}

b Oxygen gas

7 **a** + 6

b All species (H,N,S & O)

8 **a** Oxidation process: $Na_{(s)}/Na^{+}_{(aq)}$

Reduction process: $Ag^{+}_{(aq)}/Ag_{(s)}$

b $Na_{(s)}$

9 **a** +6

b $Cu^{2+}_{(aq)}$ is reduced and $Fe_{(s)}$ is oxidised.

c [As $Cu^{2+}_{(aq)}$ is being reduced, it is therefore the oxidising agent. As a result, $Cu_{(s)}$ is the conjugate reducing agent.^{1}]

[As $Fe_{(s)}$ is oxidised, it is therefore the reducing agent. As a result, $Fe^{2+}_{(aq)}$ is the conjugate oxidising agent.^{2}]

✓ ✗ I have identified the oxidising agent and its conjugate reducing agent.^{1}

✓ ✗ I have identified the reducing agent and its conjugate oxidising agent.^{2}

10 **a** [$Cu_{(s)}$oxidation number changed from 0 to +2 during the reaction, therefore it was oxidised.^{1}][As it was oxidised it is the reducing agent.^{2}][The oxidation number of N in $HNO_{3(aq)}$ changed from +5 to +4 in NO_2, therefore $NO_3^{-}{}_{(aq)}$ was reduced.^{3}][As it was reduced, it is the oxidising agent.^{4}]

✓ ✗ I have identified whether $Cu_{(s)}$ was oxidised or reduced depending on its change in oxidation number.^{1}

✓ ✗ I have identified whether $Cu_{(s)}$ is the oxidising or reducing agent.^{2}

✓ ✗ I have identified whether $NO_3^{-}{}_{(aq)}$ was oxidised or reduced depending on its change in oxidation number.^{3}

✓ ✗ I have identified whether $NO_3^{-}{}_{(aq)}$ is the oxidising or reducing agent.^{4}

b [The oxidation number for $Al_{(s)}$ changed from 0 to +3, therefore it was oxidised.^{1}][As it was oxidised it is the reducing agent.^{2}][The oxidation number of $H^{+}_{(aq)}$ from $H_2SO_{4\,(aq)}$ changed from +1 to 0 in $H_{2(g)}$, therefore it was reduced.^{3}][As it was reduced it is the oxidising agent.^{4}]

✓ ✗ I have identified whether $Al_{(s)}$ was oxidised or reduced depending on its change in oxidation number.^{1}

✓ ✗ I have identified whether $Al_{(s)}$ is the oxidising or reducing agent.^{2}

✓ ✗ I have identified whether hydrogen was oxidised or reduced depending on its change in oxidation number.^{3}

✓ ✗ I have identified whether $H^{+}_{(aq)}$ is the oxidising or reducing agent.^{4}

Multiple lessons

11 **a** $C_3H_{8\,(g)} + 5O_{2\,(g)} \rightarrow 3CO_{2\,(g)} + 4H_2O_{(l)}$

b Propane (C_3H_8) is being oxidised and oxygen (O_2) is being reduced.

4B Writing equations for redox reactions

Theory review questions

1 B **2** D **3** A **4** A

Exam-style questions

Within lesson

5 B **6** C

7 **a** $Se_{(s)} + 3H_2O_{(l)} \rightarrow SeO_3^{2-}{}_{(aq)} + 6H^{+}_{(aq)} + 4e^{-}$

b $6OH^{-}_{(aq)} + 3Se_{(s)} + 4Cr(OH)_{3(aq)} \rightarrow 4Cr_{(s)} + 3SeO_3^{2-}{}_{(aq)} + 9H_2O_{(l)}$

8 **a** Oxidation: $CH_3CH_2OH_{(l)} + H_2O_{(l)} \rightarrow CH_3COOH_{(l)} + 4H^{+}_{(aq)} + 4e^{-}$

Reduction: $Cr_2O_7^{2-}{}_{(aq)} + 14H^{+}_{(aq)} + 6e^{-} \rightarrow 2Cr^{3+}_{(aq)} + 7H_2O_{(l)}$

b Complete: $2Cr_2O_7^{2-}{}_{(aq)} + 3CH_3CH_2OH_{(l)} + 16H^{+}_{(aq)} \rightarrow 4Cr^{3+}_{(aq)} + 3CH_3COOH_{(l)} + 11H_2O_{(l)}$

9 **a** Reduction: $Fe^{3+}_{(aq)} + 3e^{-} \rightarrow Fe_{(s)}$

Oxidation: $Mg_{(s)} \rightarrow Mg^{2+}_{(aq)} + 2e^{-}$

b $2Fe^{3+}_{(aq)} + 3Mg_{(s)} \rightarrow 2Fe_{(s)} + 3Mg^{2+}_{(aq)}$

c $Mg_{(s)}$

10 **a** [The student's prediction is inaccurate.^{1}][This is because according to the electrochemical series $Fe_{(s)}$ is a stronger reducing agent than $Pb_{(s)}$ which is the opposite to what the student thought.^{2}][Therefore, the following reaction will occur instead $Cu^{2+}_{(aq)} + Fe_{(s)} \rightarrow Cu_{(s)} + Fe^{2+}_{(aq)}$.^{3}]

✓ ✗ I have identified whether the student's prediction is accurate or inaccurate.^{1}

✓ ✗ I have justified my answer with the use of the electrochemical series.^{2}

✓ ✗ I have written the redox equation that will be occurring.^{3}

b The copper solution will become less blue and the strip of iron will gradually have a layer of a shiny bronze coloured substance (copper) on it and appear corroded.

Multiple lessons

11 **a** $Na_{(s)} \rightarrow Na^+_{(aq)} + e^-$

$Ag^+_{(aq)} + e^- \rightarrow Ag_{(s)}$

b Oxidation process: $Na_{(s)} / Na^+_{(aq)}$

Reduction process: $Ag^+_{(aq)} / Ag_{(s)}$

12 **a** Oxidation reaction: $Ni_{(s)} \rightarrow Ni^{2+}_{(aq)} + 2e^-$

Reduction reaction: $H_2SO_{4(aq)} + 2H^+_{(aq)} + 2e^- \rightarrow SO_{2(g)} + 2H_2O_{(l)}$

b $Ni_{(s)} + H_2SO_{4\,(aq)} + 2H^+_{(aq)} \rightarrow Ni^{2+}_{(aq)} + SO_{2\,(g)} + 2H_2O_{(l)}$

c [Yes, this is an example of a redox reaction.[1]][This is because there is an exchange of electrons, which is evident from the oxidation state of sulfur, S, changing from +6 to +4 (reduction) and the oxidation state of carbon, C, changing from 0 to +4 (oxidation).[2]]

✓ ✗ I have determined whether this is an example of a redox reaction.[1]

✓ ✗ I have justified my answer with reference to the oxidation state changes of the reacting species.[2]

4C Galvanic cells

Theory review questions

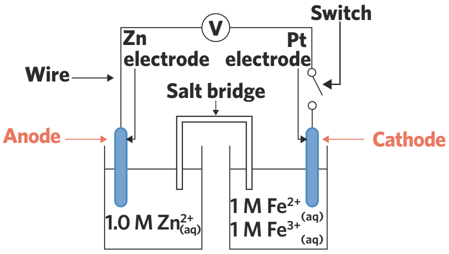
1 C **2** B **3** D

Exam style questions

Within lesson

4 D **5** C **6** B

7 **a**



[Both Fe^{3+} and Fe^{2+} are stronger oxidising agents than Zn^{2+}.[1]] [Therefore, oxidation occurs at the Zn/Zn^{2+} half-cell and reduction occurs at the Fe^{2+}/Fe^{3+}half-cell.[2]]

✓ ✗ I have identified the anode and cathode in the given set up.[1]

✓ ✗ I have compared the strength of the reducing agents (stronger oxidising agents is also accepted).[2]

✓ ✗ I have determined electrodes at which oxidation and reduction occur.

b

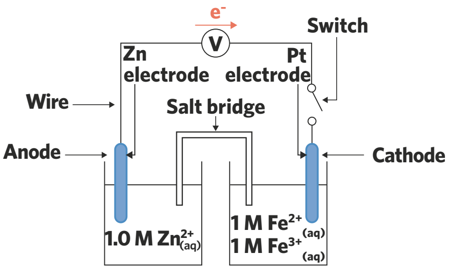


Image: VCAA 2015 Exam Section A Q26

c Anode: $Zn_{(s)} \rightarrow Zn^{2+}_{(aq)} + 2e^-$

Cathode: $Fe^{3+}_{(aq)} + e^- \rightarrow Fe^{2+}_{(aq)}$

$Fe^{2+}_{(aq)} + 2e^- \rightarrow Fe_{(s)}$

d $Zn_{(s)} \rightarrow Zn^{2+}_{(aq)} + 2e^-$, $E^0 = 0.76$ V

$Fe^{3+}_{(aq)} + e^- \rightarrow Fe^{2+}_{(aq)}$, $E^0 = +0.77$ V

The maximum voltage measured: 0.76 + 0.77 = 1.53 V

8 **a**

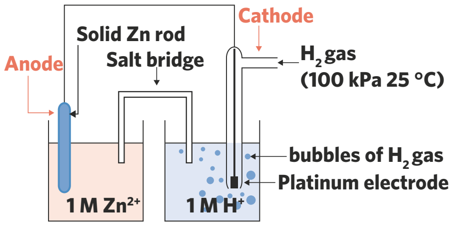
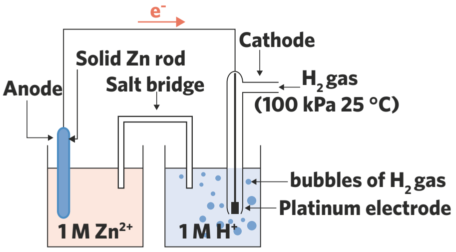


Image: VCAA 2016 Exam Section A Q29

b Anode: Oxidation reaction

Cathode: Reduction reaction

c



Multiple lessons

9 **a**

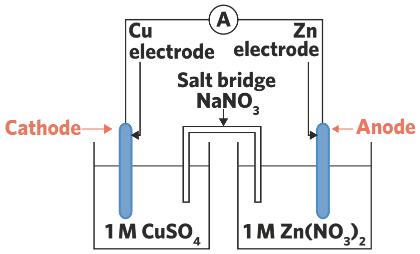


Image: VCAA 2018 Exam Section A Q11

b **i** Oxidation: $Zn_{(s)} \rightarrow Zn^{2+}_{(aq)} + 2e^-$

ii Reduction: $Cu^{2+}_{(aq)} + 2e^- \rightarrow Cu_{(s)}$

c $Zn_{(s)} + Cu^{2+}_{(aq)} \rightarrow Cu_{(s)} + Zn^{2+}_{(aq)}$

d

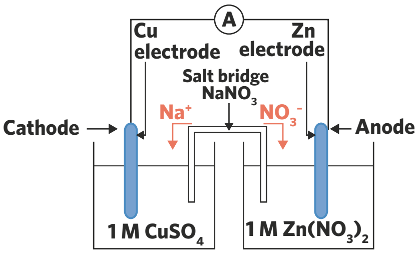


Image: VCAA 2018 Exam Section A Q11

10 **a** [The chloride ions found in the salt bridge are able to form an insoluble precipitate, AgCl.[1]][This would affect the functioning of the cell because silver ions are necessary for the redox reaction to occur.[2]]

✓ ✗ I have explained that an insoluble precipitate will be formed.[1]

✓ ✗ I have linked this to the effect on galvanic cell function.[2]

b [No electricity was generated because a salt bridge is essential to any galvanic cell's function and without it no electricity is able to be generated.[1]][This is because it completes the circuit and maintains charge neutrality in each half-cell.[2]]

✓ ✗ I have stated the importance of a salt bridge in a galvanic cell.[1]

✓ ✗ I have explained its function.[2]

c Anode: $Cu_{(s)} \rightarrow Cu^{2+}_{(aq)} + 2e^-$

Cathode: $Ag^+_{(aq)} + e^- \rightarrow Ag_{(s)}$

$2Ag^+_{(aq)} + Cu_{(s)} \rightarrow 2Ag_{(s)} + Cu^{2+}_{(aq)}$

$V = +0.80 - (+0.34) = 0.46V$

4D Designing galvanic cells

Theory review questions

1 A **2** C

Exam-style questions

Within lesson

3 C **4** A

5 **a** [The electrochemical series is measured under standard conditions and is therefore only an accurate predictor for reactions when they are occurring at standard conditions (1.0 M concentrations, 100 kPa and 298 K).[1]][Since the temperature is above 298 K, the relative strength of the oxidising and reducing agents is subject to change, accounting for the predicted reaction not occurring.[2]]

✓ ✗ I have identified the importance of standard conditions for the electrochemical series to be accurate.[1]

✓ ✗ I have linked my answer to the question.[2]

b [The standard electrode potential values are measured using concentrations of 1.0 M.[1]][Since the concentrations of the solution may be decreasing or increasing depending on whether a metal is being oxidised or an ion is being reduced, the voltage will be subject to change as concentrations change throughout the experiment.[2]]

✓ ✗ I have identified the importance of 1.0 M concentrations in determining an accurate predicted voltage.[1]

✓ ✗ I have linked my answer to the question.[2]

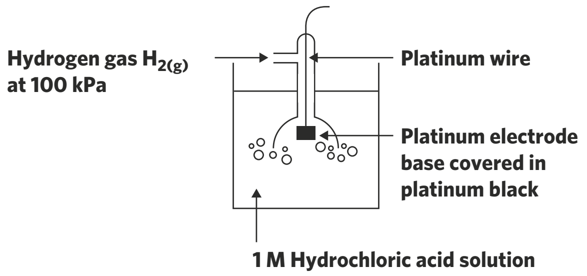
6 **a** [The $Sn^{4+}_{(aq)}/Sn^{2+}_{(aq)}$ half cell has not been set up correctly.[1]] [This is because an inert electrode is not being used and since $Fe_{(s)}$ can reduce $Sn^{4+}_{(aq)}$ and become $Fe^{2+}_{(aq)}$, the electrode will start to corrode over time.[2]]

✓ ✗ I have stated which half cell was not set up correctly.[1]

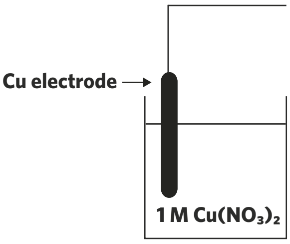
✓ ✗ I have justified my answer with reference to the reactivity of $Fe_{(s)}$.[2]

b An inert electrode like platinum could be used.

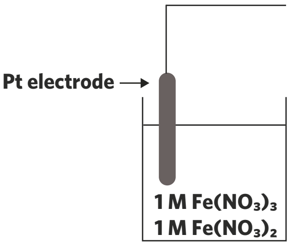
c



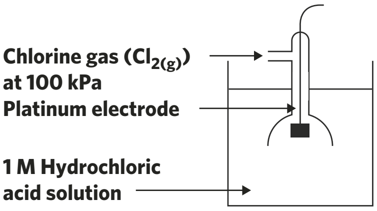
7 **a**



b



c



8 **a** No water is present because lithium would react explosively with water because lithium is a very strong reducing agent.

b It is a common choice because it is a very good reducing agent and therefore when it is combined with iodine, it creates a large voltage.

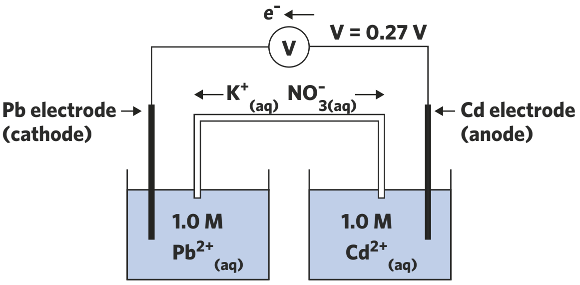
c $2Li_{(s)} + I_{2(s)} \rightarrow 2LiI_{(s)}$

Multiple lessons

9 **a** $Cd_{(s)} \rightarrow Cd^{2+}_{(aq)} + 2e^-$

b $Cd_{(s)} + Pb^{2+}_{(aq)} \rightarrow Cd^{2+}_{(aq)} + Pb_{(s)}$

c



10 **a** [$Cr_2O_7{}^{2-}{}_{(aq)}$ is a stronger oxidising agent than $H^+{}_{(aq)}$ because it was reduced, as shown by the change in colour of the solution to blue, indicating the presence of Cr^{3+} ions in cell 1.^{1}][$Cr_{(s)}$ is a stronger reducing agent than $H_{2(g)}$ because it was oxidised as shown by the electrode becoming corroded in cell 2 due to $Cr_{(s)}$ becoming Cr^{3+} ions.^{2}][$MnO_4^-{}_{(aq)}$ is a stronger oxidising agent than $H^+{}_{(aq)}$ because $H^+{}_{(aq)}$ was reduced, as shown by the increase in pH, made observable by colour change of the solution containing methyl red (there was a decrease in the concentration of H^+ ions) in cell 3.^{3}]

✓ ✗ I have identified the strength of $Cr_2O_7{}^{2-}{}_{(aq)}$ relative to $H^+{}_{(aq)}$ based on experimental observations.^{1}

✓ ✗ I have identified the strength of relative to $Cr_{(s)}$ relative to $H^+{}_{(aq)}$ based on experimental observations.^{2}

✓ ✗ I have identified the strength of relative to $MnO_4{}^-{}_{(aq)}$ relative to $H^+{}_{(aq)}$ based on experimental observations.^{3}

b [Based on the results, we are only able to determine that cell 3 and cell 1 have greater standard electrode potentials than cell 2^{1}][however we are unable to differentiate between cells 3 and 1 in terms of their electrode potential.^{2}]

✓ ✗ I have identified the main conclusion based on the experimental observations.^{1}

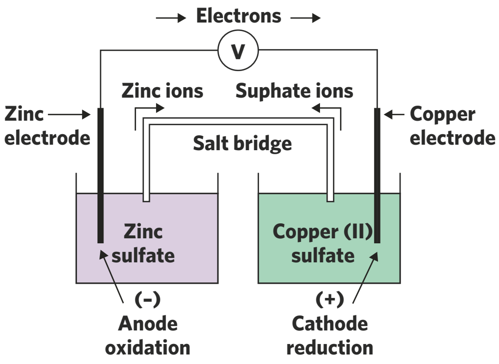
✓ ✗ I have identified the main reason why we are not able to determine the order of the electrode potentials.^{2}

c [The observations only reveal qualitative information.^{1}][The addition of a voltmeter will allow us to measure the potential difference between the half cells and therefore enable quantitative data to be measured.^{2}]

✓ ✗ I have identified the qualitative nature of the data collected.^{1}

✓ ✗ I have described how the use of a voltmeter can allow for the measurement of quantitative data.^{2}

11 **a**



b $Zn_{(s)} + Cu^{2+}{}_{(aq)} \rightarrow Zn^{2+}{}_{(aq)} + Cu_{(s)}$

c [The purpose of the salt bridge is to complete the circuit and maintain charge neutrality by preventing the buildup of excess charge.^{1}]

✓ ✗ I have identified the purpose of the salt bridge based on neutrality.^{1}

d [Increase the temperature.^{1}][Increase the concentration of reactants.^{2}]

✓ ✗ I have linked an increase in reaction rate to an increase in temperature.^{1}

✓ ✗ I have linked an increase in reaction rate to an increase in concentration of reactants.^{2}

e [If we increase the temperature or change the concentrations,^{1}][the electrochemical series cannot predict the voltage accurately because its values only apply under standard conditions.^{2}]

✓ ✗ I have identified a change in standard conditions is occurring.^{1}

✓ ✗ I have explained this effect on the accuracy of the electrochemical series.^{2}

4E Direct and indirect redox reactions

Theory review questions

1 B **2** D **3** A

Exam-style questions

Within lesson

4 $Cl_{2\,(g)} + 2e^- \rightarrow 2Cl^-{}_{(aq)}$

$2H_2O_{(l)} \rightarrow O_{2(g)} + 4H^+{}_{(aq)} + 4e^-$

[As $Cl_{2\,(g)}$ is the strongest oxidising agent present with a higher E^0 value than the strongest reducing agent $H_2O_{(l)}$,^{1}][a spontaneous redox reaction will occur.^{2}]

✓ ✗ I have written the redox half-reactions.

✓ ✗ I have identified whether an oxidising and a reducing agent is present.^{1}

✓ ✗ I have stated whether a reaction will occur or not based on the electrochemical series.^{2}

5 $Br_{2\,(l)} + 2e^- \rightarrow 2Br^-{}_{(aq)}$ $E^0 = +1.09$ V

$Mg^{2+}{}_{(aq)} + 2e^- \rightarrow Mg_{(s)}$ $E^0 = -2.37$ V

[Both compounds are oxidising agents,^{1}][therefore no reaction will occur.^{2}]

✓ ✗ I have written the half-reactions of the compounds.

✓ ✗ I have identified whether the compounds are oxidising agents or reducing agents.^{1}

✓ ✗ I have identified whether a reaction will occur according to the electrochemical series.^{2}

6 **a** [In the reaction, $Ni^{2+}{}_{(aq)}$ is the strongest oxidising agent and has a higher E^0 value than $Mg_{(s)}$, the strongest reducing agent, in the electrochemical series,^{1}][therefore a redox reaction will occur.^{2}]

✓ ✗ I have identified which species is the oxidising agent and which is the reducing agent.^{1}

✓ ✗ I have stated whether a redox reaction will occur.^{2}

b $Ni^{2+}{}_{(aq)} + Mg_{(s)} \rightarrow Ni_{(s)} + Mg^{2+}{}_{(aq)}$

c [This is a direct redox reaction[1]][because the reactants undergo reduction and oxidation in the same vessel.[2]]

✓ ✗ I have stated whether a direct or indirect redox reaction occurred.[1]

✓ ✗ I have supported my answer referencing where reduction and oxidation took place.[2]

Multiple lessons

7 **a** Oxidation: $Zn_{(s)} \rightarrow Zn^{2+}_{(aq)} + 2e^-$

Reduction: $Ag^+_{(aq)} + e^- \rightarrow Ag_{(s)}$

b $Zn_{(s)} + 2Ag^+_{(aq)} \rightarrow Zn^{2+}_{(aq)} + 2Ag_{(s)}$

c Chemical energy is transformed into heat energy.

8 **a** Oxidation: $Zn_{(s)} \rightarrow Zn^{2+}_{(aq)} + 2e^-$

Reduction: $Cu^{2+}_{(aq)} + 2e^- \rightarrow Cu_{(s)}$

b $Cu^{2+}_{(aq)}$ is the oxidising agent and $Zn_{(s)}$ is the reducing agent.

c [This is an example of an indirect redox reaction[1]][because the reactants are kept in separate beakers.[2]]

✓ ✗ I have identified if the reaction is a direct or indirect redox reaction.[1]

✓ ✗ I have used the placement of the reactants to explain why.[2]

9 **a** [Of the species present, $Pb^{2+}_{(aq)}$ is the only oxidant present, whereas $Al_{(s)}$ and $Cu_{(s)}$ are both reducing agents.[1]][In order for $Pb^{2+}_{(aq)}$ to oxidise a reducing agent, it needs to have a higher E^0 value of the reducing agent.[2]][As a result, when $Pb^{2+}_{(aq)}$ is in a reaction with $Al_{(s)}$, it will be able to oxidise aluminium solid whereas it will not be able to spontaneously oxidise $Cu_{(s)}$ as solid copper has a higher E^0 value than $Pb^{2+}_{(aq)}$.[3]]

✓ ✗ I have identified the nature of the species available to take part in the reaction.[1]

✓ ✗ I have identified the condition in which a spontaneous redox reaction will occur.[2]

✓ ✗ I have identified the reactions that will and will not occur.[3]

b Reduction: $Pb^{2+}_{(aq)} + 2e^- \rightarrow Pb_{(s)}$

Oxidation: $Al_{(s)} \rightarrow Al^{3+}_{(aq)} + 3e^-$

Overall: $3Pb^{2+}_{(aq)} + 2Al_{(s)} \rightarrow 3Pb_{(s)} + 2Al^{3+}_{(aq)}$

c $E^0 = E^0_{reduction} - E^0_{oxidation}$

$E^0 = -0.13 + 1.66$

$E^0 = 1.53\ V$

4F Fuel cells

Theory review questions

1 Fuel cells convert **chemical** energy to electrical energy by two simultaneous reactions, an **oxidation** reaction and a **reduction** reaction.

2 A **3** B

Exam-style questions

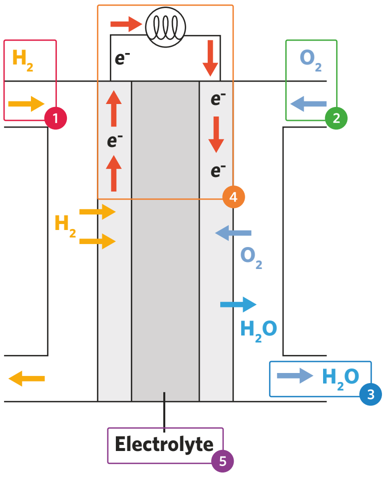
Within lesson

4 C **5** A

6 **a** $2H_{2(g)} + O_{2(g)} \rightarrow 2H_2O_{(g)}$

b Redox reaction

c



✓ ✗ I have drawn hydrogen gas as a reactant.[1]

✓ ✗ I have drawn oxygen gas as reactant.[2]

✓ ✗ I have drawn water as a product.[3]

✓ ✗ I have correctly drawn the movement of electrons.[4]

✓ ✗ I have labelled the location of the electrolyte.[5]

d The electrolyte allows only the movement of ions between electrodes in order for a redox reaction to occur.

e $H_{2(g)} \rightarrow 2H^+_{(aq)} + 2e^-$

f Positive

7 **a** Combustion reaction

b [The model powered by a fuel cell would be more efficient,[1]][as there are less energy transformations, so a smaller amount of energy is lost as compared to the petrol-powered car.[2]]

✓ ✗ I have identified which model would be more efficient.[1]

✓ ✗ I have justified my answer with respect to the amount of energy transformations.[2]

c Hydrogen gas needs to be stored at very high pressure, and is flammable.

d [The hydrogen fuel cell only produces water, and so has minimal impact on the environment.[1]][The combustion of petrol however, produces many pollutants and greenhouse gases, such as CO_2, CO and NO_2 so has a much more detrimental effect on the environment.[2]]

✓ ✗ I have identified the product of the fuel cell and its effect on the environment.[1]

✓ ✗ I have identified the product of the combustion reaction and its effect on the environment.[2]

8 **a** more, porous electrodes are more expensive to produce. Also: they operate at high temperatures and pure hydrogen gas is expensive to produce.

b galvanic

c fuel

9 **a** $O_{2(g)} + 2H_2O_{(l)} + 4e^- \rightarrow 4OH^-_{(aq)}$

b From the anode to the cathode.

c $E^0_{cell} = E^0_{reduction} - E^0_{oxidation}$

$= 0.40 - (-0.83) = 1.23\ V$

Multiple lessons

10 **a** Chemical energy to electrical energy

b $CH_{4(g)} + 2O_{2(g)} \rightarrow 2H_2O_{(g)} + CO_{2(g)}$

c $CH_{4(g)} + 2H_2O_{(g)} \rightarrow CO_{2(g)} + 8H^+_{(aq)} + 8e^-$, negative

d $O_{2(g)} + 4H^+_{(aq)} + 4e^- \rightarrow 2H_2O_{(g)}$

e $CH_{4(g)}$

f [Porous electrodes allow a greater surface area for the reaction to take place, meaning the reaction takes place faster,[1]] [but are more expensive to manufacture.[2]]

✓ ✗ I have listed one advantage of porous electrodes.[1]

✓ ✗ I have listed one disadvantage of porous electrodes.[2]

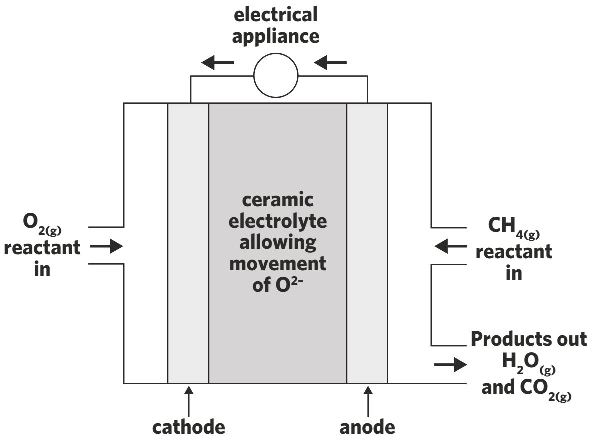
g [No.[1]] [Methane from natural gas is a fossil fuel. This means it is not replenished by natural processes at a rate faster than or equal to its rate of consumption, and is therefore not renewable.[2]]

✓ ✗ I have identified that methane from natural gas is not renewable.[1]

✓ ✗ I have explained why with reference to the definition of a renewable fuel.[2]

11 **a** $CH_{4(g)} + 4O^{2-}_{(s)} \rightarrow CO_{2(g)} + 2H_2O_{(g)} + 8e^-$

b



✓ ✗ I have labelled the anode.

✓ ✗ I have labelled the cathode.

✓ ✗ I have labelled the electrolyte.

✓ ✗ I have identified the reactants being pumped in and the products being pumped out.

c The water vapour could be used to spin a turbine to convert mechanical energy into electrical energy to increase the efficiency of the fuel cell.

d [The contractor's statement is incorrect.[1]] [The generation of electricity from the combustion of methane involves many intermediate steps as chemical energy is converted to thermal energy, then to mechanical energy and finally into electrical energy, with energy lost at each step.[2]] [In a fuel cell, chemical energy is directly converted to electrical energy which means it has a greater efficiency.[3]]

✓ ✗ I have commented on the accuracy of the statement.[1]

✓ ✗ I have described the energy transformations in a combustion power station.[2]

✓ ✗ I have described the energy transformations in a fuel cell.[3]

e A renewable source of methane is biogas which is produced from the anaerobic digestion by bacteria of organic matter.

Chapter 4 review

Multiple choice

1	A	**2**	D	**3**	D	**4**	B	**5**	C
6	C	**7**	B	**8**	D	**9**	C	**10**	C

Short answer

11 **a** [The student's conclusion is wrong.[1]] [From the data book, $Cu^{2+}_{(aq)} + 2e^- \rightarrow Cu_{(s)}$ has an electrode potential of 0.34 V. We also know that $Ge^{2+}_{(aq)} + Cu_{(s)} \rightarrow$ no observed reaction.[2]] [This means $Ge^{2+}_{(aq)} + 2e^- \rightarrow Ge_{(s)}$ has a smaller electrode potential than 0.34 V.[3]]

✓ ✗ I have stated whether the student's conclusion is correct or incorrect.[1]

✓ ✗ I have used the appropriate equations and their corresponding electrode potentials from the databook and the given information.[2]

✓ ✗ I have linked those equations to explain my answer.[3]

b [From the data book, $Cu^{2+} + 2e^- \rightarrow Cu_{(s)}$ has an electrode potential of 0.34 V and $Sn^{4+} + 2e^- \rightarrow Sn^{2+}_{(aq)}$ has an electrode potential of 0.15 V.[1]] [We also know that $Ge^{2+}_{(aq)} + Sn^{2+}_{(aq)} \rightarrow Ge_{(s)} + Sn^{4+}_{(aq)}$ and $Ge^{2+}_{(aq)} + Cu_{(s)} \rightarrow$ no observed reaction.[2]] [Therefore, the electrode potential of $Ge^{2+}_{(aq)} + 2e^- \rightarrow Ge_{(s)}$ is between 0.15 V and 0.34 V.[3]]

✓ ✗ I have used the appropriate equations and their corresponding electrode potentials from the data book.[1]

✓ ✗ I have used the appropriate equations and their corresponding electrode potentials from the given information.[2]

✓ ✗ I have linked those equations to determine the range of the electrode potential value.[3]

12 **a** **i** [The reaction occurring in the hydrogen half cell is $2H^+_{(aq)} + 2e^- \rightarrow H_{2(g)}$^{1}][As the concentration of H^+ in the standard hydrogen half-cell decreases over time, the pH of the solution would increase.^{2}]

✓ ✗ I have identified the reaction occurring in the half cell.^{1}

✓ ✗ I have used the reaction to explain the change in pH.^{2}

ii The occurring reactions are:

[$H_{2(g)} \rightarrow 2H^+_{(aq)} + 2e^-$ and $Cu^{2+}_{(aq)} + 2e^- \rightarrow Cu_{(s)}$^{1}]

[As seen in the half reactions, hydrogen gas is being oxidised and therefore electrons would move from the standard hydrogen half-cell to the half-cell containing the copper electrode.^{2}]

✓ ✗ I have identified the reactions which occurred.^{1}

✓ ✗ I have used the reactions to explain the direction of electron flow.^{2}

iii [In the test cell involving silver, silver ions are being reduced as shown in the half equation $Ag^+_{(aq)} + e^- \rightarrow Ag_{(s)}$^{1}][resulting in the formation of $Ag_{(s)}$. Subsequently the mass of the silver electrode increased as a result of the reaction.^{2}]

✓ ✗ I have identified the reaction occuring in the test cell.^{1}

✓ ✗ I have used the reaction to explain the increase in mass of the silver electrode.^{2}

b [Based on the experimental notes, the reaction involving calcium showed that Ca^{2+} is a weaker oxidising agent than H^+.^{1}][Given that there is only one E^0 value corresponding to this is conclusion, –2.9 V, the cell potential value of the half equation $CaSO_{4(s)} + 2e^- \rightleftharpoons Ca_{(s)} + SO_4^{2-}{}_{(aq)}$ is –2.9 V.^{2}]

✓ ✗ I have used the correct experimental note to determine the oxidising agent with the lowest strength.^{1}

✓ ✗ I have used the experimental note to determine the half-equation and its cell potential value.^{2}

c [Based on the experimental notes, both Cu^{2+} and Ag^+ are stronger oxidising agents than H^+ but there was no information provided to determine the order of the strength of each oxidising agent.^{1}][To determine the order, the copper and silver half cells would have to be connected to one another to determine which is the stronger oxidising/reducing agent.^{2}][Therefore, the cell potential values of the other two equations cannot be identified experimentally.^{3}]

✓ ✗ I have explained why there was not enough information provided in the experimental notes.^{1}

✓ ✗ I have stated what would be needed to determine which would be the stronger oxidising/reducing agent.^{2}

✓ ✗ I have linked the information in the experimental notes with my conclusion.^{3}

13 **a** The Cu electrode is the anode and the Ag electrode is the cathode.

b **i** Oxidation: $Cu_{(s)} \rightarrow Cu^{2+}_{(aq)} + 2e^-$

ii Reduction: $Ag^+_{(aq)} + e^- \rightarrow Ag_{(s)}$

c $Cu_{(s)} + 2Ag^+_{(aq)} \rightarrow 2Ag_{(s)} + Cu^{2+}_{(aq)}$

d [Mia's calculation is incorrect.^{1}][The value of the electrode potential of a redox reaction remains the same even when we multiply that reaction by a coefficient to obtain a balanced overall redox reaction.^{2}]

✓ ✗ I have determined whether the student's calculation is correct or incorrect.^{1}

✓ ✗ I have justified my answer by explaining the rule of calculating the cell potential.^{2}

Key science skill question

14 **a** $SO_{2(g)} + 2H_2O_{(l)} \rightarrow SO_4{}^{2-}{}_{(aq)} + 4H^+_{(aq)} + 2e^-$

Oxidation reaction

b Oxidising agent (oxidant)

c $m(CaSO_4) = 1.500 - 0.735$

$= 0.765$ g

$n(SO_2)_{\text{in sample}} = n(CaSO_4)$

$= \frac{0.765}{136.2} = 5.617 \times 10^{-3}$ mol

$m(SO_2) = 64.1 \times 5.617 \times 10^{-3} = 0.360$ g

$\%(SO_2) = \frac{0.360}{60.0} \times 100 = 0.600\%$

d [It is possible that less SO_2 was oxidised by hydrogen peroxide than expected, therefore a lower $m(CaSO_4)$ and lower $m(SO_2)$ was calculated, hence less $\%(SO_2)$ was calculated.^{1}][They could have powderised the peanuts in a blender or crushed the peanuts to allow all SO_2 to be oxidised by hydrogen peroxide.^{2}]

✓ ✗ I have explained why the percentage of sulfur dioxide was lower than expected.^{1}

✓ ✗ I have suggested one way to obtain a more accurate result.^{2}

5A Principles of a chemical reaction

Theory review questions

1 B **2** C **3** C **4** A

Exam-style questions

Within lesson

5 B

6 [The temperature of the reaction might be low resulting in a very small proportion of particles having sufficient energy to overcome the activation energy barrier.[1]] [The particles may also be colliding with an undesirable orientation leading to fewer successful collisions.[2]]

✓ ✗ I have explained how the temperature of the reaction could mean that a small number of particles have sufficient energy to overcome the activation energy barrier.[1]

✓ ✗ I have explained how the orientation of the collisions could result in fewer successful collisions.[2]

7 a [Particles in area A would have relatively low kinetic energies.[1]] [Particles in area B would have relatively moderate kinetic energies.[2]] [Particles in area C would have relatively high kinetic energies.[3]]

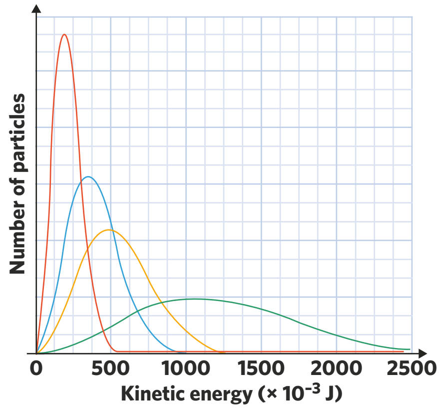
✓ ✗ I have identified the energy level of particles in area A.[1]

✓ ✗ I have identified the energy level of particles in area B.[2]

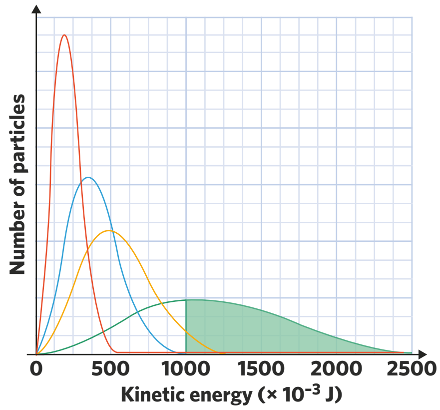
✓ ✗ I have identified the energy level of particles in area C.[3]

b Particles in area A and B would not be able to overcome the activation energy barrier, but particles in area C would be able to overcome the activation energy barrier.

8 a

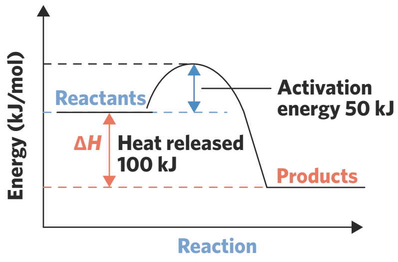


b



Multiple lessons

9 a



✓ ✗ I have correctly labelled the axis with units as kJ/mol.

✓ ✗ I have labelled the reactants and the products.

✓ ✗ I have labelled the activation energy and heat released/enthalpy change.

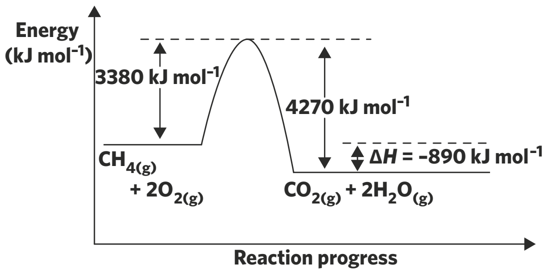
b Exothermic reaction

c 150 kJ mol^{-1}

10 a $CH_{4(g)} + 2O_{2(g)} \rightarrow CO_{2(g)} + 2H_2O_{(g)}$ $\Delta H = -890$ kJ mol^{-1}

b Exothermic reaction

c



✓ ✗ I have correctly labelled the axis with units as kJ/mol.

✓ ✗ I have correctly shown the activation energy of the forward reaction.

✓ ✗ I have correctly shown the energy released in the formation of the products.

✓ ✗ I have correctly labelled the heat released/enthalpy change of the reaction

5B Rates of reaction

Theory review questions

1 C **2** B

3 If sodium hydroxide of 50 °C were added instead, the rate of the reaction would **increase**.

If hydrochloric acid of half the concentration were used the rate of the reaction would **decrease**.

If the mixture were stirred the rate of the reaction would **increase**.

Exam-style questions

Within lesson

4 C **5** B

6 a $HCl_{(aq)} + NaHCO_{3(s)} \rightarrow NaCl_{(aq)} + CO_{2(g)} + H_2O_{(l)}$

b [During the reaction, solid sodium bicarbonate is consumed, resulting in the production of gaseous carbon dioxide.[1]][This gas produced is then lost into the atmosphere, resulting in a decrease in the mass of the flask.[2]]

✓ ✗ I have identified evidence from the reaction.[1]

✓ ✗ I have explained using the experimental set-up why the mass changes.[2]

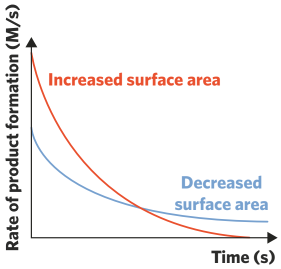
c [The rate of the reaction has decreased in trial 2 compared to that of trial 1.[1]][For this to occur, the mass of sodium bicarbonate would need to be decreased as this would result in fewer reactant particles available leading to a decrease in the frequency of collisions and consequently fewer successful collisions between reactant particles in a given amount of time.[2]][This would result in a decrease in the rate of reaction.[3]]

✓ ✗ I have identified the change in rate that is shown by the graph.[1]

✓ ✗ I have identified which change needs to be made to achieve this rate change.[2]

✓ ✗ I have linked my answer to the question.[3]

d



✓ ✗ I have drawn trial 3 with a faster initial slope than trial 1.

✓ ✗ I have labelled the axes.

e [When the sodium bicarbonate is crushed, the surface area increases.[1]][This increases the proportion of reactant particles exposed to react thereby increasing the frequency of collisions between reactants meaning the number of successful collisions increases in a given amount of time, and therefore increasing the rate of the reaction.[2]]

✓ ✗ I have explained how the change affects surface area.[1]

✓ ✗ I have described how changes in surface area affect the rate of reaction.[2]

7 **a** [Breaking the nail into smaller pieces increases the surface area of the nail pieces.[1]][A greater surface area means there is an increased area for reactants to be in contact, resulting in an increase in collisions in a given amount of time between reactant particles that could result in a reaction.[2]][Therefore, the rate of the reaction would increase.[3]]

✓ ✗ I have identified the effect of the change on the reactant particles.[1]

✓ ✗ I have used collision theory to explain the effect on the rate of the reaction.[2]

✓ ✗ I have linked my answer to the question.[3]

b [Nails more exposed to the sun are at a higher temperature than those in the shade and so particles have a higher average kinetic energy.[1]][This means a greater proportion of particles can collide with sufficient energy to meet the requirements of the activation energy.[2]][Furthermore, there would be an increase in the number of overall collisions in a given amount of time.[3]][Together, this would result in an increase in the rate of the reaction.[4]]

✓ ✗ I have identified the effect of the change on the reactant particles.[1]

✓ ✗ I have used collision theory to explain the effect on the energy of reactant particles.[2]

✓ ✗ I have used collision theory to explain the effect on the number of collisions.[3]

✓ ✗ I have linked my answer to the question.[4]

c [An increase in pressure at constant temperature of one of the reactants would decrease the volume of the vessel and therefore, increase the concentration of oxygen gas .[1]][This would result in an increase in the frequency and number of successful collisions in a given time.[2]][Therefore, Alex's statement is incorrect as an increase in pressure would instead increase the rate of the reaction that rusts the nails.[3]]

✓ ✗ I have identified the effect of the change on the reactant particles.[1]

✓ ✗ I have used collision theory to explain the effect on the rate of the reaction.[2]

✓ ✗ I have evaluated the validity of Alex's statement.[3]

Multiple lessons

8 **a** [The rate of the reaction is calculated by measuring the change in mass of the flask and its contents over time[1]][due to the formation and escape of the gaseous product nitrogen dioxide.[2]]

✓ ✗ I have identified the change that would be measured to identify rate of reaction.[1]

✓ ✗ I have described how this measure can indicate the rate of reaction.[2]

b Independent variable – the concentration of nitric acid; dependent variable – the rate of change in mass of the flask and contents.

c [The incorrect calibrating of the scales is an error that affects each weight measurement in the same way,[1]][and so is categorised as a systematic error.[2]]

✓ ✗ I have identified the effect of the error.[1]

✓ ✗ I have linked this effect to the type of error occuring.[2]

d [Trials with greater concentrations of nitric acid will have a higher proportion of reactant particles present, resulting in a greater frequency of collisions.[1]][More collisions means that there is an increase in the number of successful collisions in a given amount of time, resulting in a faster rate of reaction.[2]][Dr Lan's statement is not correct.[3]]

✓ ✗ I have identified the effect of concentration on the reaction rate.^{1}

✓ ✗ I have explained how the reaction rate is affected by concentration changes.^{2}

✓ ✗ I have identified whether Dr Lan's statement is correct or incorrect.^{3}

e [When the reaction is conducted at 50 °C rather than 25 °C (SLC), reactant particles have more average kinetic energy and so on average a greater proportion have sufficient energy for a successful collision.^{1}][In addition, higher average kinetic energy results in more frequent collisions.^{2}][Therefore, the rate of consumption of copper would be expected to increase when conducted in the hot water bath, and so the concentration of copper would be expected to decrease.^{3}]

✓ ✗ I have identified the effect of temperature on the energy of reactant particles.^{1}

✓ ✗ I have identified the effect of temperature on the frequency of collisions.^{2}

✓ ✗ I have used collision theory to identify the effect of the change on the concentration of copper.^{3}

9 **a** $CH_{4(g)} + 2O_{2(g)} \rightarrow 2H_2O_{(g)} + CO_{2(g)}$

b $890 \times 2 = 1780$ *kJ*

c [Neon gas is an inert gas and so does not result in a reaction upon collision with reactant molecules.^{1}][As a result, assuming constant temperature and volume, there is no change to the frequency of successful collisions between reactant particles.^{2}][As a result, there is no change to the rate of the reaction.^{3}]

✓ ✗ I have identified neon gas as an inert gas.^{1}

✓ ✗ I have identified the change to the reactant particles.^{2}

✓ ✗ I have identified the change to the rate of the reaction.^{3}

d [The universal gas equation $PV = nRT$ shows that if pressure and volume are constant but the number of moles decreases, the temperature of a gas must increase.^{1}][This increase in temperature will increase the rate of the remaining reaction.^{2}]

✓ ✗ I have used the universal gas equation to deduce the change in conditions.^{1}

✓ ✗ I have used the change in conditions to identify the change in the rate of the reaction.^{2}

5C Catalysts

Theory review questions

1 C **2** B **3** A

Exam-style questions

Within lesson

4 B **5** C

6 **a** Activation energy 1

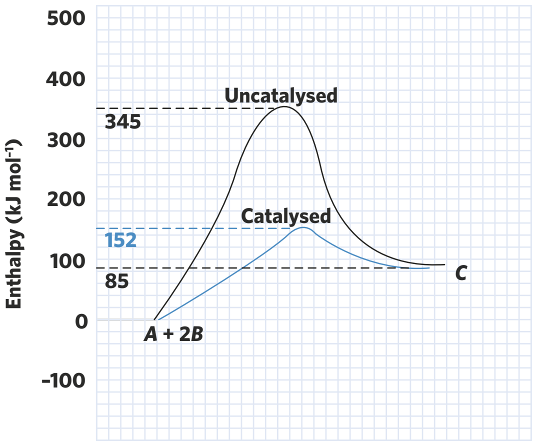
b [Catalysts lower the activation energy of a reaction by providing an alternative pathway for the reaction to occur.^{1}][Of the 2 energy values, activation energy 1 has the lowest value^{2}][and therefore would represent the activation energy of the catalysed reaction.^{3}]

✓ ✗ I have explained what catalysts do.^{1}

✓ ✗ I have identified how catalysts affect the activation energy.^{2}

✓ ✗ I have linked my answer back to the question.^{3}

7 **a**



b [The activation energy for the reaction is higher in the presence of catalyst *Y* than in the presence of catalyst *X*.^{1}][This means a smaller proportion of reactant particles have enough energy for successful collisions when catalyst *Y* is used.^{2}][Therefore, catalyst *Y* will cause the reaction to occur slower.^{3}]

✓ ✗ I have compared the activation energy for the reaction when each catalyst is used.^{1}

✓ ✗ I have compared the number of successful collisions when each catalyst is used.^{2}

✓ ✗ I have used my comparison to answer the question.^{3}

8 **a** [In the presence of a catalyst, the activation energy of the reaction between the gaseous molecules is reduced by providing an alternate reaction pathway.^{1}][This means that a greater proportion of particles have enough kinetic energy for successful collisions.^{2}] [Therefore, the reaction rate increases.^{3}]

✓ ✗ I have described how the activation energy changes in the presence of a catalyst.^{1}

✓ ✗ I have linked the change in activation energy to the number of successful collisions between molecules.^{2}

✓ ✗ I have used my explanation to conclude that the reaction rate increases.^{3}

b [The student's conclusion is incorrect because the vertical axis of the curve represents the number of molecules with a given kinetic energy, not the value of the kinetic energy.^{1}][The area under E_{a2} and the right side of the curve is larger than the area under E_{a1} and the curve.^{2}][Therefore, more molecules have enough kinetic energy to overcome the activation energy of the reaction and so the reaction rate will increase.^{3}]

✓ ✗ I have described what the vertical axis of the curve represents.^{1}

✓ ✗ I have compared the area under the curve to the right of E_{a2} and E_{a1}.^{2}

✓ ✗ I have used the curve to explain why the reaction rate will increase.^{3}

Multiple lessons

9 **a** $S_{(s)} + \frac{3}{2}O_{2(g)} \rightarrow SO_{3(g)}$ $\Delta H = -395.2 \text{ kJ mol}^{-1}$

$-\frac{1}{2}(2SO_{2(g)} + O_{2(g)} \rightarrow 2SO_{3(g)})$ $-\frac{1}{2}(\Delta H = -198.2 \text{ kJ mol}^{-1})$

$S_{(s)} + \cancel{\frac{3}{2}}\cancel{O}_{2(g)} \rightarrow \cancel{SO}_{3(g)}$ $\Delta H = -395.2 \text{ kJ mol}^{-1}$

$\cancel{SO}_{3(g)} \rightarrow SO_{2(g)} + \cancel{\frac{1}{2}}O_{2(g)}$ $\Delta H = 99.1 \text{ kJ mol}^{-1}$

$S_{(s)} + O_{2(g)} \rightarrow SO_{2(g)}$ $\Delta H = -296.1 \text{ kJ mol}^{-1}$

[The reaction is exothermic^{1}][because the enthalpy change is negative, meaning that the reaction releases energy.^{2}]

✓ ✗ I have determined whether the reaction is endothermic or exothermic.^{1}

✓ ✗ I have explained my answer based on the calculated enthalpy change.^{2}

b [If a catalyst is added, the reaction rate will increase.^{1}][This is because the catalyst will create an alternative pathway with a lower activation energy, meaning that a greater proportion of reactant particles have enough energy for successful collisions.^{2}]

✓ ✗ I have described how the reaction rate will change if a catalyst is added.^{1}

✓ ✗ I have explained my answer based on the number of successful collisions.^{2}

10 **a** Manganese (IV) oxide

b [A way in which the rate of reaction can be measured is through measuring the amount of product produced in a given amount of time.^{1}][Based on the graph, it can be seen that when manganese oxide is used, it produces more oxygen per unit time compared to copper (II) oxide and zinc oxide.^{2}][Therefore, compared to the other two catalysts, the use of manganese oxide increases the rate of reaction the most.^{3}]

✓ ✗ I have explained how we can measure the rate of reaction.^{1}

✓ ✗ I have used evidence from the graph to support my answer.^{2}

✓ ✗ I have compared against the other catalysts.^{3}

c [Doubling the amount of hydrogen peroxide increases the concentration of hydrogen peroxide present in the reaction.^{1}]
[The increase in the number of hydrogen peroxide molecules in the system increases the number of collisions, leading to an increase in the number of successful collisions in a given time.^{2}][As a result, more oxygen and water would be produced in a given amount of time as the rate of reaction has increased.^{3}]

✓ ✗ I have identified the effect of adding more hydrogen peroxide.^{1}

✓ ✗ I have explained the effects of having more hydrogen peroxide.^{2}

✓ ✗ I have linked the answer to the question.^{3}

5D Equilibrium reactions

Theory review questions

1 C **2** B **3** B
4 C **5** B **6** A

Exam-style questions

Within lesson

7 A **8** C

9 **a** $[NO] = \frac{3.0}{7.0} = 0.43 \text{ M}$, $[N_2] = \frac{2.0}{7.0} = 0.29 \text{ M}$, $[O_2] = \frac{1.0}{7.0} = 0.14 \text{ M}$

$Q_c = \frac{[0.29][0.14]}{[0.43]^2} = 0.22$

b [Since Q_c is smaller than K_c,^{1}][the reaction would need to favour the forward direction in order to reach equilibrium.^{2}]

✓ ✗ I have compared Q_c and K_c values.^{1}

✓ ✗ I have identified the direction of the reaction required to reach equilibrium.^{2}

c $K_{c(new)} = \frac{1}{K_{c(old)}} = \frac{1}{8} = 0.13$

10 **a** $[CO] = \frac{3.0}{7.5} = 0.40 \text{ M}$

$[Cl_2] = \frac{5.6}{7.5} = 0.747 \text{ M}$

Concentration (mol L^{-1})	$CO_{(g)}$	$Cl_{2(g)}$ ⇌	$COCl_{2(g)}$
n	1	1	1
Initial	0.40	0.747	0.00
Change	$-x$	$-x$	$+x$
Equilibrium	$0.40 - x$	$0.747 - x$	0.32

$0.00 + x = 0.32$

$x = 0.32$

$[CO] = 0.40 - x = 0.40 - 0.32 = 0.080 \text{ M}$

$[Cl_2] = 0.747 - x = 0.747 - 0.32 = 0.427 = 0.43 \text{ M}$

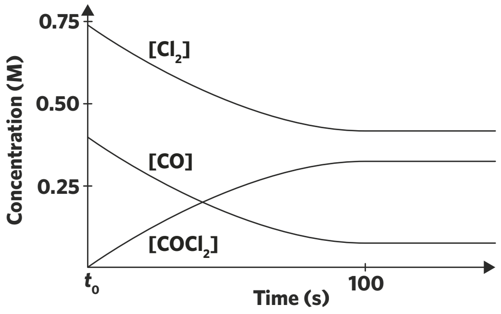
b $K_c = \frac{[COCl_2]}{[CO][Cl_2]}$

c $K_c = \frac{[COCl_2]}{[CO][Cl_2]} = \frac{(0.32)}{(0.080) \times (0.427)} = 9.368 = 9.4$

Units: $\frac{M}{M \times M} = \frac{M}{M^2} = M^{-1}$

$K_c = 9.4 \text{ M}^{-1}$

d



11 **a** **i** [At the beginning, the reaction vessel contained only $NOCl_{(g)}$ and can only react in one direction, which means that the forward reaction $2NOCl_{(g)} \rightarrow 2NO_{(g)} + Cl_{2(g)}$ is the only reaction occurring initially.[1]][This implies that the rate of this reaction will always be greater than the rate of the backwards reaction $2NO_{(g)} + Cl_{2(g)} \rightarrow 2NOCl_{(g)}$ while the system is reaching equilibrium.[2]]

✓ ✗ I have explained the consequences of the reaction vessel's initial conditions on the direction of the reaction.[1]

✓ ✗ I have described how this relates to the respective rates of the forward and backward reactions while the system is reaching equilibrium.[2]

ii [At equilibrium, the rates of the forward and backward reactions are equal.[1]][This means that the rate of the backward reaction will never be greater than that of the forward reaction.[2]]

✓ ✗ I have described the effect of equilibrium on the rate of the forward and backward reactions.[1]

✓ ✗ I have linked my answer to the question.[2]

b **i** $[NOCl] = \frac{10.0}{5.00} = 2.00\ M$

Concentration (mol L^{-1})	**$2NOCl_{(g)}$**	**$2NO \rightleftharpoons$**	**$Cl_{2(g)}$**
n	2	2	1
Initial	2.00	0.00	0.00
Change	$-\ 2x$	$+\ 2x$	$+\ x$
Equilibrium	$2.00 - 2x$	$+\ 2x$	0.600

At equilibrium:

$0.00 + x = 0.600$

$x = 0.600\ M$

$[NOCl] = 2.00 - 2x = 2.00 - 2 \times 0.600 = 0.800\ M$

$[NO] = 2x = 2 \times 0.600 = 1.20\ M$

$[Cl_2] = 0.600\ M$

$$K_c = \frac{[NO]^2[Cl_2]}{[NOCl]^2} = \frac{(1.20)^2 \times (0.600)}{(0.800)^2} = 1.35$$

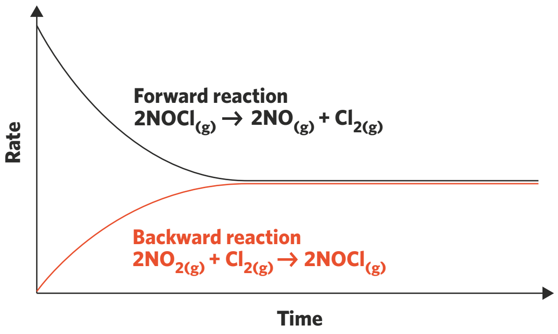
$$\text{Units: } \frac{M^2 \times M}{M^2} = \frac{M^3}{M^2} = M$$

$K_c = 1.35\ M$

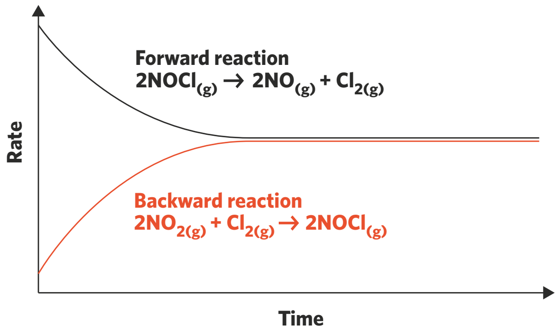
ii $\frac{2}{3}NO_{(g)} + \frac{1}{3}Cl_{2(g)} \rightleftharpoons \frac{2}{3}NOCl_{(g)}$ can be obtained from the reaction $2NOCl_{(g)} \rightleftharpoons 2NO_{(g)} + Cl_{2(g)}$ by reversing it and multiplying its coefficients by $\frac{1}{3}$. This means that the new equilibrium constant is given by $((K_{initial})^{-1})^{\frac{1}{3}} = (K_{initial})^{\frac{-1}{3}}$.

$(1.35\ M)^{\frac{-1}{3}} = 0.905\ M^{\frac{-1}{3}}$.

c **i**



ii



12 **a** $K_c = \frac{[HCN][CO_2][H_2]}{[CO]^2[NH_3]}$

b **i** $Q_c = \frac{(13.4) \times (15.3) \times (19.2)}{(0.163)^2 \times (40.0)} = 3704$

$3704 > 0.175$

[Since $Q_c > K_c$, the system will establish equilibrium by increasing the proportion of the concentration of reactants.[1]][This means that a net backward reaction will occur to establish equilibrium.[2]]

✓ ✗ I have included the calculation of Q_c in my answer.

✓ ✗ I have compared the values of Q_c and K_c.[1]

✓ ✗ I have identified how the difference in these values will relate to the system as it establishes equilibrium.[2]

ii

Concentration (mol L^{-1})w	**$2CO_{(g)}$**	**$NH_{3(g)} \rightleftharpoons$**	**$HCN_{(g)}$**	**$CO_{2(g)}$**	**$H_{2(g)}$**
n	2	1	1	1	1
Initial	0.163	40.0	13.4	15.3	19.2
Change	$+\ 2x$	$+\ x$	$-\ x$	$-\ x$	$-\ x$
Equilibrium	$0.163 + 2x$	$40.0 + x$	$13.4 - x$	$15.3 - x$	$19.2 - x$

$19.2 - x = 13.6$

$x = 5.6\ M$

At equilibrium, $[NH_3] = 40.0 + x$

$[NH_3] = 40.0 + 5.6 = 45.6\ M$

$n(NH_3) = 45.6 \times 7000 = 3.192 \times 10^5\ mol$

$M(NH_3) = (14.0) + (3 \times 1.0) = 17.0\ g\ mol^{-1}$

$m(NH_3) = 3.192 \times 10^5 \times 17.0 \simeq 5.43 \times 10^6\ g$

iii

Concentration (mol L^{-1})	**$2CO_{(g)}$**	**$NH_{3(g)} \rightleftharpoons$**	**$HCN_{(g)}$**	**$CO_{2(g)}$**	**$H_{2(g)}$**
n	2	1	1	1	1
Initial	0.163	40.0	13.4	15.3	19.2
Change	$+\ 2x$	$+\ x$	$-\ x$	$-\ x$	$-\ x$
Equilibrium	$0.163 + 2x$	$40.0 + x$	0.00100	$15.3 - x$	$19.2 - x$

$13.4 - x = 0.00100$

$x = 13.399$

$[CO] = 0.163 + 2 \times 13.399 = 26.961\ M$

$[NH_3] = 40.0 + 13.399 = 53.399\ M$

$[HCN] = 0.00100$

$[CO_2] = 15.3 - 13.399 = 1.901\ M$

$[H_2] = 19.2 - 13.399 = 5.801\ M$

$$K_c = \frac{[HCN][CO_2][H_2]}{[CO]^2[NH_3]} = \frac{(0.00100) \times (1.901) \times (5.801)}{(26.961)^2 \times (53.399)}$$

$$\simeq 2.84 \times 10^{-7}$$

iv [As the temperature of the reaction vessel was decreased to T_2, the value of K_c decreased from 0.175 to 2.84×10^{-7}.[1]] [A decreased temperature leading to a decreased value of K_c is consistent with an endothermic reaction.[2]]

✓ ✗ I have described the relationship between the temperature change and the new value of K_c.[1]

✓ ✗ I have determined whether the reaction is exothermic or endothermic.[2]

c [A system at equilibrium will not spontaneously leave equilibrium unless some change is made to the system. Since no changes were made to the system or environment, none of the concentrations should have changed from their equilibrium values.[1]] [The only concentrations that were observed to change on the analysis software were those of NH_3 and HCN. This is not possible as HCN requires the carbon from CO and if it were actually being produced, then all other reagent concentrations would be changing as well.[2]] [As a result, the chemist is justified in making his hypothesis.[3]]

✓ ✗ I have explained that if no change is made to the system or environment, then a system in dynamic equilibrium will remain in equilibrium.[1]

✓ ✗ I have explained how the observed concentration changes of NH_3 and HCN are not possible.[2]

✓ ✗ I have identified whether the chemist is justified in making his hypothesis.[3]

d [It is not possible to determine anything about the relative value of this reaction's equilibrium constant.[1]] [Although this reaction was observed to proceed at a much higher rate, a reaction's value of K_c is an indicator of extent of reaction and is not necessarily linked to the rate of reaction.[2]]

✓ ✗ I have determined whether or not this information can be used in calculating the relative value of this reaction's equilibrium constant.[1]

✓ ✗ I have explained that K_c is only an indicator of the extent of a reaction not its rate of reaction.[2]

Multiple lessons

13 a

Concentration (mol L^{-1})	$2SO_{2(g)}$	$O_{2(g)} \rightleftharpoons$	$2SO_{3(g)}$
n	2	1	2
Initial	0.00	0.00	3.00
Change	+ 2x	+ x	– 2x
Equilibrium	+ 2x	+ x	3.00 – 2x

$$Kc = \frac{[SO_3]^2}{[SO_2]^2[O_2]} = \frac{(3.00 - 2x)^2}{(2x)^2 \times (x)} = \frac{(3.00 - 2x)^2}{4x^3} = 12700\ M^{-1}$$

Assuming that $3.00 \rightarrow x$

$3.00 - 2x \simeq 3.00$

$\frac{3.00^2}{4x^3} = 12700$

$9.00 = 50800x^3$

$x^3 = 1.772 \times 10^{-4}$

$x \simeq 0.05617$

(NB: Not using this approximation gives $x \simeq 0.055$)

Therefore, $[SO_2]$ at equilibrium = $2x = 2 \times 0.05617 = 0.112$ M

b [The approximation is most valid when the amount that the concentration of $SO_{3(g)}$ changes is minimal to its initial concentration. This occurs when the equilibrium position greatly favours the formation of products, which means that it has a high value of K_c.[1]] [As the reaction is exothermic, decreasing the temperature will increase the value of K_c.[2]] [Therefore, the approximation is most valid when the temperature is very low.[3]]

✓ ✗ I have described how the validity of the approximation relates to the value of K_c.[1]

✓ ✗ I have linked the exothermic nature of the reaction to the effect of temperature on its K_c value.[2]

✓ ✗ I have determined the conditions of temperature that will favour the use of the approximation.[3]

c $[SO_2] = 2x = 2 \times 0.05617 = 0.112336$ M

$n(SO_2) = 0.112336 \times 700.0 = 78.635$ mol

$[O_2] = x = 0.05617$ M

$n(O_2) = 0.05617 \times 700.0 = 39.318$ mol

$[SO_3] = 3.00 - 2x = 3.00 - 2 \times 0.05617 = 2.8877$ M

$n(SO_3) = 2.8877 \times 700.0 = 2021$ mol

Temperature = 552 + 273 = 825 K

$PV = nRT$

All gases exert the same amount of pressure per mol. The total pressure of a mixture of gases is the sum of the partial pressures of each gas.

$P \times 700.0 = (n(SO_2) + n(O_2) + n(SO_3)) \times 8.31 \times 825$

$P \times 700.0 = (78.635 + 39.318 + 2021) \times 8.31 \times 825$

$$P = \frac{(78.635 + 39.318 + 2021) \times 8.31 \times 825}{700.0}$$

$P = 20953$ kPa

14 a $Q_c = \frac{[NH_3]^2}{[N_2][H_2]^3} = \frac{(0.800)^2}{(0.400) \times (0.0700)^3} = 4665\ M^{-2}$

b $Q_c = 4665\ M^{-2}$ $K_c = 3000\ M^{-2}$

$Q_c \neq K_c$

Therefore, the system is not at equilibrium.

c [$Q_c > K_c$.[1]] [This means that the system will favour the formation of reactants as it establishes equilibrium, leading to a net backward reaction.[2]]

✓ ✗ I have related the value of Q_c to the stated value of K_c.[1]

✓ ✗ I have determined the direction in which the reaction will proceed to establish equilibrium.[2]

d [K_c is not an indicator of rate of reaction, only of the extent to which the reaction proceeds.[1]] [As a result, although the value of K_c can be high, the system's rate of reaction can still be quite low.[2]]

✓ ✗ I have stated the distinction between K_c and the rate of reaction.[1]

✓ ✗ I have linked this concept to the observation of the chemist.[2]

d [A catalyst will not increase the amount of NH_3 present once the system reaches equilibrium.[1]] [This is because a catalyst only affects the rate of the forward and backward reaction by an equal amount, not the value of K_c and so will not affect the extent of the reaction.[2]]

✓ ✗ I have stated whether the addition of a catalyst will affect the equilibrium concentration of NH_3.[1]

✓ ✗ I have explained why this is true with reference to the value of K_c.[2]

5E Le Châtelier's principle

Theory review questions

1 C **2** B **3** B

Exam-style questions

Within lesson

4 C **5** B **6** D **7** A

8 [Adding an inert gas at constant temperature and volume only increases the pressure of the reaction vessel, rather than affecting any concentrations.[1]][Therefore, equilibrium has not been disturbed which means no response is required.[2]][Therefore, the concentration of oxygen will remain the same.[3]]

✓ ✗ I have explained the effect of the addition of an inert gas.[1]

✓ ✗ I have stated that equilibrium will not be disturbed.[2]

✓ ✗ I have linked this fact to the concentration of oxygen.[3]

9 **a**

Change applied	Observation of gas syringe
Increase in temperature at constant volume	Lighter
Addition of $NO_{2(g)}$ at constant volume/temperature	Darker
Removal of $NO_{2(g)}$ at constant volume/temperature	Lighter

b [Xavier's prediction is incorrect.[1]][This is because when the plunger is pushed in, all the concentrations increase, disturbing equilibrium and necessitating a response. Therefore, a net back reaction will occur as this reaction consumes 2 mol gas to produce 1 mol gas, shifting the position of equilibrium to the left.[2]][However, Le Châtelier's principle only partially opposes this change which means the concentration of the brown gas, $NO_{2(g)}$, will still be greater than it was before the plunger was pushed down.[3]][Since the colour is proportional to the concentration of $NO_{2(g)}$, a greater concentration of $NO_{2(g)}$ means the gas syringe will be darker rather than lighter.[4]]

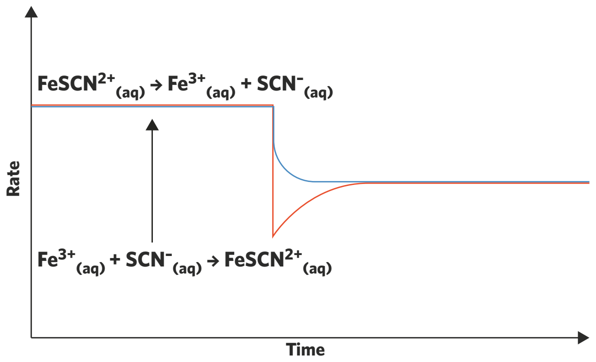
✓ ✗ I have stated whether his prediction is correct or incorrect.[1]

✓ ✗ I have explained why Xavier's statement that the position of equilibrium will shift to the left is correct.[2]

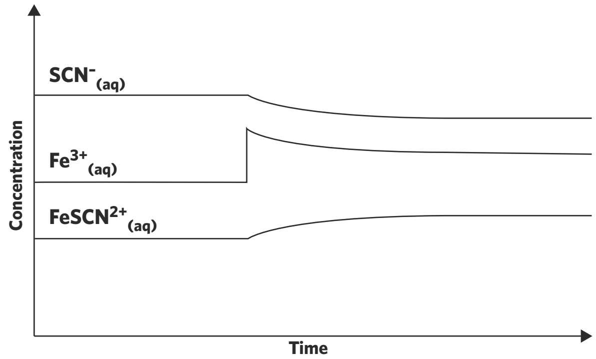
✓ ✗ I have defined how Le Châtelier's principle is only a partial opposition to any change.[3]

✓ ✗ I have linked the concentration of $NO_{2(g)}$ to the ultimate colour of the syringe.[4]

10 **a**



b



c [For an exothermic reaction, a decrease in temperature results in an increase in the value of K_c, disturbing equilibrium and hence necessitating a response.[1]][According to Le Châtelier's principle, the system will partially oppose this decrease in temperature by favouring the forward, exothermic reaction as this produces some thermal energy in an attempt to partially counteract the decrease in temperature.[2]][Therefore, the position of equilibrium will shift to the right, resulting in more products being produced and thereby increasing the value of K_c.[3]]

✓ ✗ I have stated that equilibrium has been disturbed, necessitating a response.[1]

✓ ✗ I have used Le Châtelier's principle to justify the change that will occur.[2]

✓ ✗ I have stated the overall effect on the position of equilibrium.[3]

d [In the concentration-time graph, all three species experience a gradual change, which means that a temperature change has occurred.[1]][The concentrations of $Fe^{3+}_{(aq)}$ and $SCN^{-}_{(aq)}$ have increased gradually, which indicates that the change in temperature triggered the back reaction to be favoured.[2]][Therefore, the temperature was increased as the endothermic reaction was favoured.[3]]

✓ ✗ I have used the fact that there were no sharp changes in concentration to determine that a temperature change occurred.[1]

✓ ✗ I have identified which way the equilibrium position shifted.[2]

✓ ✗ I have deduced whether it was a temperature increase or decrease.[3]

e [The sharp increase in the rate of the $FeSCN^{2+}_{(aq)} \rightarrow Fe^{3+}_{(aq)} + SCN^{-}_{(aq)}$ reaction and not in the $Fe^{3+}_{(aq)} + SCN^{-}_{(aq)} \rightarrow FeSCN^{2+}_{(aq)}$ reaction^{1}][suggests that $FeSCN^{2+}_{(aq)}$ was added at constant volume and temperature.^{2}]

✓ ✗ I have identified the key change in the graph.^{1}

✓ ✗ I have identified a cause for the change in the graph.^{2}

Multiple lessons

11 a A catalyst increases the rate of a chemical reaction by providing an alternate energy pathway with a lower activation energy.

b $2C_8H_{18(l)} + 17O_{2(g)} \rightarrow 16CO_{(g)} + 18H_2O_{(g)}$

c [A catalytic converter helps to increase the rate of reaction of the decomposition of carbon monoxide, allowing a much smaller amount to escape.^{1}][It is compulsory that this occurs in cars because carbon monoxide poses a serious health risk if inhaled, for example by pedestrians, because it binds to haemoglobin more strongly than oxygen does, establishing competing equilibrium reactions. This can lead to fatal cases of carbon monoxide poisoning.^{2}]

✓ ✗ I have mentioned the role of the catalytic converter in reducing the amount of carbon monoxide released.^{1}

✓ ✗ I have mentioned the health risks associated with carbon monoxide poisoning.^{2}

d [Catalysts do not affect the final position of equilibrium.^{1}][This is because they increase the rates of the forward and backward reactions by equal amounts, allowing equilibrium to be reached more rapidly, but not changing its final position.^{2}]

✓ ✗ I have stated that catalysts do not affect the position of equilibrium.^{1}

✓ ✗ I have justified my answer with reference to the function of catalysts.^{2}

12 a $K_c = \dfrac{[Cl_2]^3[I_2]}{[ICl_3]^2}$

b

	$[ICl_3]$	$[Cl_2]$	$[I_2]$
I	0.70	0	0
C	-0.60	+0.90	+0.30
E	0.10	0.90	0.30

$$K_c = \frac{(0.90)^3(0.30)}{(0.10)^2} = 21.9 = 2.2 \times 10^1\ M^2$$

c [As the reaction is endothermic, an increase in temperature of the vessel would favour the forward reaction^{1}][as the system would want to partially oppose the change by absorbing the increased energy.^{2}][As a result, there would be more iodine and chlorine gas being produced, consequently increasing the concentration of chlorine and iodine gas.^{3}]

✓ ✗ I have identified the effect of an increase in temperature on the direction of the reaction.^{1}

✓ ✗ I have explained why the direction of the reaction is favoured.^{2}

✓ ✗ I have linked my answer to the question.^{3}

d The equilibrium constant would increase.

Chapter 5 review

Multiple choice

1	D	**2**	D	**3**	B	**4**	B	**5**	C
6	D	**7**	B	**8**	A	**9**	A	**10**	C

Short answer

11 a i $K_c = \dfrac{[NH_3]^2}{[N_2][H_2]^3}$

ii M^{-2}

iii $\sqrt{0.118} = 0.344$

b

	Magnitude of K_c	$[N_{2(g)}]$	**Rate of the forward reaction**
Temperature is decreased	Increase	Decrease	Decrease
Volume is increased	No change	Decrease	Decrease
3.0 mol of Neon gas is introduced to the reaction vessel	No change	No change	No change
Ammonia gas is added (at constant volume)	No change	Increase	Increase

c i Lower

ii $Q_c = \dfrac{\left[\frac{4.0}{1.0}\right]^2}{\left[\frac{2.0}{1.0}\right]\left[\frac{3.0}{1.0}\right]^3}$

$Q_c = \dfrac{8}{27} = 0.296$

$0.296 \neq 8.0$

[At equilibrium, both Q_c and K_c would be equal.^{1}][As $Q_c \neq K_c$, this mixture is not at equilibrium.^{2}]

✓ ✗ I have identified the relationship between Q_c and K_c at equilibrium.^{1}

✓ ✗ I have related my answer to the question.^{2}

✓ ✗ I have included calculations to support my answer.

iii $\dfrac{\left[\frac{4.0}{V}\right]^2}{\left[\frac{2.0}{V}\right]\left[\frac{3.0}{V}\right]^3} = 8.0$

$\dfrac{\frac{16}{V^2}}{\frac{54}{V^4}} = 8.0$

$\dfrac{16\ V^2}{54} = 8.0$

$V^2 = 27$

$V = 5.2\ L$

iv [This increase in volume will result in a decrease in the pressure of the reaction vessel, disturbing the equilibrium.^{1}][According to Le Châtelier's principle, the system will move to partially oppose the change by favouring the side with more particles.^{2}][This results in the backwards reaction being favoured, causing an increase in the amount of mol of $N_{2(g)}$ present at equilibrium.^{3}]

[However, since the volume of the reaction vessel has doubled, the overall concentration of $N_{2(g)}$ at equilibrium will have decreased.[4]]

✓ ✗ I have described the effect of an increase in volume on the reaction vessel.[1]

✓ ✗ I have justified my answer with reference to Le Châtelier's principle.[2]

✓ ✗ I have explained the change's effect on the amount in mol of $N_{2(g)}$.[3]

✓ ✗ I have explained the change's effect on the concentration of $N_{2(g)}$.[4]

12 **a** **i**

	$[H_2]$	$[I_2]$ $\rightleftharpoons$	$2[HI]$
n(I)	2.00	5.00	0
n(C)	-1.30	-1.30	+2.60
n(E)	0.70	3.70	2.60

$[H_2] = 0.175$ M

$[I_2] = 0.925$ M

$[HI] = 0.650$ M

ii $K_c = \dfrac{[HI]^2}{[H_2]\,[I_2]}$

$K_c = \dfrac{(0.65)^2}{(0.175)(0.925)}$

$K_c = 2.61$

b **i** [At the beginning, the reaction vessel contained only hydrogen and iodine and can only react in one direction, which means that the forward reaction $H_{2(g)} + I_{2(g)} \rightleftharpoons 2HI_{(g)}$ is the only reaction occurring initially.[1]] [This implies that the rate of this reaction will always be greater than the rate of the backwards reaction $2HI_{(g)} \rightleftharpoons H_{2(g)} + I_{2(g)}$ while the system is reaching equilibrium.[2]]

✓ ✗ I have explained the consequences of the reaction vessel's initial conditions on the direction of the reaction.[1]

✓ ✗ I have described how this relates to the respective rates of the forward and backward reactions while the system is reaching equilibrium.[2]

ii [At equilibrium, the rates of the forward and backward reactions are equal.[1]] [This means that the rate of the backward reaction will never be greater than that of the forward reaction.[2]]

✓ ✗ I have described the effect of equilibrium on the rate of the forward and backward reactions.[1]

✓ ✗ I have linked my answer to the question.[2]

c **i** Decrease

ii The intensity of the purple colour will have increased compared to that of the reaction vessel described in part a.

13 **a** $[SO_3] = \dfrac{0.080}{5.0} = 0.016$ M

$[SO_2] = \dfrac{0.040}{5.0} = 0.008$ M

$[O_2] = \dfrac{0.010}{5.0} = 0.002$ M

$K_c = \dfrac{[SO_3]^2}{[SO_2]^2[O_2]}$

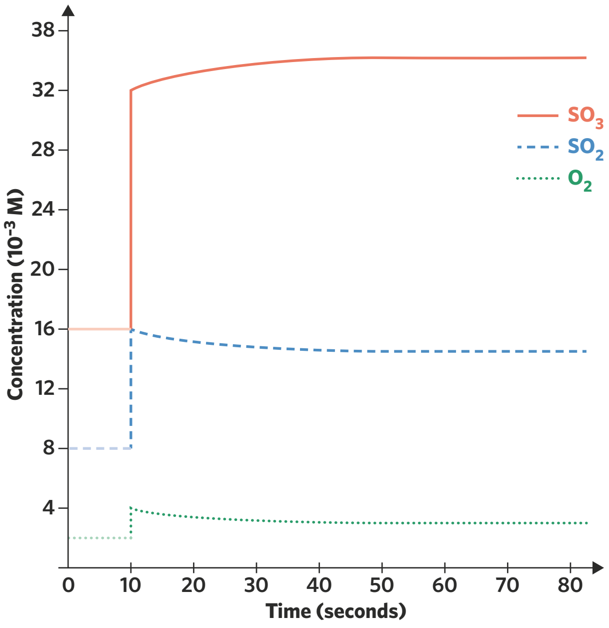
$K_c = \dfrac{(0.016)^2}{(0.008)^2(0.002)}$

$K_c = 2.0 \times 10^3\ M^{-1}$

b **i** Increase

ii Increase

c



d **i** [The forward reaction for the synthesis of SO_3 is exothermic.[1]] [This means that an increase in temperature will actually favour the backward reaction, as the system moves to partially oppose the increase in energy, leading to a decrease in the overall yield of SO_3.[2]]

✓ ✗ I have stated that the forward reaction is exothermic.[1]

✓ ✗ I have described how an increase in temperature will affect the yield of SO_3.[2]

ii [A catalyst increases the rate of reaction by providing an alternate reaction pathway with a lower activation energy.[1]] [This means that a larger proportion of reactant molecules at a given temperature have sufficient energy to react and form products as the system reaches equilibrium.[2]] [While both the executive's and chemist's solutions will act to increase the overall rate of reaction, unlike an increase in temperature, the use of a catalyst will not decrease the yield of SO_3 as catalysts do not alter the position of the final equilibrium.[3]]

✓ ✗ I have described how a catalyst affects a reaction's activation energy.[1]

✓ ✗ I have identified how this affects the system's rate of reaction.[2]

✓ ✗ I have compared the two potential solutions with reference to both the rate and the yield of the reaction.[3]

Key science skill question

14 **a** 1. PPE (Personal Protective Equipment) such as a face mask

2. Operating the experiment within a fume hood

b [The two syringes contain different levels of the gas and so any colour change will be proportional to the initial starting concentrations.[1]] [Also, each syringe was compressed to a different extent, so a quantitative comparison is impossible given the different starting concentrations.[2]] [Furthermore, colour changes are very subjective and difficult to assess quantitatively.[3]]

✓ ✗ I have identified the effect of having varying levels of gas.[1]

✓ ✗ I have identified the effect of an inconsistency with the method.[2]

✓ ✗ I have identified the effect of using qualitative information to take quantitative measurements.[3]

c [The amount of NO_2 initially present in the syringes should either be measured or equal in both syringes.[1]] [The syringes should be compressed to an equal extent.[2]] [The assessment of the change in the intensity of the colour should be performed by only one of the two students, or through a computerised method such as measuring the intensity and absorbance of light shining through the syringe.[3]]

✓ ✗ I have referred to the amount of substance used.[1]

✓ ✗ I have referred to the method.[2]

✓ ✗ I have referred to the analysis of data.[3]

6A Electrolytic reactions

Theory review questions

1 B **2** D **3** B

Exam-style questions

Within lesson

4 B

5 **a** [Sarah's statement is incorrect because an electrolytic reaction will only occur given a sufficient voltage.^{1}][Therefore, if sufficient voltage is not applied for the electrolysis reaction between $Pb_{(s)}$ and $Ni^{2+}_{(aq)}$, no reaction will occur which explains why nothing is observed.^{2}]

✓ ✗ I have evaluated the accuracy of Sarah's statment.^{1}

✓ ✗ I have explained her experimental results.^{2}

b Oxidation half equation: $Pb_{(s)} \rightarrow Pb^{2+}_{(aq)} + 2e^-$

Reduction half equation: $Ni^{2+}_{(aq)} + 2e^- \rightarrow Ni_{(s)}$

6 **a** $Pb^{2+}_{(aq)} + 2H_2O_{(l)} \rightarrow PbO_{2(s)} + 4H^+_{(aq)} + 2e^-$

b $Pb^{2+}_{(aq)} + 2e^- \rightarrow Pb_{(s)}$

c $2Pb^{2+}_{(aq)} + 2H_2O_{(l)} \rightarrow Pb_{(s)} + PbO_{2(s)} + 4H^+_{(aq)}$

7 **a** Oxidation: $Fe_{(s)} \rightarrow Fe^{3+}_{(l)} + 3e^-$

Reduction: $Mg^{2+}_{(l)} + 2e^- \rightarrow Mg_{(s)}$

b $2Fe_{(s)} + 3Mg^{2+}_{(l)} \rightarrow 2Fe^{3+}_{(l)} + 3Mg_{(s)}$

8 **a** [The student's prediction is inaccurate.^{1}][This is because according to the electrochemical series $Cu^{2+}_{(aq)}$ is a stronger oxidising agent than $Co^{2+}_{(aq)}$ which means $Cu^{2+}_{(aq)}$ will react preferentially.^{2}]

✓ ✗ I have identified whether the student's prediction is accurate or inaccurate.^{1}

✓ ✗ I have justified my answer with the use of the electrochemical series.^{2}

b Since different electrolytic reactions require different voltages, the student could change the voltage to a level where one reaction is favoured over another.

Multiple lessons

9 [$Cu^{2+}_{(aq)}$, is a strong oxidising agent and together with $Zn_{(s)}$, a strong reducing agent, will result in a spontaneous redox reaction.^{1}] [This means that it can generate electricity in a galvanic cell without any forcing conditions.^{2}][On the other hand, $Cu_{(s)}$, a reducing agent with an E^0 value that is higher than the oxidising agent $Zn^{2+}_{(aq)}$, therefore a spontaneous redox reaction cannot occur.^{3}][As a result, this electrolytic reaction cannot generate electricity and has to be forced to occur by an external power source.^{4}]

✓ ✗ I have used the electrochemical series to justify why a spontaneous redox reaction occurs between $Cu^{2+}_{(aq)}$ and $Zn_{(s)}$.^{1}

✓ ✗ I have linked this fact to the ability for this reaction to generate electricity in a galvanic cell.^{2}

✓ ✗ I have used the electrochemical series to justify why a spontaneous redox reaction cannot occur between $Zn^{2+}_{(aq)}$ and $Cu_{(s)}$.^{3}

✓ ✗ I have linked this fact to the inability for this reaction to generate electricity in a galvanic cell.^{4}

10 **a** $Ni_{(s)} \rightarrow Ni^{2+}_{(aq)} + 2e^-$

$Ag^+_{(aq)} + e^- \rightarrow Ag_{(s)}$

b Oxidation process: $Ni_{(s)}/Ni^{2+}_{(aq)}$

Reduction process: $Ag^+_{(aq)}/Ag_{(s)}$

c $Ni^{2+}_{(aq)} + 2Ag_{(s)} \rightarrow Ni_{(s)} + 2Ag^+_{(aq)}$

11 **a** [No.^{1}][This is a spontaneous redox reaction because according to the electrochemical series the $Cu^{2+}_{(aq)}$ is a strong oxidant with a higher E^0 value than the reducing agent $Pb_{(s)}$ and therefore, this reaction does not need to be forced to occur.^{2}]

✓ ✗ I have identified whether this is an electrolytic reaction.^{1}

✓ ✗ I have referenced the electrochemical series.^{2}

b $Cu_{(s)} + Pb^{2+}_{(aq)} \rightarrow Cu^{2+}_{(aq)} + Pb_{(s)}$

c [Since $Cu^{2+}_{(aq)}$ ions are entering the solution, it will turn a darker blue colour.^{1}][Because $Pb^{2+}_{(aq)}$ is being reduced to form $Pb_{(s)}$ at the cathode, a plating of lead metal will appear on the copper electrode.^{2}][The anode will appear corroded as $Cu_{(s)}$ is oxidised to form $Cu^{2+}_{(aq)}$ ions.^{3}]

✓ ✗ I have stated what will be observed in the solution.^{1}

✓ ✗ I have stated what will be observed at the cathode.^{2}

✓ ✗ I have stated what will be observed at the anode.^{3}

d [Yes the teacher is justified in his anger.^{1}][This is because the $Pb_{(s)}$ present in the solution after electrolysis has coated the copper electrode instead of forming the initial lead strip, making it difficult to salvage any of the metal for use by the class.^{2}]

✓ ✗ I have explained whether the teacher should be angry.^{1}

✓ ✗ I have explained what has happened to the $Pb_{(s)}$ in the solution.^{2}

6B Electrolytic cells

Theory review questions

1 C **2** C

3 Electrolytic cells undergo **redox** reactions, converting **electrical** energy to **chemical** energy. The voltage of the power source can be calculated by the equation $E^0_{\text{cell}} = \mathbf{E^0_{reduction}} - E^0_{\text{oxidation}}$. Electrons flow from the power source to the **cathode** and from the **anode** back to the power source.

Exam-style questions

Within lesson

4 B **5** A

6 **a** [This statement is incorrect ^{1}][as the reactions occurring in galvanic cells are spontaneous and therefore galvanic cells do not require a power supply.^{2}]

✓ ✗ I have identified the correctness of the statement.^{1}

✓ ✗ I have explained my answer.^{2}

b [This statement is incorrect^{1}][as galvanic cells convert chemical energy to electrical energy, and electrolytic cells convert electrical energy to chemical energy.^{2}]

✓ ✗ I have identified the correctness of the statement.^{1}

✓ ✗ I have explained my answer.^{2}

c [This statement is incorrect^{1}][as the polarities of the anode and cathode of a galvanic cell are opposite to those in an electrolytic cell.^{2}]

✓ ✗ I have identified the correctness of the statement.^{1}

✓ ✗ I have explained my answer.^{2}

7 **a** [Molten.^{1}][If an aqueous electrolyte is used, since water is a stronger oxidising agent than lithium ions, water will be reduced and as a result, lithium metal will not be produced.^{2}][Therefore, to avoid water being reduced, a molten electrolyte should be used.^{3}]

✓ ✗ I have identified what type of electrolyte is required.^{1}

✓ ✗ I have used evidence from the electrochemical series that supports my answer.^{2}

✓ ✗ I have linked my answer to the question.^{3}

b **i** [With an iron anode, iron is the strongest reducing agent present,^{1}][and so the reaction at the anode will be $Fe_{(s)} \rightarrow Fe^{2+}_{(l)} + 2e^{-}$.^{2}][With an iron cathode, iron will not take place in the reaction as it is not able to be reduced and it is not at the anode.^{3}][Consequently, the reaction at the anode will remain $2Cl^{-}_{(l)} \rightarrow Cl_{2(g)} + 2e^{-}$.^{4}][This difference in reactions at the anode explains why different products, $Fe^{2+}_{(l)}$ or $Cl_{2(g)}$, are produced with different electrodes.^{5}]

✓ ✗ I have identified the effect of the iron anode.^{1}

✓ ✗ I have identified the reaction occurring at the anode in cell 1.^{2}

✓ ✗ I have identified the effect of the iron cathode.^{3}

✓ ✗ I have identified the reaction occurring at the anode in cell 2.^{4}

✓ ✗ I have linked the reactions to the products made.^{5}

ii [The desired reaction is the conversion of lithium ions to solid lithium.^{1}][The iron anode is a stronger reducing agent than $Cl^{-}_{(l)}$ and could be oxidised in this reaction, meaning that it may crumble.^{2}][The carbon anode is inert and does not react, so does not affect the reaction.^{3}][Therefore, the carbon anode in cell 2 would result in the desired reaction and the electrode not crumbling.^{4}]

✓ ✗ I have identified the desired reaction.^{1}

✓ ✗ I have identified the reaction occurring with the iron electrode.^{2}

✓ ✗ I have identified the reaction occurring with the carbon electrode.^{3}

✓ ✗ I have made a concluding statement as to which electrode is required.^{4}

c [The voltage required for the reaction between Cl^{-} and Li^{+} to occur is given by $E^{0}_{cell} = E^{0}_{reduction} - E^{0}_{oxidation}$^{1}] [$= -3.04 - (1.36) = -4.40$ V ^{2}][As the supplied voltage, 1.05 V, is less than the required voltage, −4.40 V, it is expected that the reaction will not occur, and the solid lithium will not be produced.^{3}]

✓ ✗ I have given an equation to calculate the voltage required for the cell to operate.^{1}

✓ ✗ I have calculated the required voltage.^{2}

✓ ✗ I have compared the required voltage to the supplied voltage to explain why the reaction will not occur.^{3}

8 **a** [Carbon electrodes are inert and therefore would not take part in the reaction.^{1}][The prediction stated implies that the student believed that water is the strongest oxidising or reducing agent, resulting in the production of hydrogen or oxygen gas respectively.^{2}][However, according to the electrochemical series, the tin (II) ion is the strongest oxidising and reducing agent and therefore will be reduced to solid tin and oxidised to tin (IV) ions respectively.^{3}][As a result, no bubbles would have been observed in the reaction.^{4}]

✓ ✗ I have identified the main characteristic of carbon electrodes.^{1}

✓ ✗ I have identified the reason for the student's prediction.^{2}

✓ ✗ I have used the electrochemical series to account for the unexpected observation.^{3}

✓ ✗ I have linked my answer to the question.^{4}

b Anode: $Sn^{2+}_{(aq)} \rightarrow Sn^{4+}_{(aq)} + 2e^{-}$

Cathode: $Sn^{2+}_{(aq)} + 2e^{-} \rightarrow Sn_{(s)}$

c [The use of molten reactants would eliminate the presence of water, however tin (II) ions would still be the strongest oxidising and reducing agent.^{1}][Therefore, there would be no change in the overall reaction of the cell.^{2}]

✓ ✗ I have identified the effect of using molten reactants.^{1}

✓ ✗ I have linked my answer back to the question.^{2}

Multiple lessons

9 **a** Reducing agent: Copper solid, Oxidising agent : Water

b $2H_2O_{(l)} + 2e^{-} \rightarrow H_{2(g)} + 2OH^{-}_{(aq)}$

c $2H_2O_{(l)} + Cu_{(s)} \rightarrow H_{2(g)} + 2OH^{-}_{(aq)} + Cu^{2+}_{(aq)}$

d [From the electrochemical series, we can see that water is a stronger oxidising agent than sodium ions, and so will be reduced in preference.[1]][This changes the reaction, meaning the desired product, sodium metal, is no longer produced. The use of a molten reactant would eliminate this issue,[2]][however would add significant cost to the project, due to the high heat required.[3]][Therefore, to counteract this and reduce the operating costs a carbon electrode can be used instead of a platinum electrode as it is much cheaper.[4]]

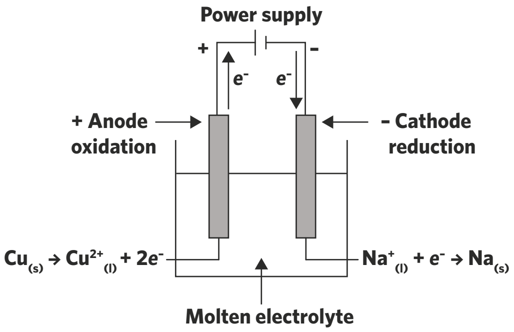
✓ ✗ I have identified which reactant is the strongest reducing agent/oxidising agent.[1]

✓ ✗ I have described the effect of the electrolyte on the product obtained.[2]

✓ ✗ I have described the effect of the electrolyte on the project requirements.[3]

✓ ✗ I have identified a way to minimise operating costs.[4]

e



✓ ✗ I have labelled the power supply.[1]

✓ ✗ I have labelled the anode with its charge.[2]

✓ ✗ I have labelled the cathode with its charge.[3]

✓ ✗ I have labelled the reaction occurring at the anode.[4]

✓ ✗ I have labelled the reaction occurring at the cathode.[5]

✓ ✗ I have labelled the electrolyte as molten.[6]

✓ ✗ I have correctly drawn the direction of flow of electrons.[7]

f 3.05 V

g [The safety data sheet indicates that sodium may ignite when in contact with water.[1]][As a result, the company should store the sodium samples in a dry, airtight container to minimise the chance of explosion.[2]]

✓ ✗ I have identified relevant evidence from the Material Safety Data Sheet.[1]

✓ ✗ I have listed an appropriate measure to store the sample.[2]

6C Faraday's laws

Theory review questions

1 C **2** D

Exam-style questions

Within lesson

3 A **4** A

5 a $n(e^-):n(Ag^+)$

1:1

Therefore $n(e^-) = 0.412$ mol

$Q = 0.412 \times 96500 = 39758\ C$

$t = \frac{39758}{3.1} = 12825.2 = 1.3 \times 10^4$ seconds

b [Although in the same conditions, with a 3.1 A current applied for 1.3 x 10^4 secs (as calculated in part a), and the same electric charge, there would be less cobalt solid produced as compared to silver.[1]][This is due to the 1:1 mol ratio between electrons and silver compared to the 2:1 ratio of cobalt.[2]][Therefore, for the same amount of electric charge, there would be half the quantity (in mol) of cobalt solid produced compared to silver.[3]]

✓ ✗ I have compared the amount of cobalt produced relative to silver.[1]

✓ ✗ I have used the mole ratio to explain the difference.[2]

✓ ✗ I have linked my answer to the question.[3]

6 a $Q = 3.50 \times (21.0 \times 60) = 4410\ C = 4.41 \times 10^3\ C$

b $n(e^-) = n(\text{Li}^+) = 4.22 \times 10^{-2}$ mol

$Q = 4.22 \times 10^{-2} \times 96500 = 4072.3$ C

$Q = It$

$I = \frac{4072.3}{(9.0 \times 60)} = 7.54 = 7.5$ A

7 a 0.045 faraday is equivalent to 0.045 mol of electrons.

$Cr^{3+}{}_{(aq)} + 3e^- \rightarrow Cr_{(s)}$

$n(Cr_{(s)}) = \frac{0.045}{3} = 0.015$ mol

b For copper:

$Cu^{2+}{}_{(aq)} + 2e^- \rightarrow Cu_{(s)}$

$n(Cu) = \frac{0.045}{2} = 0.0225$ mol

Sodium ions will not undergo reduction in a $NaNO_{3(aq)}$ solution as Na^+ is a weaker oxidising agent than water.

[Therefore 0.023 mol of copper and no sodium would be produced.[1]][Using the same amount of electric charge, copper would be the metal with the greatest number of moles produced, followed by chromium and sodium.[2]]

✓ ✗ I have included values in my answer.[1]

✓ ✗ I have compared the amount, in mol, of solid metal produced given the same electric charge.[2]

✓ ✗ I have included calculations in my answer.

8 a $n(Cr) = \frac{1.02}{52.0} = 0.0196$ mol

b 0.0392 F means 0.0392 mol of electrons have passed through the circuit. As this is double the quantity of chromium deposited, the oxidation state must be +2.

Multiple lessons

9 **a** $Q = 1.20 \times (2 \times 60) = 144\ C$

$n(e^-) = \frac{144}{96500} = 0.001492$ mol

The mol ratio between $n(e^-)$ and $n(A^{x+})$is:

$0.001492/7.46 \times 10^{-4} = 2$

Therefore x is 2

b $E^0_{cell} = E^0_{reduction} - E^0_{oxidation}$

$-1.67 = x - (+1.23)$

$x = -0.44$ V

[Therefore the reduction half-equation has an E^0 of -0.44V.[1]] [Using the electrochemical series in our data book, we can see this corresponds to the half-equation $Fe^{2+}_{(aq)} + 2e^- \rightarrow Fe_{(s)}$. Therefore the half-equation occurring at the cathode is $Fe^{2+}_{(aq)} + 2e^- \rightarrow Fe_{(s)}$.[2]]

✓ ✗ I have identified the E^0 value of the reduction half-equation.[1]

✓ ✗ I have identified the corresponding reduction reaction.[2]

✓ ✗ I have included calculations in my answer.

10 **a** $X^{2+}_{(l)} + 2e^- \rightarrow X_{(s)}$

b $Q = It = 2.98 \times (12.0 \times 60) = 2145.6\ C$

$n(e^-) = \frac{2145.6}{96500} = 0.02223$ mol

$n(X) = \frac{0.02223}{2} = 0.0111$ mol

c $M(X) = \frac{0.97}{0.0111} = 87.4\ g\ mol^{-1}$

According to the periodic table, this molar mass corresponds to strontium.

11 **a** **i** $2H_2O_{(l)} \rightarrow O_{2(g)} + 4H^+_{(aq)} + 4e^-$

ii $Ni^{2+}_{(aq)} + 2e^- \rightarrow Ni_{(s)}$

b $Q = It = 0.351 \times (10.0 \times 60) = 210.6\ C$

$n(e^-) = \frac{210.6}{96500} = 0.002182$ mol

$n(Ni) = \frac{0.002181}{2} = 0.001091$ mol

$m(Ni) = 0.001091 \times 58.7 = 0.06405\ g = 6.41 \times 10^{-2}\ g$

c [If a lead cathode were used instead of platinum electrode, there would be no change[1]] [as $Pb_{(s)}$ is acting as the cathode so there is a flow of electrons constantly passing through it[2]] [meaning it cannot itself be oxidised[3]].

✓ ✗ I have described the effect of the use of a lead cathode.[1]

✓ ✗ I have stated why there would be no change.[2]

✓ ✗ I have stated whether lead can be oxidised or not.[3]

12 **a** $Cu^+_{(aq)} + e^- \rightarrow Cu_{(s)}$

b i [Potassium cyanide provides CN^- for the reaction identified.[1]] [As a result, the forward reaction would be preferred to partially oppose the excess cyanide ions present,[2]] [resulting in a decrease in the concentration of the Cu+ ion.[3]]

✓ ✗ I have identified the role of potassium cyanide.[1]

✓ ✗ I have described how potassium cyanide affects the concentration of CN^-.[2]

✓ ✗ I have linked my answer to the question.[3]

ii [Adding a catalyst would have no effect on the value of K_c.[1]] [A catalyst will speed up both the forward and reverse reactions to the same extent, therefore K_c is not affected.[2]]

✓ ✗ I have identified the effect of adding a catalyst on K_c.[1]

✓ ✗ I have explained my answer.[2]

c $Q = It$

$Q = 0.331 \times 90 = 29.79\ C$

$n(e^-) = \frac{29.79}{96500} = 3.087 \times 10^{-4}$ mol

$n(Cu) = 3.087 \times 10^{-4}$ mol

$n(Cu) = 3.087 \times 10^{-4} \times 63.5 = 0.0196$ g

6D Primary and secondary cells

Theory review questions

1 B **2** B **3** C **4** C

Exam-style questions

Within lesson

5 D

6 [Sunlight increases the temperature of the battery in the phone.[1]] [This would increase the rate of the redox reactions occurring in the battery,[2]] [leading to the battery undergoing discharge more quickly.[3]] [As a result, the battery would be drained a lot quicker.[4]]

✓ ✗ I have identified the increase the temperature of the battery.[1]

✓ ✗ I have identified the effect of an increase in temperature on reaction rate.[2]

✓ ✗ I have described the effect of battery function as a result of the temperature increase.[3]

✓ ✗ I have linked my answer to the question.[4]

7 **a** $ZnO_{(s)} + 2Ag_{(s)} \rightarrow Zn_{(s)} + Ag_2O_{(s)}$

b $2Ag_{(s)} + 2OH^-_{(aq)} \rightarrow Ag_2O_{(s)} + H_2O_{(l)} + 2e^-$

c [The products of the cell reaction must remain in contact with the electrodes[1]] [and must be in a form that allows it to be converted back to reactants.[2]] [If the products cannot be converted back to reactants then the cell will not be able to be recharged.[3]] [Also, an external power source needs to be present to provide the energy necessary to power the non-spontaneous reaction.[4]]

✓ ✗ I have stated that the products must be in contact with the electrodes.[1]

✓ ✗ I have stated that the products must be in a form that allows it to be converted back to reactants.[2]

✓ ✗ I have connected the conditions to the cell's rechargeability.[3]

✓ ✗ I have identified the function of the external battery source.[4]

8 **a** Electrical energy is converted into chemical energy.

b $PbSO_{4\,(s)} + 2H_2O_{(l)} \rightarrow PbO_{2\,(s)} + 4H^+_{(aq)} + SO_4{}^{2-}{}_{(aq)} + 2e^-$

c Positive terminal.

Multiple lessons

9 **a** [Primary cell[1]][because some of the products of the discharge reaction move away from their respective electrode and therefore, the cell cannot be recharged.[2]]

✓ ✗ I have identified the type of cell it is.[1]

✓ ✗ I have supported my answer stating whether it can be recharged or not.[2]

b Cathode: $2MnO_{2(s)} + H_2O_{(l)} + 2e^- \rightarrow Mn_2O_{3\,(s)} + 2OH^-{}_{(aq)}$

Anode: $Zn_{(s)} \rightarrow Zn^{2+}{}_{(aq)} + 2e^-$

10 **a** [A primary cell cannot be recharged, whilst a secondary cell can.[1]] [In a primary cell, the products of the discharge reaction move away from the electrodes, whilst in secondary cells the products of the discharge reaction remain in contact with the appropriate electrodes, and therefore can undergo the reverse reaction to be recharged.[2]]

✓ ✗ I have identified how primary and secondary cells differ with regards to recharging.[1]

✓ ✗ I have identified how primary and secondary cells differ with regards to discharge.[2]

b [Lithium is a strong reducing agent[1]][and so is more readily oxidised than other reducing agents, meaning it can produce a high voltage,[2]] [and therefore it is a desirable reactant for galvanic cells.[3]]

✓ ✗ I have identified the strength of lithium as a reducing agent.[1]

✓ ✗ I have described the effect of using lithium on the cell voltage.[2]

✓ ✗ I have linked my answer to the question.[3]

c $2Li_{(s)} + 2H_2O_{(l)} \rightarrow 2LiOH_{(aq)} + H_{2\,(g)}$

[Due to the strength of lithium solid as a reducing agent, the reaction between water and solid lithium will result in an explosive reaction.[1]] [The $H_{2(g)}$ produced is flammable and may be ignited by an electric spark, causing the battery to explode.[2]]

✓ ✗ I have included a balanced redox reaction between lithium and water.

✓ ✗ I have identified the type of reaction that will occur between lithium and water.[1]

✓ ✗ I have described the danger of the products formed during this reaction.[2]

11 **a** [The zinc electrode is the anode[1]][where oxidation occurs.[2]] [The silver electrode is the cathode,[3]][where reduction occurs.[4]]

✓ ✗ I have identified which electrode is the anode.[1]

✓ ✗ I have identified the reaction that occurs at the anode.[2]

✓ ✗ I have identified which electrode is the cathode.[3]

✓ ✗ I have identified the reaction that occurs at the cathode.[4]

b Anode: $Zn_{(s)} \rightarrow Zn^{2+}{}_{(aq)} + 2e^-$

Cathode: $Ag^+{}_{(aq)} + e^- \rightarrow Ag_{(s)}$

c The electrons flow from the zinc electrode (anode) to the silver electrode (cathode).

d The concentration of Zn^{2+} ions increases.

Chapter 6 review

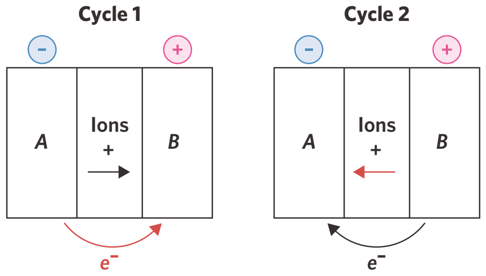
Multiple choice

1	D	**2**	D	**3**	C	**4**	B	**5**	A
6	C	**7**	A	**8**	C	**9**	B	**10**	B

Short answer

11 **a** Cycle 1 – discharge, Cycle 2 – recharge

b



c [The purpose of an electrolyte in a primary cell is to complete the circuit by allowing the flow of charged particles[1]][and to maintain the charge neutrality.[2]]

✓ ✗ I have identified the function of an electrolyte in relation to electrical electron flow.[1]

✓ ✗ I have identified the function of an electrolyte in relation to electrical neutrality.[2]

d [Not all batteries are rechargeable.[1]][This is because primary cells are unable to be recharged, whereas secondary cells can be recharged because the products of the discharge reaction stay in direct contact with their respective electrodes.[2]]

✓ ✗ I have stated whether all batteries can be recharged.[1]

✓ ✗ I have explained the difference between primary and secondary cells.[2]

12 **a** [Iron would not be an appropriate choice as the anode[1]][because, according to the electrochemical series, $Fe_{(s)}$ is a stronger reducing agent than $H_2O_{(l)}$ and therefore the anode will start to undergo oxidation, disintegrate and crumble.[2]]

✓ ✗ I have stated whether the anode is suitable or not.[1]

✓ ✗ I have explained why it is not a suitable choice.^{2}

b [This is not predicted by the electrochemical series because H_2O is a weaker reducing agent than Cl^-.^{1}][Since the solution of KCl has a molarity of 4.0 M, the electrolysis of KCl is not occurring under standard conditions (1.0 M concentrations) and therefore, the electrochemical series is not an accurate predictor.^{2}] [Consequently, chlorine gas could be produced at the anode, accounting for the smell.^{3}]

✓ ✗ I have stated whether this reaction is predicted by the electrochemical series.^{1}

✓ ✗ I have stated why the experiment is not occurring under standard conditions.^{2}

✓ ✗ I have accounted for the smell of chlorine gas.^{3}

c Chris could carry out the experiment in a fume hood.

13 **a** [The electrode on the right will be the cathode.^{1}][This is because $Zn_{(s)}$ is a stronger reducing agent than $Ce^{3+}{}_{(aq)}$ according to the electrochemical series.^{2}]

✓ ✗ I have stated which electrode will be the cathode.^{1}

✓ ✗ I have justified my answer.^{2}

b $2Ce^{3+}{}_{(aq)} + Zn^{2+}{}_{(aq)} \rightarrow 2Ce^{4+}{}_{(aq)} + Zn_{(s)}$

c [The role of the proton exchange membrane is to complete the circuit by allowing the flow of charged particles (in this case protons).^{1}][However, at the same time, it only allows protons to go through because it has to stop the aqueous ions Zn^{2+}, Ce^{4+} and Ce^{3+} from escaping their respective electrolytes otherwise the cell would not be able to be recharged.^{2}]

✓ ✗ I have stated why it is necessary for protons to pass through both electrolytes.^{1}

✓ ✗ I have stated why the membrane only allows protons to go through.^{2}

d [This is a renewable source of energy^{1}][because the source of electrons for the electrolysis is being driven by solar panels which harness the energy of the sun, a naturally occurring process that can be replenished as fast, or faster than it is consumed.^{2}]

✓ ✗ I have stated whether it is a renewable source of energy.^{1}

✓ ✗ I have justified my answer with reference to the definition of a renewable energy source.^{2}

14 **a** $MH + OH^- \rightarrow M + H_2O + e^-$

$NiOOH + H_2O + e^- \rightarrow Ni(OH)_2 + OH^-$

b [As a result of the cold temperatures in Antarctica, battery performance is reduced because the rates of the chemical reactions occurring in the battery to convert chemical energy into electrical energy are slower due to the reduced average kinetic energy of the particles,^{1}][meaning that the battery doesn't produce enough energy to turn the phone on.^{2}]

✓ ✗ I have explained why colder temperatures reduce battery performance.^{1}

✓ ✗ I have linked this reduced battery performance to the phone not turning on.^{2}

15 **a** [The silver ring should be connected to the negative terminal of the power supply.^{1}][This is because we want the reduction reaction $Au^+{}_{(aq)} + e^- \rightarrow Au_{(s)}$ to occur on the silver ring which means the silver ring has to act as the negatively charged cathode.^{2}]

✓ ✗ I have stated which terminal of the power supply the ring should be attached to.^{1}

✓ ✗ I have justified my response.^{2}

b $m(Au) = 0.240\ cm^3 \times 19.3\ g/cm^3 = 4.63\ g$

c $n(Au) = 4.63/197.0 = 0.0235\ mol$

$Au^+{}_{(aq)} + e^- \rightarrow Au_{(s)}$

$n(e^-) = n(Au) = 0.0235$

$Q = n(e^-) \times 96500$

$Q = 0.0235 \times 96500 = 2268\ C$

$Q = It$

$2268 = 5.00 \times t$

$t = 454$ seconds

16 **a** [The lump of impure copper should be attached to the anode (positive electrode)^{1}][because the copper in the impure lump needs to be oxidised for copper ions to enter the solution.^{2}]

✓ ✗ I have stated which electrode the lump of impure copper should be attached to.^{1}

✓ ✗ I have explained my answer.^{2}

b The reaction is $Cu^{2+}{}_{(aq)} + 2e^- \rightarrow Cu_{(s)}$.

c [In this electrorefining cell, $Cu_{(s)}$ in the lump of impure copper is being oxidised and the resulting $Cu^{2+}{}_{(aq)}$ is being reduced at the plate of pure copper.^{1}][The sludge below the lump of impure copper is the solid form of all the metals present in the lump which are weaker reducing agents than $Cu_{(s)}$ as they will remain in their solid form rather than entering the solution as ions.^{2}]

✓ ✗ I have described what is happening in the electrorefining cell.^{1}

✓ ✗ I have explained what the sludge consists of.^{2}

Key science skill question

17 **a** The student is examining Faraday's second law.

b The independent variable is the choice of metal (or the charge of the metal's ion).

c The dependent variable is the mass of the metal deposited at the cathode.

d [The distance between the electrode plates.^{1}][The concentration of the electrolyte.^{2}]

✓ ✗ I have identified plate distance as a possible variable.^{1}

✓ ✗ I have identified concentration as a possible variable.^{2}

BONUS – CARTOON QUESTION ANSWERS

Multiple choice questions

1 **B**

2 **A**

Short answer questions

3 [1. In a primary cell, irreversible reactions occur, whereas in a secondary cell, reactions are reversible.[1]]

[2. The products of the discharge reaction in a secondary cell must remain in contact with the electrodes, whereas in a primary cell this is not required.[2]]

[3. As reversible reactions occur in a secondary cell, they can be recharged. A primary cell may only be discharged a single time and cannot be recharged.[3]]

- ✓ ✗ I have identified the reversibility of reactions in both cells.[1]
- ✓ ✗ **I have identified a structural feature required for the functioning of the cells.[2]**
- ✓ ✗ **I have identified the rechargeability of both cells.[3]**

4 [A battery is rechargeable (a secondary cell) if the products of the discharge reaction remain in physical contact with their respective electrodes.[1]] [This means that when an external power source is applied, the electrolytic reactions are able to convert the products of the discharge reaction into the original reactants and store electrical energy as chemical energy. If the products were not present at their respective electrodes, this would not occur.[2]] [This means that the cell can then discharge again once the reverse reaction has occurred to a sufficient extent.[3]]

- ✓ ✗ I have stated that the need for the products to remain in contact with their respective electrodes.[1]
- ✓ ✗ I have explained why this is necessary to the function of a secondary cell.[2]
- ✓ ✗ I have mentioned how this enables the cell to discharge again.[3]

7A Structure of organic compounds

Theory review questions

1 D

2 C

3 A

4 A primary amine has two **hydrogen** atoms and **an alkyl group** attached to the nitrogen atom, which forms an **amino** group **NH_2**.

5 Alcohols are also classified based on the number of alkyl groups connected to the carbon bonded to the OH group. There are three types of alcohols: **primary** alcohols, **secondary** alcohols and **tertiary** alcohols. In a primary alcohol, carbon connected to the OH group is bonded to **one** alkyl group. The carbon connected to the OH group in a secondary alcohol is bonded to **two** alkyl groups. In a tertiary alcohol, the carbon connected to the OH group is bonded to **three** alkyl groups.

6

Type of compound	Functional group
Alkene	$C{=}C$
Alkyne	$C{\equiv}C$
Aldehyde	CHO
Primary amide	**$CONH_2$**
Ketone	**CO**
Primary amine	NH_2
Alcohol	**OH**
Carboxylic acid	**COOH**
Ester	**COO**

Exam-style questions

Within lesson

7 C

8 C

9 C

10 B

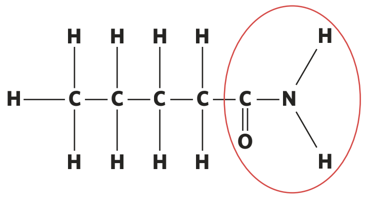
11 [Compared to long bond lengths, shorter bonds are more stable and require more energy to break.[1]][Therefore, as the carbon-hydrogen bond is shorter than the carbon-nitrogen bond,[2]][the carbon-hydrogen bond would have a higher bond energy.[3]]

✓ ✗ I have identified the relationship between bond length and bond energy.[1]

✓ ✗ I have compared the bond lengths between the carbon-nitrogen and carbon-hydrogen bonds.[2]

✓ ✗ I have identified that the carbon-hydrogen bond has a higher bond energy.[3]

12 **a** **i**



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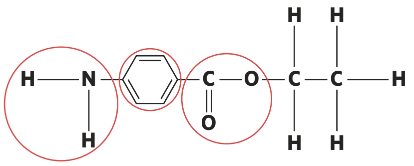

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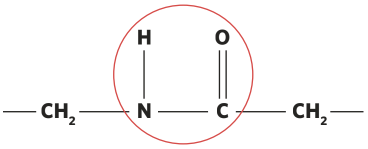
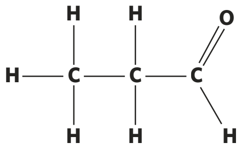


b Molecule A: amide; Molecule B: amino, benzene group, ester; Molecule C: amide

13 **a**



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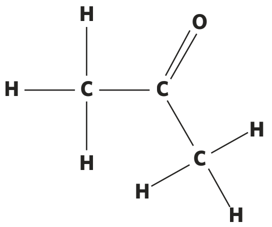
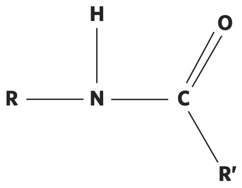


14 [Although the molecule does contain a carbonyl group and a nitrogen carbon bond in the structure, the carbonyl group is bonded to a OH (hydroxyl) group, thereby making it a carboxyl group.[1]][Furthermore, the nitrogen-carbon bond is part of NH_2, which is an amino group.[2]][If the carbonyl group was bonded to an NH within the carbon chain and not to the OH group as shown below, this would be considered as an amide functional group.[3]][As a result, the student's statement is inaccurate.[4]]



✓ ✗ I have identified the carboxyl functional group.[1]

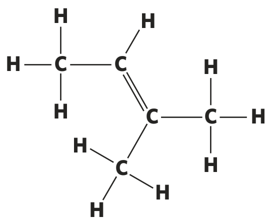
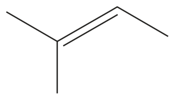
✓ ✗ I have identified the amino functional group.[2]

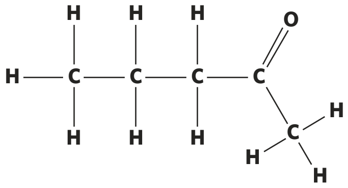
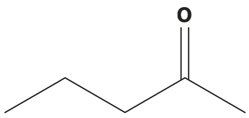
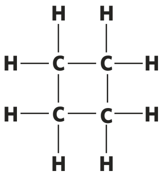
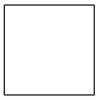
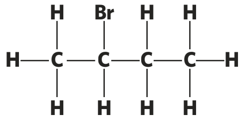
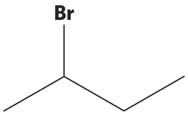
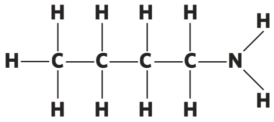
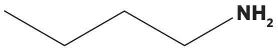
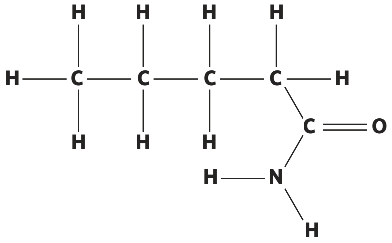
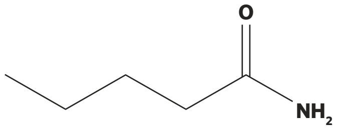
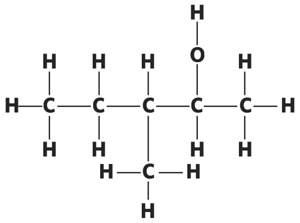
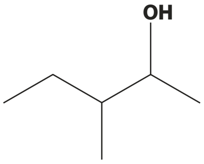
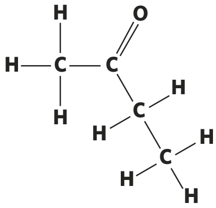
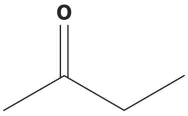
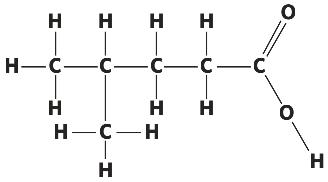
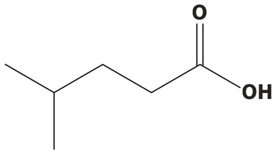
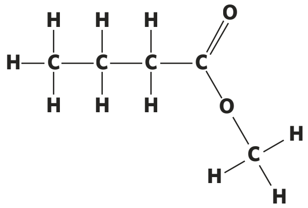
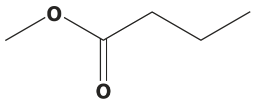
✓ ✗ I have described the structure of an amide group.[3]

✓ ✗ I have commented on the inaccuracy of the statement.[4]

✓ ✗ I have drawn a molecule to support my answer.

15

Semi-structural formulas	Structural formulas	Skeletal formulas
$CH_3CHC(CH_3)CH_3$		

$CH_3CH_2CH_2COCH_3$		
$CH_2CH_2CH_2CH_2$		
$CH_3CHBrCH_2CH_3$		
$CH_3CH_2CH_2CH_2NH_2$		
$CH_3CH_2CH_2CH_2CONH_2$		
$CH_3CH_2CH(CH_3)CH(OH)CH_3$		
$CH_3COCH_2CH_3$		
$CH_3CH(CH_3)CH_2CH_2COOH$		
$CH_3CH_2CH_2COOCH_3$		

Multiple lessons

16 **a** Renewable energy source

b [The biobutanol molecule shown is a primary alcohol[1]][as the carbon to which the hydroxyl (OH) group is bonded to is only bonded to one other carbon.[2]]

✓ ✗ I have identified biobutanol as a primary alcohol.[1]

✓ ✗ I have identified the relationship between the bonding of the hydroxyl group to the alcohol type.[2]

c 1 mol of C_4H_9OH can release 2676 kJ of energy, therefore:

$n(C_4H_9OH)$ used to produce 1033 kJ of energy $= \frac{1033\ \text{kJ}}{2676}\text{kJ}$

$= 0.386$ mol

$n(C_4H_9OH) : n(O_2)$

1 : 6

0.38602 mol : $n(O_2)$

$n(O_2) = 0.38602 \text{ mol} \times 6$

$= 2.316$ mol

$m(O_2) = 2.316 \text{ mol} \times 32.0 \text{ g mol}^{-1}$

$= 74.116$ g

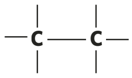
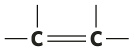
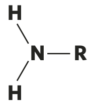
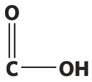
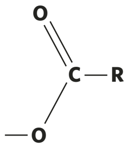
$= 74.1$ g

7B Organic compounds

Theory review questions

1 B

2

Carbon bonds/functional groups	Type of compound	Ending (suffix)
	Alkane	ane
	Alkene	ene
$-\mathrm{C}\equiv\mathrm{C}-$	Alkyne	yne
C—*X* (X is a halogen ie. Cl, Br, I,..)	Haloalkane	ane
 (R represents an alkyl group)	Primary amine	amine
O—H	Alcohol	ol
	Carboxylic acid	oic acid
	Ester	oate

3 D

Exam style questions

Within lesson

4 A

5 B

6 D

7 B

8 **a** 6 carbons

b There are 2 methyl groups present.

c 3,3-dimethylhexane

9 **a** 7 carbons

b Aldehyde functional group

c Heptanal

10 **a** Hydroxyl functional group / methyl group

b [This is a tertiary alcohol[1]][as the carbon to which the hydroxyl group is bonded to is itself bonded to three other carbons/alkyl groups.[2]]

✓ ✗ I have identified this as a tertiary alcohol.[1]

✓ ✗ I have explained the structural feature of a tertiary alcohol.[2]

c 3,5-dimethylhexan-3-ol

Multiple lessons

11 **a** 4-ethyl-2,2-dimethylhexane

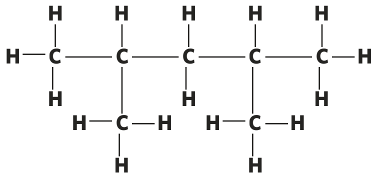
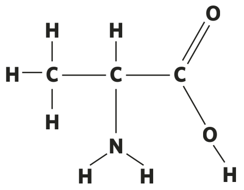
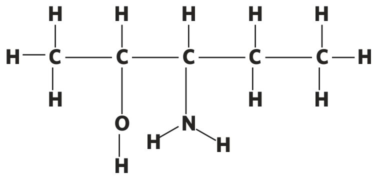
b 3,4-dimethylpent-1-ene

c pentane-2,4-diol

d 2,3-dibromobutane

e 2-aminobutan-1-ol

12

Name	Structural formula
2,4-dimethylpentane	
2-aminopropanoic acid	
3-aminopentan-2-ol	

7C Isomers

Theory review questions

1 D

2 There are two main types of stereoisomers which are **geometric isomers** and **enantiomers**. **Geometric isomers** are formed due to the inability to rotate a **carbon to carbon double** bond. **Enantiomers** are molecules whose structures cannot be placed on top of each other even though their atoms are connected in the same order.

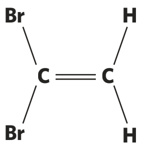
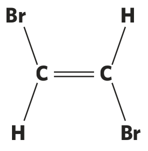
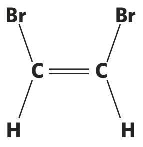
3 B

Exam-style questions

Within lesson

4 C 5 D 6 A

7 a

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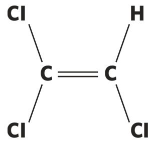

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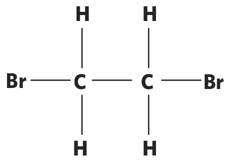
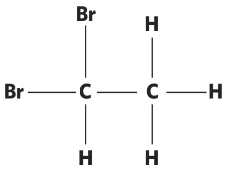

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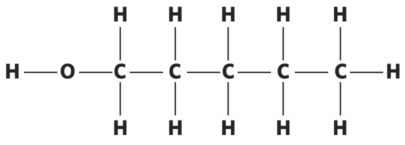
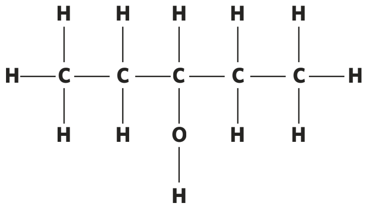
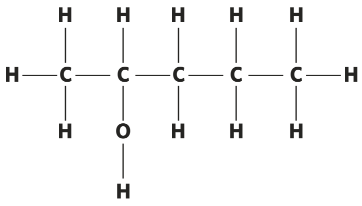
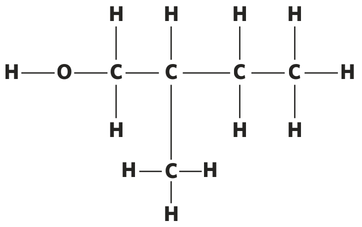
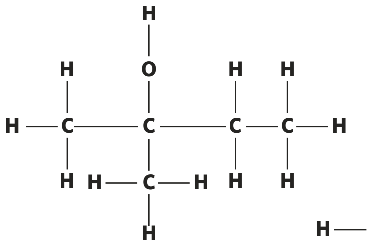
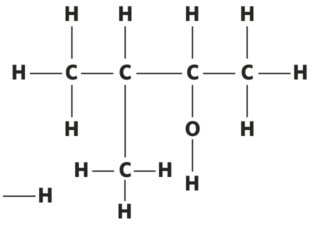
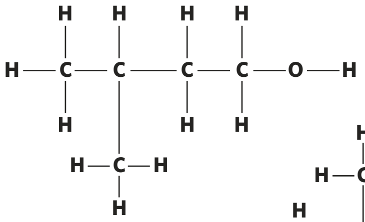
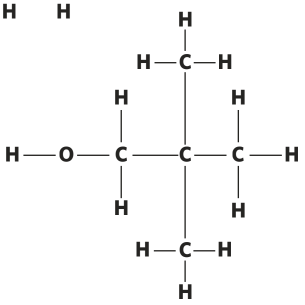
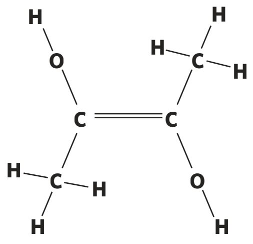









8 a i



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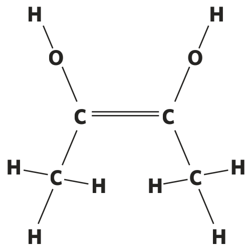
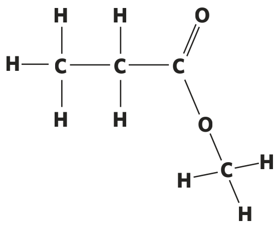


ii Yes, it is able to exist as *cis*-*trans* isomers.

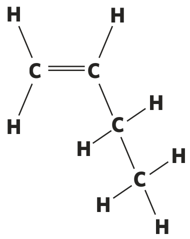
b i



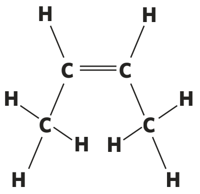
ii No, it is not able to exist as *cis*-*trans* isomers.

Multiple lessons

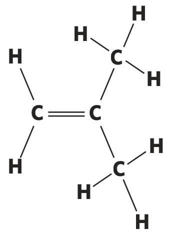
9



But-1-ene

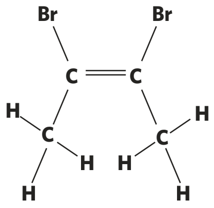
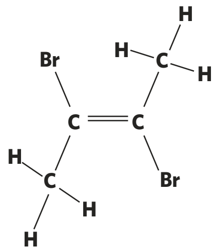


But-2-ene



2-methylpropene

10 a

b *cis*-2,3-dibromo-but-2-ene, *trans*-2,3-dibromo-but-2-ene.

7D Chirality

Theory review questions

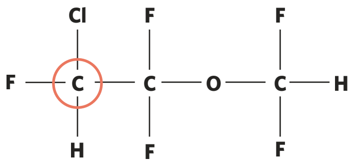
1 B **2** C **3** C

Exam-style questions

Within lesson

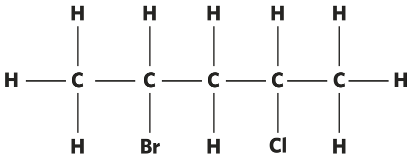
4 D **5** B **6** A

7

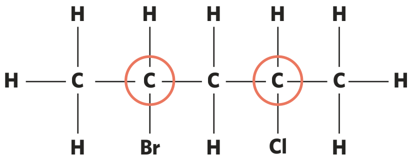


(the orange circle signifies the chiral carbon)

8 **a**



b



(circles identify chiral centres)

9 **a** C_2, C_3, C_4, C_5

b [All chiral compounds have a chiral centre however achiral compounds can also contain chiral centres.[1]][It is possible to have achiral compounds that have multiple chiral centres that can be superimposed on their mirror image.[2]][As a result, the statement that the student made was inaccurate.[3]]

✓ ✗ I have identified that achiral compounds can also contain chiral centres.[1]

✓ ✗ I have explained how compounds with chiral centres cannot be considered as chiral.[2]

✓ ✗ I have commented on the accuracy of the statement.[3]

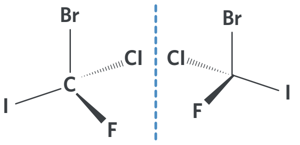
10 Chiral molecules are molecules whose structures and their mirror images cannot be superimposed.[1]][In regards to the two molecules, if the molecule on the right were rotated, it is possible for that molecule to be superimposed on the original molecule (the one on the left).[2]][As a result, these two molecules are achiral.[3]]

✓ ✗ I have explained what chiral molecules are.[1]

✓ ✗ I have explained that the molecules are superimposable.[2]

✓ ✗ I have linked my answer to the question.[3]

11 **a** [Chiral molecules have non-superimposable mirror images.[1]]
[As seen in the diagram, the mirror image of this molecule cannot be superimposed onto the original molecule.[2]]



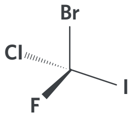
[As a result, we can consider this as being a chiral compound.[3]]

✓ ✗ I have explained what chiral molecules are.[1]

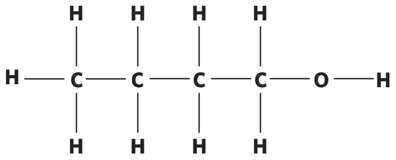
✓ ✗ I have used a diagram to show that the molecules are non-superimposable.[2]

✓ ✗ I have linked my answer to the question.[3]

b

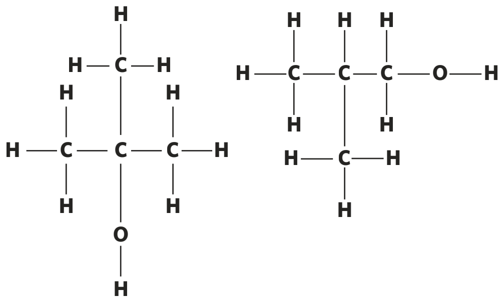


12 **a**



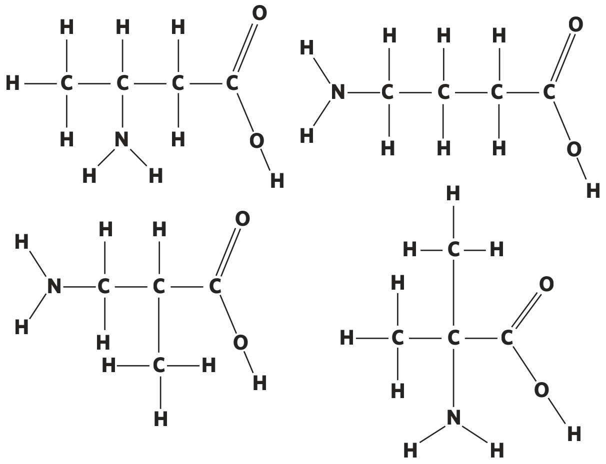
b This molecule has no chiral centre

c



d 2-methylpropan-1-ol and 2-methylpropan-2-ol

13 **a**



b 1

c 2-aminobutanoic acid

7E Properties of organic compounds

Theory review questions

1 D **2** C **3** A

Exam-style questions

Within lesson

4 A **5** C **6** A

7 **a** B

b [Dispersion forces of attraction is present in all molecules however each molecule can take part in additional intermolecular bonds that cause the boiling point of each to vary.[1]][Due to the carbonyl group, Z is able to take part in dipole-dipole interactions.[2]][The hydroxyl groups found in compound X and Y (as part of the carboxyl group) allow both molecules to take part in hydrogen bonding where, in addition, Y can also take part in dipole-dipole interactions due to the presence of a carbonyl group.[3]][Due to the fact that hydrogen bond is the strongest intermolecular force of attraction, molecules X and Y would have a higher boiling point than Z.[4]]

✓ ✗ I have identified the common intermolecular force of attraction between all molecules.[1]

✓ ✗ I have identified the intermolecular bonds involved in molecule Z.[2]

✓ ✗ I have identified the intermolecular bonds involved in X and Y.[3]

✓ ✗ I have compared the intermolecular bonds of all compounds and related it to the boiling point.[4]

8 [Due to the carbonyl group and hydroxyl group present, propanoic acid can take part in hydrogen bonding, dipole-dipole interactions as well as dispersion forces.[1]][In contrast, 2-methylbutane is a non-polar molecule and therefore molecules of 2-methylbutane are held together by only dispersion forces.[2]][Furthermore, the methyl group decreases the surface area available for bonding, thereby decreasing the strength of the dispersion forces.[3]][As hydrogen bonds and dipole interactions are stronger than dispersion forces and require more energy to break, propanoic acid would have a higher boiling point than 2-methylbutane.[4]]

✓ ✗ I have identified the intermolecular bonds involving propanoic acid.[1]

✓ ✗ I have identified the intermolecular bonds involving 2-methylbutane.[2]

✓ ✗ I have identified the effect of surface area on the intermolecular bonds involving 2-methylbutane.[3]

✓ ✗ I have compared the intermolecular bonds between propanoic acid and 2-methylbutane and related this to boiling point.[4]

9 [Compounds with a similar molecular mass can have varying boiling points due to their structures, which influence the type of intermolecular bonding they can take part in.[1]][All compounds listed are held together by dispersion forces as well as hydrogen bonds. The presence of a hydroxyl group and the amino group present in both amines and butan-1-ol allow them to take part in hydrogen bonding, the strongest type of intermolecular bond.[2]][However, there is a greater difference in electronegativity between the O and H of the hydroxyl compared to the N and H in the amino group, resulting in a stronger bond between butan-1-amine molecules.[3]][Due to the position of the amino group in butan-2-amine, it has a smaller surface area compared to butan-1-amine, and is not packed as tightly, resulting in a lower boiling point.[4]]

✓ ✗ I have identified the relationship between structure of organic compounds and boiling point.[1]

✓ ✗ I have identified the common intermolecular bonds between all molecules.[2]

✓ ✗ I have explained the difference in strength between the hydrogen bonds present.[3]

✓ ✗ I have used surface area to explain the difference in bond strength between butan-1-amine and butan-2-amine.[4]

10 [Due to the presence of hydroxyl groups and an aldehyde group, molecules of substance I take part in hydrogen and permanent dipole-dipole bonding as well as dispersion forces.[1]][Although the presence of the carboxyl group in molecule II would allow it to take part in hydrogen and dipole-dipole interactions, the impact of these strong bonds become negligible as the length of the hydrocarbon chain, held together by dispersion forces, increases.[2]][As a result, the forces of attraction between molecule I is stronger than molecule II, making it more resistant to flow.[3]]

✓ ✗ I have identified the intermolecular bonds involving molecule I.[1]

✓ ✗ I have identified the intermolecular bonds involving molecule II.[2]

✓ ✗ I have compared the flow of both molecules I and II in relation to their bonds.[3]

11 [Both molecules are non-polar alkanes and therefore are held together by dispersion forces.[1]][However, the dispersion forces between octane molecules are stronger than those of methane due to the length of octane's carbon chain allowing for a greater surface area for bonding to occur.[2]][As a result, octane would require more energy to break the bonds, thereby having a greater boiling point and viscosity.[3]]

✓ ✗ I have identified the intermolecular bonds involving both molecules.[1]

✓ ✗ I have compared the bonding between methane and octane.[2]

✓ ✗ I have identified the molecule with the greatest boiling point and viscosity.[3]

12 [The flashpoint of a compound is the lowest temperature at which the vapour of a liquid will ignite when given enough energy and oxygen.[1]] [Given that the temperatures of the United States are very close to 25 degrees celsius, there is a high risk that fuels with a flashpoint of less than 25 degrees will react and cause large combustion reaction (ie explosion) if fuel containers weren't equipped to contain the fuel in an appropriate environment.[2]]

✓ ✗ I have described the term flashpoint.[1]

✓ ✗ I have explained the importance of safety precautions relative to the flashpoint of liquid fuels.[2]

Multiple lessons

13 **a** **i** Propane

ii Glycerol or (propane-1,2,3-triol)

iii Ethanol.

b Molecule ii/propane-1,2,3-triol

c Propane, ethanol, glycerol

7F Types of organic reactions

Theory review questions

1 A **2** B **3** D **4** B

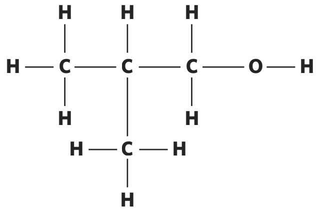
Exam-style questions

Within lesson

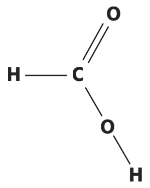
5 C **6** B **7** C

8

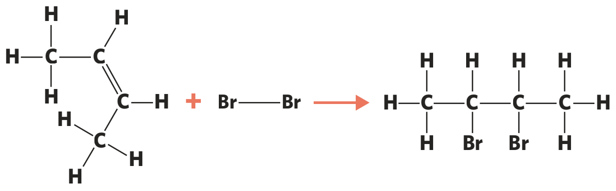
2-Methylpropan-1-ol



Methanoic acid



9 **a**



b Addition reaction

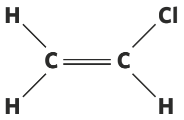
c [If bromine underwent a reaction with but-1-ene, each of the bromine atoms would be bonded to carbons 1 and 2 as opposed to carbons 2 and 3 when reacted with but-2-ene.[1]] [Although both molecules would have the same molecular formula, they are isomers of each other and therefore would be structurally different.[2]] [As a result, the products would not be the same.[3]]

✓ ✗ I have identified the main difference between both products.[1]

✓ ✗ I have identified the two products as isomers of each other.[2]

✓ ✗ I have linked my answer back to the question.[3]

10 **a**



b Chloroethene

11 The reaction that has occurred is: $CH_{4(g)} + Cl_{2(g)} \rightarrow CH_3Cl_{(g)} + HCl_{(g)}$

To determine the atom economy:

Overall atomic mass of reactants = $M(CH_4) + M(Cl_2)$

$= 16.0 \text{ g mol}^{-1} + 71.0 \text{ g mol}^{-1}$

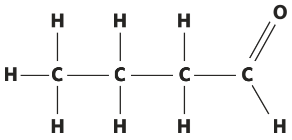
$= 87.0 \text{ g mol}^{-1}$

Overall atomic mass of chloromethane = 50.5 g mol^{-1}

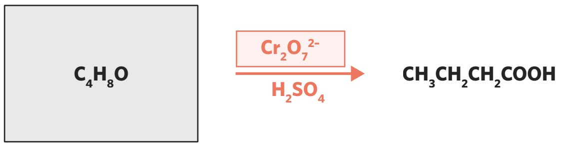
Atom economy = $\frac{50.5}{87.0} \times 100$

$= 58.0\%$

12 **a**



b



c butanoic acid

13 **a** H_2O

b Addition reaction

c $Cr_2O_7^{2-}/H^+$

14 **a** Reagent A: sodium hydroxide (NaOH)/or potassium hydroxide (KOH). Reagent B: sulfuric acid (H_2SO_4)

b Compound A is CH_3CH_2Cl. Compound B is CH_3COOH.

c Oxidation of an alcohol

d Ethyl ethanoate

Multiple lessons

15 **a** $Cr_2O_7^{2-}{}_{(aq)} + 14H^+{}_{(aq)} + 6e^- \rightarrow 2Cr^{3+}{}_{(aq)} + 7H_2O_{(l)}$

$CH_3CH_2CH_2CH_2CH_2OH_{(aq)} \rightarrow CH_3CH_2CH_2CH_2CHO_{(aq)} + 2H^+{}_{(aq)} + 2e^-$

b [The student could limit the amount of oxidising agent.[1]]

✓ ✗ I have identified one method to increase the production of aldehyde over a carboxylic acid.[1]

16 **a** According to the question

2.57 g sulfur dioxide used, reaction has a yield of 73%

The theoretical yield is:

$n(SO_2) = \frac{2.57 \text{ g}}{64.1 \text{ g mol}^{-1}}$

$= 0.0401 \text{ mol}$

$n(SO_2) : n(SO_3)$

2 : 2

0.0401 mol : x

$n(SO_3) = 0.0401 \text{ mol}$

$m(SO_3) = 80.1 \text{ g mol}^{-1}$

= 3.212 grams is the theoretical yield

Actual yield = $3.212 \times \frac{73}{100}$

= 2.34 grams of sulfur trioxide produced

b [The negative value for the heat of combustion for this reaction shows that the reaction is exothermic.[1]][Therefore, according to Le Chatelier's principle, to partially oppose the increase in temperature, the backwards reaction will be favoured.[2]][This will result in a decrease in the amount of sulfur trioxide produced which consequently decreases the yield of the reaction.[3]]

✓ ✗ I have identified the energy change of the reaction.[1]

✓ ✗ I have explained how the reaction will respond to the increase in temperature.[2]

✓ ✗ I have explained the effect of the change to the yield of sulfur trioxide.[3]

c Redox reaction

Chapter 7 review

Multiple choice

1	D	**2**	B	**3**	C	**4**	A	**5**	A
6	D	**7**	A	**8**	D	**9**	B	**10**	D

Short answer

11 **a** X - propan-1-ol, Y - ethanoic acid, Z - methyl methanoate

b Option A.

c [Although all of the compounds have the same molecular weight, they all have different functional groups present. Given that they all have similar dispersion forces acting upon their structures,[1]][propanol and ethanoic acid have a hydroxyl and carboxyl group (respectively) that are able to take part in hydrogen bonding; a very strong intermolecular force of attraction. Furthermore, the C=O bond in ethanoic acid is polar and therefore can take part in dipole - dipole interactions. In comparison, methyl methanoate, can only take part in dipole–dipole interactions[2]][which is much weaker than the intermolecular bonds of propanol and ethanoic acid.[3]][As a result, methyl methanoate would have the lowest boiling point of the three.[4]]

✓ ✗ I have identified the similarities between all molecules.[1]

✓ ✗ I have identified the functional groups and intermolecular bonds of all compounds.[2]

✓ ✗ I have compared the strength of the intermolecular bonds of the compounds.[3]

✓ ✗ I have identified the boiling point range of methyl methanoate.[4]

12 **a** Oxidation (of alcohols)

b -CHO (or aldehyde)

13 **a** $CH_3CH_2CH_2COOH_{(l)} + CH_3CH_2OH_{(l)} \rightarrow$
$CH_3CH_2CH_2\ COOCH_2CH_{3(l)} + H_2O_{(l)}$

b Ethyl butanoate

c Esterification/condensation reaction

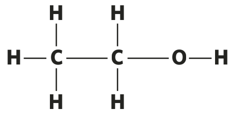
14 **a** Substitution reaction

b 2-chloro-2-methylpropane

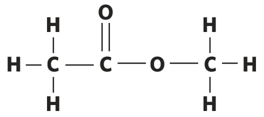
15 **a** Chloroethane

b $HCl_{(g)}$ and $Cr_2O_7{}^{2-}{}_{(aq)}$ / $H^+{}_{(aq)}$

c Compound R



Compound T



16 **a** Ethanol and ethanoic acid

b $CH_3CH_2OH_{(l)} + CH_3COOH_{(l)} \rightarrow CH_3COOCH_2CH_{3(l)} + H_2O_{(l)}$

c [Conduct an experiment to determine the boiling point of the ester produced[1]][and compare it with the known boiling point of pure ethyl ethanoate from data sources.[2]]

✓ ✗ I have identified a technique to identify a property of the ester produced.[1]

✓ ✗ I have described how the results obtained can confirm the ester produced.[2]

17 **a** $n(C_{12}H_{22}O_{11}) = \frac{1.5 \times 10^3}{342.0} = 4.39$ mol

$n(C_{12}H_{22}O_{11}) : n(C_2H_5OH)$

1 : 4

$n(C_2H_5OH) = 4 \times 4.39 = 17.54$ mol

$m(C_2H_5OH) = 17.54 \times 46\ g\ mol^{-1} = 8.1 \times 10^2\ g$

b CH_3CH_2OH

c Addition and oxidation reaction

d $H_3PO_{4\ (l)}$

18 **a** [In colder temperatures, there is not enough energy to disrupt the intermolecular bonds between the biodiesel molecules to allow the fuel to flow.[1]][This results in an increase in viscosity[2]][making it more difficult for the fuel to flow through the fuel line.[3]]

✓ ✗ I have identified the relationship between temperature and intermolecular bonds of biodiesel.[1]

✓ ✗ I have identified the effect on viscosity.[2]

✓ ✗ I have identified the impact on flow of fuel.[3]

b [Petrodiesel is a fuel consisting of non-polar hydrocarbon molecules held together by weak dispersion forces.[1]][Biodiesel is a fuel consisting of esters that contain a polar functional group and is therefore held together by both dispersion and stronger dipole–dipole interactions.[2]][As a result, biodiesel is held together more strongly,[3]][resulting in a higher boiling point and greater viscosity.[4]]

✓ ✗ I have identified the type of intermolecular bonds present in petrodiesel.[1]

- ✓ ✗ I have identified the types of intermolecular bonds present in biodiesel.[2]
- ✓ ✗ I have compared the strength of the bonds between petrodiesel and biodiesel.[3]
- ✓ ✗ I have identified the effect of bonds to the boiling point and viscosity of biodiesel.[4]

19 **a** As this is an addition reaction, the mole ratio between iodine and the unsaturated hydrocarbon will be equivalent to the number of double bonds present.

$$n(\mathrm{I_2}) = \frac{54.92\ \mathrm{g}}{253.8\ \mathrm{g\ mol^{-1}}} = 0.2164\ \mathrm{mol}$$

$$n(\text{unsaturated hydrocarbon}) = \frac{30.30\ \mathrm{g}}{280.0\ \mathrm{g\ mol^{-1}}} = 0.1082\ \mathrm{mol}$$

$n(\mathrm{I_2}) : n(\text{unsaturated hydrocarbon})$

$$0.2164\ \mathrm{mol} : 0.1082\ \mathrm{mol}$$

$$\frac{0.2164\ \mathrm{mol}}{0.1082\ \mathrm{mol}} : \frac{0.1082\ \mathrm{mol}}{0.1082\ \mathrm{mol}}$$

$$2 : 1$$

Every 1 mol of unsaturated hydrocarbon reacts with 2 mol of I_2. Therefore there are 2 double bonds present.

b B

Key science skill question

20 **a** Temperature / boiling point

b Improperly calibrated thermometer

c [As both structures are alkanes, they are held together by dispersion forces.[1]][However, compared to structure II, structure I has a larger surface area and less branching. Therefore, it has stronger dispersion forces between the molecules.[2]][As a result, structure I would have a higher boiling temperature than structure II.[3]][Structure I would then be Sample A and structure II would be sample B.[4]]

- ✓ ✗ I have identified the intermolecular forces for both molecules.[1]
- ✓ ✗ I have identified the differences in surface area.[2]
- ✓ ✗ I have related strength of bonds to the boiling point of molecules.[3]
- ✓ ✗ I have identified the structure related to each sample.[4]

NOTE: It is also possible to identify the reverse relationship – i.e. structure II having a smaller surface area.

d Structure I: Pentane

Structure II: 2-2-dimethylpropane

8A Mass spectrometry

Theory review questions

1 B **2** D **3** A **4** A

Exam-style questions

Within lesson

5 A **6** B **7** A

8 **a** [Ethanol.[1]][The peak at the highest mass-to-charge ratio, m/z = 46, indicates that the unknown compound has a relative molecular mass of 46 g mol^{-1}, which corresponds to the molecular mass of ethanol 46 g mol^{-1}.[2]]

✓ ✗ I have named the unknown alcohol.[1]

✓ ✗ I have justified my answer using the molecular mass and the relevant mass spectrum peak.[2]

b [Negative ions are not measured in mass spectrometers because their mass to charge ratio would be undefined due to the nature of their negative charge.[1]][Therefore, $[OH]^-$ would not be identified by the mass spectrometer.[2]]

✓ ✗ I have identified that negative ions can not be measured in mass spectrometers.[1]

✓ ✗ I have explained why this results in $[OH]^-$ not being identified by a mass spectrometer .[2]

9 [T^+, A^+ and B^+.[1]][Peaks on a mass spectrum are associated with positive ions, including both parent molecular and fragment. These are the species deflected and separated in the magnetic field that can then be read by the mass spectrometer.[2]]

✓ ✗ I have identified the species.[1]

✓ ✗ I have explained what the peaks on a mass spectrum represent.[2]

10 [H or H atom.[1]][The peak at m/z 31 is caused by CH_2OH^+, which require the loss of a hydrogen atom from the molecular ion, which is CH_3OH^+.[2]]

✓ ✗ I have identified the species of the lost fragment.[1]

✓ ✗ I have justified this using the value of the molecular ion given.[2]

11 **a** General formula C_nH_{2n+2}.

$M(C) = 12$

$M(H) = 1$

$(12 \times n) + (1 \times (2n + 2)) = 72$

$12n + 2n + 2 = 72$

$14n = 70$

$n = 5$

Molecular formula is C_5H_{12}

b Pentane

12 **a** $[CH_3CH_2]^+$ or $[COH]^+$

b [The base peak at 45 m/z corresponds to $[CH_2CH_2OH]^+$ from butan-2-ol.[1]][Neither methylpropan-1-ol nor methylpropan-2-ol would easily fragment to $[CH_2CH_2OH]^+$.[2]]

✓ ✗ I have identified the isomer consistent with the mass spectrum.[1]

✓ ✗ I have explained why this fragment is from the identified isomer.[2]

13 **a** $[CH_3CH_2]^+$ or $[C_2H_5]^+$

b The compound at m/z = 64 is $[CH_3CH_2{}^{35}Cl]^+$ and at m/z = 66 it is $[CH_3CH_2{}^{37}Cl]^+$.

c [The relative abundance of ^{35}Cl is three times the abundance of ^{37}Cl [1]][indicating that it is three times more likely to occur in nature and therefore in the fragmentation of chloroethane.[2]]

✓ ✗ I have described the relative abundances of the two isotopes.[1]

✓ ✗ I have explained what this indicates about their existence in nature.[2]

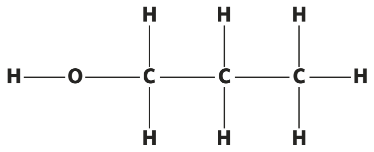
Multiple lessons

14 [Isotopes are separated and quantified by mass spectrometry, whereas the potassium dichromate test differentiates between primary, secondary and tertiary alcohols.[1]][Therefore, as uranium is not an alcohol and we're trying to differentiate between isotopes, mass spectrometry is more suitable.[2]]

✓ ✗ I have described what the two techniques determine.[1]

✓ ✗ I have used this description to justify why one is more suitable.[2]

15 **a**



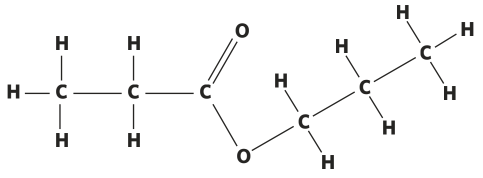
$$H{-}O{-}CH_2{-}CH_2{-}CH_3$$

[Propan-1-ol.[1]][The peak at the highest mass-to-charge ratio is 60, indicating that the unknown compound has a relative molecular mass of 60 g mol^{-1}. The molecular mass of methanol is 32 g mol^{-1}, the molecular mass of ethanol is 46 g mol^{-1} and the molecular mass of propan-1-ol is 60 g mol^{-1}. Therefore, the unknown molecule is propan-1-ol.[2]]

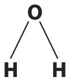
✓ ✗ I have identified the name and structural formula of the alcohol.[1]

✓ ✗ I have justified my answer by referencing each compound's molecular mass.[2]

b propyl propanoate



water



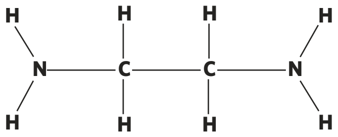
16 **a** [The base peak represents the most abundant species and so is assigned a relative abundance of 100.[1]][According to this mass spectrum, the base peak is at m/z = 30.[2]]

✓ ✗ I have explained what the base peak is.[1]

✓ ✗ I have identified the base peak.[2]

c $[H_2NCH_2]^+$

d



8B Infrared spectroscopy

Theory review questions

1 C

2 There are **2** axes in an infrared spectrum. The **horizontal axis** represents the **wavenumber** (cm^{-1}) of infrared light decreasing from left to right. The **vertical axis** shows the **transmittance** (%) of light increasing from bottom to top through the molecule we are investigating.

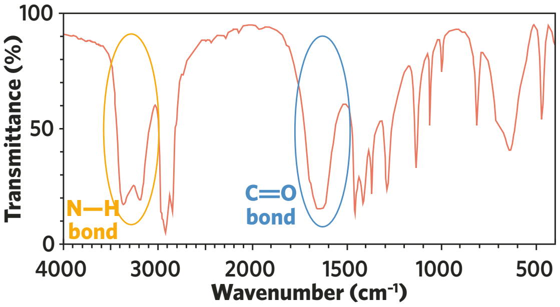
3 Infrared light with different wavenumbers has different **levels of energy**. Each bond requires a specific amount of energy to **vibrate** and therefore absorbs light with a specific **wavenumber**. Hence, this will produce different peaks of transmittance in the IR spectrum.

Exam style questions

Within lesson

4 D

5



[Amides have the $CONH_2$ functional group, involving a C═O and N—H bond.[1]][The spectrum shows a strong peak at 1650 cm^{-1} and a peak at 3200–3400 cm^{-1} [2]][which correspond to a C═O bond and N—H bond respectively.[3]][As a result, we can confirm that the molecule analysed was an amide.[4]]

✓ ✗ I have identified the functional group of an amide.[1]

✓ ✗ I have identified the key peaks present.[2]

✓ ✗ I have used the spectrum to identify the main bonds present.[3]

✓ ✗ I have linked the answer to the question.[4]

6 [There is a strong and broad peak at 3200–3600 cm^{-1},[1]][which corresponds to an O—H (alcohol) bond.[2]][Therefore, this molecule is an alcohol.[3]]

✓ ✗ I have identified a key peak in the spectrum.[1]

✓ ✗ I have identified the bond type associated with the key peak.[2]

✓ ✗ I have identified the type of compound.[3]

Multiple lessons

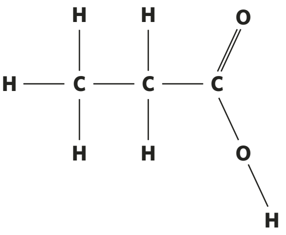
7 **a** [The spectrum shows 2 main peaks: a broad peak at 3000–3200 cm^{-1} and strong peak at 1750 cm^{-1},[1]][which correspond to the O—H (acid) and C═O (acid) bond respectively.[2]][As a result, we can conclude that this molecule is a carboxylic acid.[3]]

✓ ✗ I have identified key peaks present.[1]

✓ ✗ I have used the spectrum to identify the main bonds present.[2]

✓ ✗ I have linked the answer to the question.[3]

b propanoic acid



c propan-1-ol

8 [The strong peak at 1700 cm^{-1} shows the presence of a C═O (acid) bond. The strong and broad peak at 3200 cm^{-1} indicates an O—H (acid) bond.[1]][Therefore, this compound is a carboxylic acid with four carbons.[2]][The semi-structural formula of the compound is $CH_3CH_2CH_2COOH$[3]][and the IUPAC name of the compound is butanoic acid.[4]]

✓ ✗ I have indicated the bonds corresponding to the circled peaks with reference to the Data Book.[1]

✓ ✗ I have identified the compound as an acid.[2]

✓ ✗ I have identified the semi-structural formula of the compound.[3]

✓ ✗ I have given the correct IUPAC name of the compound.[4]

8C Nuclear magnetic resonance

Theory review questions

1 C

2 In NMR spectroscopy, the nuclei of ^{13}C atoms can spin and align with or against the external magnetic field. The energy required by a carbon nucleus for a spin flip is called a **chemical shift**. Different atoms surrounding ^{13}C atoms will produce different electron environments, which can change the **external magnetic field** experienced by the ^{13}C atoms. Therefore, different carbon environments require different **energy levels** for spin flips. Hence, different carbon environments have different **peaks** in a ^{13}C NMR spectrum.

3 B

Exam-style questions

Within lesson

4 D **5** A

6 [As the ^{13}C NMR spectrum shows one peak, this suggests that the molecule has one C environment.[1]][Also, the chemical shift of the peak is within range to represent a carbon that is bonded to an NH_2 group.[2]] [Both properties identified by the spectrum are consistent with the structure of $H_2NCH_2NH_2$.[3]]

✓ ✗ I have identified the number of peaks shown in the ^{13}C NMR spectrum and the corresponding number of C environments.[1]

✓ ✗ I have identified the chemical shift in the spectrum and the corresponding environment.[2]

✓ ✗ I have linked my answer to the question.[3]

7 **a** [There are 3 peaks in the ^{1}H NMR spectrum.[1]][The compound therefore has 3 H environments.[2]]

✓ ✗ I have identified the number of peaks in the ^{1}H NMR spectrum.[1]

✓ ✗ I have determined the number of H environments in the compound.[2]

b [There are 4 peaks in the ^{13}C NMR spectrum.[1]][The compound therefore has 4 C environments.[2]]

✓ ✗ I have identified the number of peaks in the ^{13}C NMR spectrum.[1]

✓ ✗ I have determined the number of C environments in the compound.[2]

c [In the ^{1}H NMR spectrum, the peak at 1 ppm is a triplet, thus the H environment neighbouring to the H environment causing this peak has 2 H atoms. The peak at 1 ppm also shows the presence of a CH_3 group.[1]][The peak at 2.3 ppm in the ^{1}H NMR spectrum is a quartet, indicating that the neighbouring H environment has 3 H atoms.[2]] [The peak at 3.7 ppm is a singlet so there is no H atom in the neighbouring H environment.[3]][Hence, the semi-structural formula of the compound is $CH_3CH_2COOCH_3$.[4]]

✓ ✗ I have applied the n+1 rule and chemical shift to the peak at 1 ppm.[1]

✓ ✗ I have applied the n+1 rule to the peak at 2.3 ppm.[2]

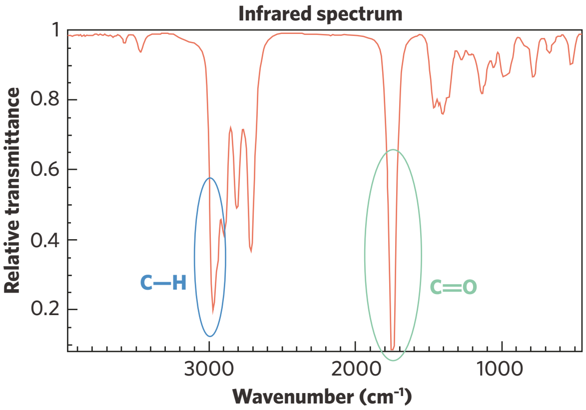
✓ ✗ I have applied the n+1 rule to the peak at 3.7 ppm.[3]

✓ ✗ I have determined the semi-structural formula of the compound.[4]

Multiple lessons

8 D

9 **a**



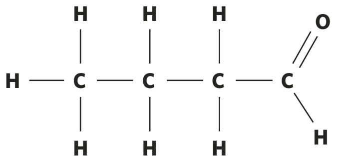
✓ ✗ I have circled the peak at 2900–3000 cm^{-1} and labelled it as a C—H bond.

✓ ✗ I have circled the peak at 1600–1700 cm^{-1} and labelled it as a C=O bond.

b

Chemical shift (ppm)	Relative peak area	Peak splitting
1.03	3	triplet
1.66	2	sextet
2.50	2	triplet
9.62	1	**triplet**

c

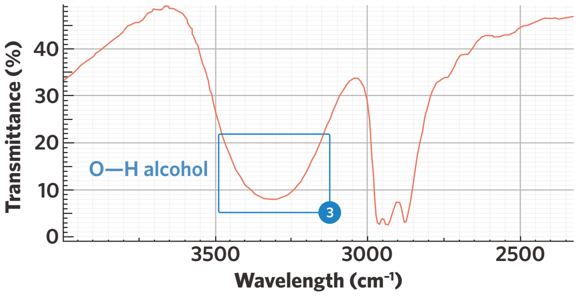


d [Four.[1]][There are 4 carbon environments in the butanal molecule, so therefore there are 4 signals.[2]]

✓ ✗ I have correctly identified four signals in the ^{13}C NMR output.[1]

✓ ✗ I have explained the link between the number of carbon environments and the number of signals.[2]

10 **a** [The strong and broad peak between 3000 and 3500 cm^{-1} indicates the presence of an O—H alcohol functional group.[1]][Therefore, the compound is an alcohol.[2]]

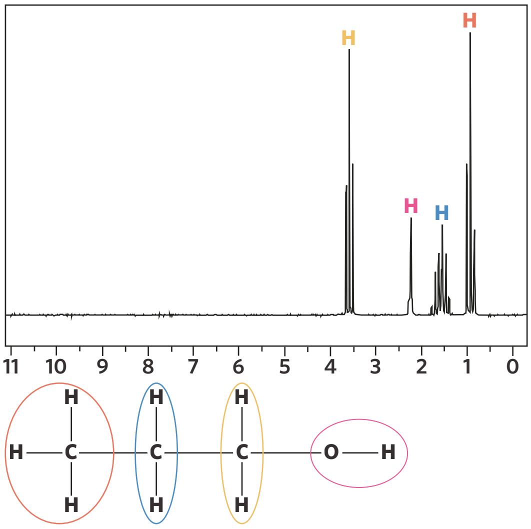


✓ ✗ I have mentioned the range of the peak and the functional group.[1]

✓ ✗ I have determined the type of organic compound.[2]

✓ ✗ I have correctly circled the peak responsible for the functional group.[3]

b



[The ^{1}H NMR spectrum shows 4 peaks, indicating that there are 4 H environments in the compound.[1]][The peak at 1 ppm is a triplet and therefore the adjacent H environment has 2 H atoms. 1 ppm also indicates a CH_3 group.[2]][The peak at 1.4 ppm is a sextet therefore the adjacent H environments have 5 H atoms. 1.4 ppm also shows the presence of a CH_2 group.[3]][The peak at 2.3 ppm is a singlet and therefore the adjacent H environment does not have any H atoms.[4]][The peak at 3.6 ppm is a triplet therefore the adjacent H environment has 2 H atoms.[5]][Hence, the semi-structural formula of the compound is $CH_3CH_2CH_2OH$.[6]]

✓ ✗ I have indicated the number of peaks in the ^{1}H NMR spectrum.[1]

✓ ✗ I have applied the *n*+1 rule and chemical shift to the peak at 1 ppm.[2]

✓ ✗ I have applied the *n*+1 rule and chemical shift to the peak at 1.4 ppm.[3]

✓ ✗ I have applied the *n*+1 rule to the peak at 2.3 ppm.[4]

✓ ✗ I have applied the *n*+1 rule to the peak at 3.6 ppm.[5]

✓ ✗ I have determined the semi-structural formula of the compound.[6]

c propan-1-ol

11 **a** [The molecular ion peak of the spectrum is at m/z 74.[1]]

a ×(molar mass of $C_4H_{10}O$) = 74

a ×(74) = 74

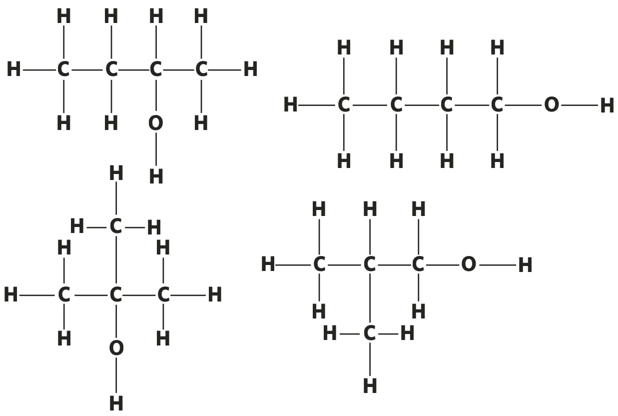
a = 1

So the molecular formula of the compound is $C_4H_{10}O$.

✓ ✗ I have identified the molecular ion peak.[1]

✓ ✗ I have shown the calculation to get the molecular formula of the compound.

b



c [The compound is oxidised, creating a ketone. This means the compound is a secondary alcohol.[1]][Therefore, the IUPAC name of the compound is butan-2-ol.[2]]

✓ ✗ I have identified the type of compound based on the given information.[1]

✓ ✗ I have given the correct IUPAC name of the compound.[2]

d [Butan-2-ol is not responsible for the given ^{13}CNMR spectrum[1]] [as butan-2-ol has 4 different C environments, whereas the ^{13}C NMR spectrum only shows 3 peaks.[2]]

✓ ✗ I have concluded that the compound is not responsible for the given ^{13}C NMR spectrum.[1]

✓ ✗ I have explained my answer based on the number of peaks in the given ^{13}C NMR spectrum.[2]

8D Combining techniques

Theory review questions

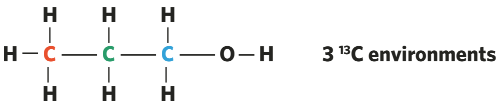
1 C **2** B **3** C **4** D **5** A

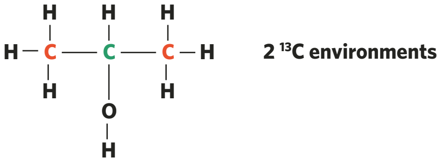
Exam-style questions

Within lesson

6 B **7** A **8** D

9 **a**





[^{13}C NMR gives us information about the number of carbon environments in a molecule.[1]][Due to the symmetry of propan-2-ol at carbon number 2, the carbon attached to the hydroxyl functional group, propan-2-ol has only 2 carbon environments. In contrast, propan-1-ol has 3 unique carbon environments.[2]][As a result, the ^{13}C NMR spectrum for propan-2-ol would show 2 peaks and propan-1-ol, 3 peaks.[3]][We would be able to use this difference in the number of peaks to distinguish between the two molecules.[4]]

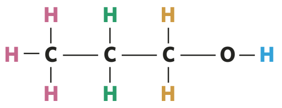
✓ ✗ I have described the function of ^{13}C NMR.[1]

✓ ✗ I have related the structure of the compounds to the number of carbon environments.[2]

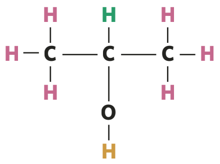
✓ ✗ I have identified the number of peaks for each molecule.[3]

✓ ✗ I have linked the answer back to the question.[4]

b



4 ¹H environments



3 ¹H environments

[¹H NMR gives us information on the different hydrogen environments in a molecule[1]][It can be seen that propan-1-ol has 4 different hydrogen environments whereas propan-2-ol has 3 different hydrogen environments.[2]][As a result, propan-1-ol would show 4 peaks in a low resolution ¹H NMR whereas propan-2-ol would have 3 peaks.[3]][We would be able to use this difference in the number of peaks to distinguish between the two molecules.[4]]

✓ ✗ I have described the function of ¹H NMR.[1]

✓ ✗ I have related the structure of the compounds to the number of hydrogen environments.[2]

✓ ✗ I have identified the number of peaks for each molecule.[3]

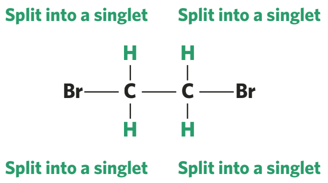
✓ ✗ I have linked the answer back to the question.[4]

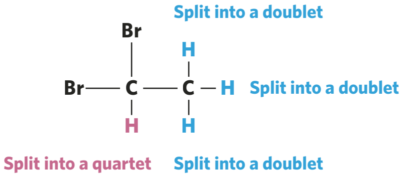
10 **a** [Bromine can exist as a range of different isotopes, commonly ^{79}Br and ^{81}Br with a mass of 79 g mol $^{-1}$ and 81 g mol $^{-1}$ respectively.[1]][Therefore, depending on the bromine isotope present in the molecule, the parent ion can have different m/z ranging from 186-190.[2]]

✓ ✗ I have identified that bromine has isotopes.[1]

✓ ✗ I have explained the effect of the isotopes on the m/z of the parent ion and why they are referred to as the molecular ion peak.[2]

b





[There are two possible isomers with the formula $C_2H_4Br_2$.[1]][As can be seen, 1,1-dibromoethane has one deshielded proton split into a quartet and 3 which are split into a doublet whereas 1,2-dibromoethane will have a splitting pattern of a one singlet.[2]][As a result, the information on the table corresponds with 1,1-dibromoethane.[3]]

✓ ✗ I have identified that $C_2H_4Br_2$ has isomers.[1]

✓ ✗ I have identified the splitting patterns of each molecule.[2]

✓ ✗ I have correctly identified the isomer.[3]

✓ ✗ I have included a diagram of both molecules.

11 **a** [Since both compounds have the same molecular formula, Jasmine could not distinguish which compound was in the sample based on the position of the molecular ion peak[1]][as they would have the same m/z reading.[2]]

✓ ✗ I have identified that the compounds cannot be distinguished.[1]

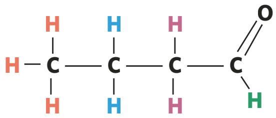
✓ ✗ I have justified why mass spectrometry may not be an ideal technique for these molecules.[2]

b [The chemist could look at the fingerprint region of the IR spectrum and compare it to the spectra produced by a pure sample of butanal and butan-2-one.[1]][Since the fingerprint region is a unique identifier, the IR spectrum belongs to the compound which has the exact same fingerprint region.[2]]

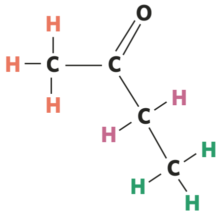
✓ ✗ I have suggested a way that the chemist could determine the identity of the compound.[1]

✓ ✗ I have explained why this technique will work.[2]

c



4 ¹H environments



3 ¹H environments

[Butanal has 4 proton environments and therefore would show 4 peaks in the spectrum whereas butan-2-one has 3 proton environments which would translate to 3 peaks in the spectrum.[1]][As a result, we can conclude that the compound is butanal.[2]]

✓ ✗ I have related the structure of a compound to the number of proton environments.[1]

✓ ✗ I have identified the molecule that correlates to the information given.[2]

Multiple lessons

12 **a** M(E.F.) = 12 × 3 + 6 × 1 + 16 × 2

$= 74\ \text{g mol}^{-1}$

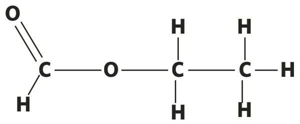
Therefore, the molecular formula is $C_3H_6O_2$

b [The three possible compounds with the molecular formula $C_3H_6O_2$ are a carboxylic acid, an alcohol or an ester.[1]][The absence of a broad O—H absorption band in the 2500–3500 cm^{-1} region indicates that this compound is not a carboxylic acid or an alcohol. Therefore, it is an ester.[2]]

✓ ✗ I have identified the possible compounds that could have this molecular formula.[1]

✓ ✗ I have explained how the absence of a functional group in the IR spectrum can reveal the identity of the compound.[2]

c



ethyl methanoate

d [This is an esterification/ condensation reaction.[1]]

[$HCOOH_{(l)} + CH_3CH_2OH_{(l)} \xrightarrow{H_2SO_{4(l)}} HCOOCH_2CH_{3(l)} + H_2O_{(l)}$[2]]

✓ ✗ I have named the type of reaction.[1]

✓ ✗ I have written the full equation, including appropriate reagents.[2]

8E Chromatography

Theory review questions

1 D **2** C **3** D

Exam-style questions

Within lesson

4 A **5** B **6** C **7** D

8 [HPLC is based upon the repeated transfer of components between the stationary and mobile phase.[1]][Components which are more strongly adsorbed to the stationary phase will spend more time stationary compared to those which are more strongly desorbed into the mobile phase.[2]][Therefore, the components experience different rates of motion leading to separation on the column.[3]]

✓ ✗ I have identified the basic principle of HPLC.[1]

✓ ✗ I have explained how components have different retention times.[2]

✓ ✗ I have linked this idea to separation.[3]

9 **a** [The doctor would have to run a set of known concentrations of acetylsalicylic acid in the HPLC column under the same conditions.[1]][A calibration curve can then be constructed to relate the area under the peak to the concentration of acetylsalicylic acid in the patient's blood.[2]]

✓ ✗ I have identified the process of creating a calibration curve.[1]

✓ ✗ I have explained how a calibration curve can be used to determine the concentration of acetylsalicilic acid in the patient's blood.[2]

b [An increase in temperature will mean that the components in the HPLC column are less adsorbed to the stationary phase and more strongly desorbed in the mobile phase as the components are more soluble with an increased temperature.[1]][This leads to a decreased retention time.[2]]

✓ ✗ I have explained the effect of temperature on the components in the sample.[1]

✓ ✗ I have identified the effect of temperature on retention time.[2]

10 [Methanol is a polar molecule and therefore, its intermolecular forces are dispersion forces, permanent dipole-dipole bonding and hydrogen bonding.[1]][To have a longer retention time, a component needs to be more strongly adsorbed to the stationary phase than desorbed into the mobile phase. Since in normal phase HPLC, there is a polar stationary phase, the polar methanol molecules will be more strongly adsorbed onto the polar stationary phase than to the non-polar stationary phase in reverse phase HPLC.[2]][This means that normal phase HPLC will have a longer retention time for methanol.[3]]

✓ ✗ I have identified the intermolecular forces of attraction in methanol.[1]

✓ ✗ I have explained how polarity affects retention time.[2]

✓ ✗ I have identified which type of HPLC will have a longer retention time.[3]

11 **a** [The worker could run a pure sample of caffeine in the HPLC column under the same conditions to find the retention time of caffeine.[1]][This retention time can then be matched to the chromatogram produced with a sample of Katherine's coffee to see if a corresponding peak is present.[2]]

✓ ✗ I have explained a way to find the retention time of pure caffeine.[1]

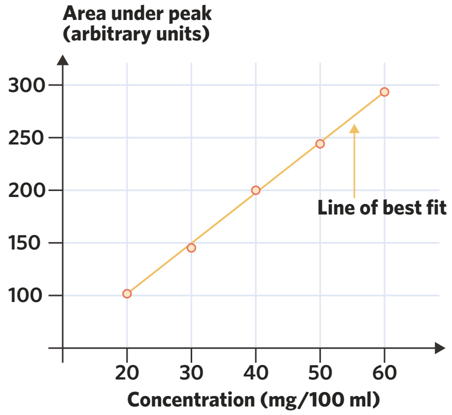
✓ ✗ I have shown how this could be used to confirm the presence of caffeine in Katherine's coffee.[2]

b [The worker would have to run a set of known concentrations of caffeine in the HPLC column under the same conditions.[1]][A calibration curve can then be constructed to relate the area under the peak to the concentration of caffeine in Katherine's coffee.[2]]

✓ ✗ I have explained a way to create a calibration curve.[1]

✓ ✗ I have shown how creating a calibration curve can be used to determine the concentration of caffeine.[2]

c



✓ ✗ I have used the values to draw a line of best fit.

✓ ✗ I have included labels for all axes.

d [The table of results show that the caffeine in Katherine's coffee has an area under the peak of 180.[1]][Using the calibration curve, it can be seen that this correlates to a concentration of around 38 mg/100 mL.[2]][As a result, the claim she made was inaccurate.[3]]

✓ ✗ I have referred to the results from Katherine's analysis.[1]

✓ ✗ I have used the calibration curve to find the caffeine concentration of Katherine's coffee.[2]

✓ ✗ I have made reference to the accuracy of Katherine's claim.[3]

Multiple lessons

12 **a** S - methane

R - propane

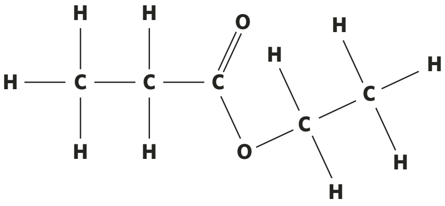
P - ethanol

Q - propanoic acid

b $C_2H_6O_{(l)} + C_3H_6O_{2(l)} \rightarrow C_5H_{10}O_{2(l)} + H_2O_{(l)}$

Product: ethyl propanoate

c



d [During mass spectrometry, the molecule is broken into fragments due to the bombardment of electrons.[1]][The disadvantage with this is that the sample would be destroyed and therefore cannot be used as evidence.[2]]

✓ ✗ I have identified the function of mass spectrometry.[1]

✓ ✗ I have explained the disadvantage of the technique.[2]

13 **a** Non-polar stationary phase

b [The branching of propan-2-ol[1]][reduces the surface area available for intermolecular bonding to occur between the molecules and doesn't allow molecules to stack efficiently. In contrast, propan-1-ol is a linear molecular with a greater surface area, thereby allowing for stronger intermolecular forces of attractions and more efficient stacking of molecules. Due to the weaker intermolecular force between propan-2-ol, less energy would be required to break the intermolecular bonds[2]][and therefore would have a lower boiling point than propan-1-ol.[3]]

✓ ✗ I have identified that propan-2-ol is branched.[1]

✓ ✗ I have described the relationship between surface area and boiling point.[2]

✓ ✗ I have identified that propan-2-ol has a lower boiling point.[3]

c Ketone or aldehyde and carboxylic acid

8F Volumetric analysis

Theory review questions

1 A

2 B

3 B

Exam-style questions

Within lesson

4 C

5 D

6 A

7 **a** $C_6H_5COOH_{(aq)} + NaOH_{(aq)} \rightarrow C_6H_5COONa_{(aq)} + H_2O_{(l)}$

b Avg titre of $C_6H_5COOH = \frac{(12.01+12.10+11.98)}{3}$

$= 12.03$ mL

$n(C_6H_5COOH) = 0.20 \times (\frac{12.03}{1000})$

$= 0.002406$ mol

$n(C_6H_5COOH) : n(NaOH)$

$1 : 1$

$n(NaOH) = 0.002406$

$C(NaOH) = \frac{0.002406}{(20.00 \div 1000)}$

$= 0.12$ M

c A standard solution is a solution of a precisely known concentration.

8 **a** $n(MnO_4^-) = 0.500 \times (\frac{18.91}{1000})$

$= 0.009445$ mol

$n(MnO_4^-) : n(C_2O_4^{2-})$

$2 : 5$

$n(C_2O_4^{2-}) = \frac{0.009455}{2} \times 5$

$n(C_2O_4^{2-}) = 0.023638$

$C(C_2O_4^{2-}) = \frac{0.02363}{(25.00 \div 1000)}$

$= 0.946$ M

b 25.00 : 200.00

1 : 8

$C(H_2C_2O_4) = 0.946 \times 8$

$= 7.564$ M

$n(H_2C_2O_4) = 7.56 \times (\frac{25.00}{1000})$

$= 0.1891$ mol

$m(H_2C_2O_4) = 0.1891 \times 90$

$= 17.0$ g

9 **a** $NH_{3(aq)} + HCl_{(aq)} \rightarrow NH_4{}^{+}{}_{(aq)} + Cl^{-}{}_{(aq)}$

b $n(HCl) = 0.10 \times (\frac{14.56}{1000})$

$= 0.001456$ mol

$n(HCl) : n(NH_3)$

1 : 1

$n(NH_3) = 0.001456$

$C(NH_3) = \frac{0.001456}{(20.00 \div 1000)}$

$= 0.0728$ M

c 25.00 mL of household cleaner was diluted to 250.00 mL

25.00 : 250.00

1 : 10

Dilution factor of 10

The $C(NH_3)$ in the 20.00 mL aliquot = $C(NH_3)$ in the 250.00 mL flask

Therefore the $C(NH_3)$ in original sample = 0.0728×10

$= 0.728$ M

d [When a strong acid such as HCl reacts with a weak base such as NH_3, it is expected that the solution at endpoint would be more acidic and therefore will have a pH less than 7.[1]][According to the data book, phenolphthalein and phenol red have colour changes from a pH of 8.3–10.0 and 6.8–8.4 respectively, which is outside the range of the endpoint of this reaction.[2]][In contrast bromophenol blue's colour change occurs at a pH of 3.0–4.6, which is more acidic,[3]][and as a consequence would be the preferred indicator for the reaction between HCl and NH_3.[4]]

✓ ✗ I have described the effect of reacting a strong acid with a weak base.[1]

✓ ✗ I have used data to explain the incompatibility of phenolphthalein and phenol red.[2]

✓ ✗ I have used data to explain why bromophenol blue can be used in the reaction.[3]

✓ ✗ I have linked the answer back to the question.[4]

10 **a** Mean titre of NaOH $= \frac{(13.51 + 13.67 + 13.55)}{3}$

$= 13.577$ mL

$n(NaOH) = 0.50\text{ M} \times (\frac{13.577}{1000})$

$= 0.006789$ mol

$n(NaOH) : n(C_6H_8O_7)$

3 : 1

$n(C_6H_8O_7) = \frac{0.006789}{3}$

$= 0.002263$ mol

$C(C_6H_8O_7) = \frac{0.002263}{(20.00 \div 1000)}$

$= 0.11$ M

b [As they are used to produce standard solutions of accurately known concentration,[1]][primary standards cannot react with the surrounding environment.[2]][Sodium hydroxide is able to react with moisture (and carbon dioxide) in the air, and so it cannot be used as a primary standard because the concentration of the solution cannot be guaranteed.[3]]

✓ ✗ I have described the purpose of a standard solution.[1]

✓ ✗ I have identified a property of primary standards relevant to this question.[2]

✓ ✗ I have explained why sodium hydroxide cannot be used as a primary standard.[3]

c n(potassium phthalate) required for a 250.00 mL sample at 1M

$= 1.0 \times (\frac{250.00}{1000})$

$= 0.250$ mol

m(potassium phthalate) $= 0.250 \times 204.2$

$= 51.05$ g

1. Accurately weigh 51.05 g potassium hydrogen phthalate
2. Transfer potassium hydrogen phthalate into a volumetric flask
3. Add deionised water into the volumetric flask to approximately halfway
4. Swirl the volumetric flask to dissolve the solute completely
5. Add enough deionised water to make the solution to 250.00mL

✓ ✗ I have identified the mass of potassium hydrogen phthalate required.[1]

✓ ✗ I have outlined the steps to produce a potassium hydrogen phthalate standard solution.[2]

Multiple lessons

11 **a** $2MnO_4{}^{-}{}_{(aq)} + 6H^{+}{}_{(aq)} + 5H_2O_{2(aq)} \rightarrow 2Mn^{2+}{}_{(aq)} + 8H_2O_{(l)} + 5O_{2(g)}$

b [An acid-base titration curve shows the change in pH of the analyte solution during the course of the titration reaction[1]][whereas redox titration curves show the E^0 V changes throughout the reaction.[2]]

✓ ✗ I have identified the variable that is measured during an acid-base titration reaction.[1]

✓ ✗ I have identified the variable that is measured during a redox titration reaction.[2]

c $n(\text{KMnO4}) = \frac{1.50}{158}$

$= 0.009494$ mol in 1 L of solution

$C(\text{KMnO}_4) = \frac{0.009494}{1}$

$= 0.009494$ M

$n(\text{MnO}_4^-) = 0.009494 \times (\frac{12.01}{1000})$

$= 0.0001140$ mol

$n(\text{MnO}_4^-) : n(\text{H}_2\text{O}_2)$

2 : 5

$n(\text{H}_2\text{O}_2) = \frac{0.0001140 \times 5}{2}$

$= 0.000285$

$C(\text{H}_2\text{O}_2) = \frac{0.000285}{(20.00 \div 1000)}$

$= 0.0143$ M

d [Wear gloves when handling hydrogen peroxide.[1]][Wear safety glasses.[2]]

✓ ✗ I have identified a way to minimize burns.[1]

✓ ✗ I have identified a way to minimize eye damage.[2]

12 a $\text{MnO}_4{}^-{}_{(aq)} + 8\text{H}^+{}_{(aq)} + 5e^- \rightarrow \text{Mn}^{2+}{}_{(aq)} + 4\text{H}_2\text{O}_{(l)}$

b $n(\text{MnO}_4^-) = 0.500 \times (\frac{14.55}{1000})$

$= 0.007275$ mol

Fe^{2+} is oxidised according to the redox half-equation

$\text{Fe}^{2+}{}_{(aq)} \rightarrow \text{Fe}^{3+}{}_{(aq)} + e^-$

$n(\text{MnO}_4^-) : n(\text{Fe}^{2+})$

1 : 5

$n(\text{Fe}^{2+}) = 0.007275 \times 5$

$= 0.036375$ mol

$C(\text{FeSO}_4) = \frac{0.036375}{(20.0 \div 1000)}$

$= 1.82$ M

c 25.00 : 250.00

1 : 10

Dilution factor of 10

$C(\text{FeSO}_4)$ in original sample = 1.82 × 10

= 18 M

Chapter 8 review

Multiple choice

1	D	**2**	C	**3**	D	**4**	C	**5**	D
6	D	**7**	A	**8**	A	**9**	B	**10**	B

Short answer

11 a [Three.[1]][The proton NMR spectrum shows three signals, indicating three different hydrogen environments in compound W.[2]]

✓ ✗ I have correctly identified the number of hydrogen environments.[1]

✓ ✗ I have explained the link between the number of signals and the number of hydrogen environments.[2]

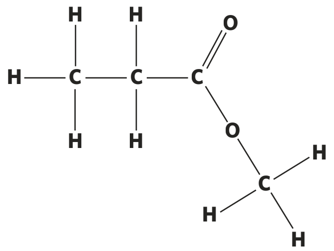
b [The presence of 2 oxygens in the molecular formula suggests compound *W* contains either an ester group, carboxyl group or 2 hydroxyl groups.[1]][The IR spectrum given shows no strong and broad O—H peak at 2500–3500 (acid) or 3200–3600 cm^{-1} (alcohol), suggesting the compound contains an ester group[2]][and therefore is an ester compound.[3]]

✓ ✗ I have identified the different types of compounds that could result due to the presence of 2 oxygens.[1]

✓ ✗ I have used evidence from the IR spectrum, molecular formula, or proton NMR spectrum to support my response.[2]

✓ ✗ I have identified the type of functional group present.[3]

c

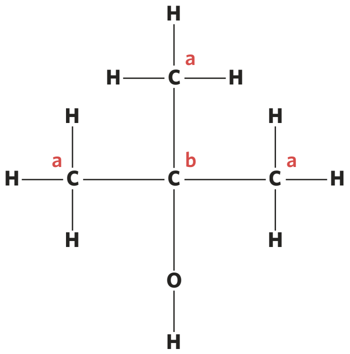


Methyl propanoate

12 a [TMS is a chemical used to provide a standard for all ^{13}C NMR spectra, and allows a common point of reference for chemical shifts.[1]]

✓ ✗ I have described the purpose of TMS as providing a reference point for the chemical shift.[1]

b



[As identified in the structural formula, 2-methylpropan-2-ol has two different carbon environments, (labelled a and b).[1]] [The ^{13}C NMR spectrum given shows three peaks, indicating three carbon environments in the unidentified molecule. [2]][Therefore the molecule James proposes is not consistent with the ^{13}C NMR data provided. [3]]

✓ ✗ I have identified the number of carbon environment in the molecule.[1]

✓ ✗ I have identified the number of peaks in the spectrum.[2]

✓ ✗ I have linked the answer to the question.[3]

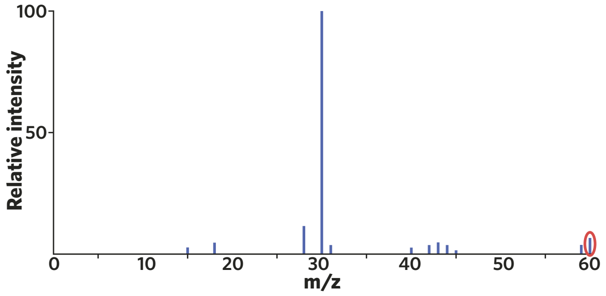
✓ ✗ I have included a diagram.

13 [The IR spectrum shows a medium, broad peak around 3300–3500 cm^{-1} and a strong peak around 1630–1680 cm^{-1},[1]][corresponding to the N—H bond and the C═O bond in the amide functional group respectively.[2]]

✓ ✗ I have identified key peaks in the spectrum.^{1}

✓ ✗ I have linked the peaks present to the structure of the compound.^{2}

14 **a**



b [The parent peak corresponds to the molecular ion of the organic compound, so the *m/z* of the molecular ion must be 60 m/z.^{1}]

molar mass of $x*(CH_4N) = 60$

$x*(12 + 4 + 14) = 60$

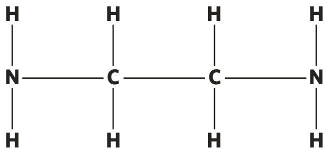
$x = \frac{60}{30} = 2$

$x = 2$, so the [molecular formula of the unknown sample is $C_2H_8N_2$.^{2}]

✓ ✗ I have identified the parent peak gives the m/z of the molecular ion.^{1}

✓ ✗ I have identified the molecular formula for the sample.^{2}

c



d $[NH_2CH_2]^+$ or $[CH_2NH_2]^+$

e [Mass spectrometry gives data about the mass to charge ratio of fragments in a molecule.^{1}][This information does not indicate which functional groups are present in the molecule.^{2}][Other analytical techniques such as IR spectroscopy would be required to determine the functional groups in the molecule.^{3}]

✓ ✗ I have explained the information mass spectrometry provides.^{1}

✓ ✗ I have made a statement as to whether mass spectrometry gives information about functional groups.^{2}

✓ ✗ I have suggested a way that the functional groups could be determined in a molecule.^{3}

f [The spectrum shows only one peak, indicating the presence of only one carbon environment in the molecule.^{1}][The structure determined in part c is consistent with this, as it also has only one carbon environment.^{2}]

✓ ✗ I have used the spectrum to identify the number of carbon environments in the molecule.^{1}

✓ ✗ I have linked the answer to the question.^{2}

15 **a** 53 seconds (52–54 seconds acceptable)

b The area underneath the peaks indicates the relative abundance of each substance in the perfume.

c [*S, R, Q, P*^{1}][Ethanol is a polar molecule due to the presence of a hydroxyl group,^{2}][therefore substances in the sample that are more polar will have a greater affinity for the stationary phase and hence will have a longer retention time.^{3}]

✓ ✗ I have identified the order of polarity.^{1}

✓ ✗ I have identified the polarity of the stationary phase.^{2}

✓ ✗ I have described the effect of the polarity of molecules on retention time.^{3}

d The retention times of all components will increase.

e *S, R, Q, P*

Key science skill question

16 **a** [In order to produce 500 mL of a 0.100 mol L^{-1} solution of sodium carbonate:

$n(Na_2CO_3) = (\frac{500}{1000})\ L \times 0.100\ mol\ L^{-1}$

$= 0.0500\ mol$

$m(Na_2CO_3) = 0.0500 \times 106$

$= 5.30\ g$^{1}]

[Step 1. Accurately measure 5.30 g of sodium carbonate

Step 2. Transfer the sample of sodium carbonate into a 500.0 mL volumetric flask and add enough water to fill the flask halfway.

Step 3. Stir the flask to allow the sample to dissolve

Step 4. Fill up the volumetric flask until the volume reaches 500.0 mL^{2}]

✓ ✗ I have determined the exact mass of sodium carbonate required.^{1}

✓ ✗ I have listed the steps in producing a standard.^{2}

b The concentration of hydrochloric acid

c [By using a 20.0 mL aliquot instead of 25.0 mL as outlined in the steps, the average titre of hydrochloric acid used during the reaction would be less than 21.4 mL.^{1}][Due to the fact that the concentration of hydrochloric acid is calculated based on the titre used, a lower average titre would result in the calculation of a concentration that would be greater than the true value,^{2}][therefore his results would not be accurate.^{3}]

✓ ✗ I have identified the effect of using a 20.0 mL aliquot instead of 25.0 mL.^{1}

✓ ✗ I have described how the calculated concentration would be greater than the true value.^{2}

✓ ✗ I have linked the answer back to the question.^{3}

9A Structure of proteins

Theory review questions

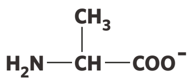
1 C **2** B **3** D

Exam style questions

Within lesson

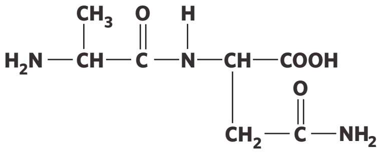
4 C **5** D **6** B **7** C

8 **a**



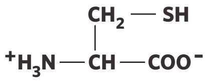
$H_2N-\overset{\displaystyle CH_3}{\overset{|}{CH}}-COO^-$

b



c Hydrogen bonds resulting from peptide linkages

9 **a**



${}^+H_3N-\overset{\displaystyle CH_2-SH}{\overset{|}{CH}}-COO^-$

b Disulfide bridges, permanent dipole-dipole forces and dispersion forces

10 **a** **i** Primary structure

ii Secondary structure

iii Tertiary structure

iv Quaternary structure

b [Primary structure: peptide bonds.[1]] [Secondary structure: hydrogen bonds.[2]] [Tertiary structure: hydrogen bonds, ionic bonds, disulfide bridges, permanent dipole-dipole forces and dispersion forces.[3]] [Quaternary structure: hydrogen bonds, ionic bonds, disulfide bridges, permanent dipole-dipole forces and dispersion forces.[4]]

✓ ✗ I have determined the bonds present in primary structure.[1]

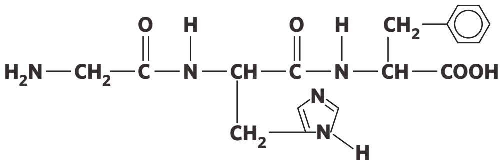
✓ ✗ I have determined the bonds present in secondary structure.[2]

✓ ✗ I have determined the bonds present in tertiary structure.[3]

✓ ✗ I have determined the bonds present in quaternary structure.[4]

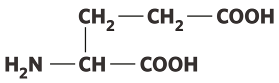
11 **a** Essential amino acids are amino acids that cannot be synthesised by the human body.

b



Multiple lessons

12 **a** [The amino acid present in the sample was glutamic acid.[1]]



$H_2N-\overset{\displaystyle CH_2-CH_2-COOH}{\overset{|}{CH}}-COOH$

✓ ✗ I have determined the amino acid present in the sample.[1]

✓ ✗ I have drawn the structural formula for glutamic acid.

b [Glutamic acid has the greatest retention time.[1]] [As it is more polar than glycine, it is more strongly adsorbed to the polar stationary phase.[2]] [and therefore would have the greatest retention time.[3]]

✓ ✗ I have determined the amino acid with the greatest retention time.[1]

✓ ✗ I have compared the structure of both amino acids and the interaction with the stationary phase.[2]

✓ ✗ I have linked my answer to the question.[3]

9B Breakdown of proteins

Theory review questions

1 B **2** D **3** A

Exam-style questions

Within lesson

4 C

5 [Cooking the meat will prevent food poisoning by E. coli [1]] [as the high temperatures will denature the proteins in the bacteria, inhibiting their biological activity when ingested by the body.[2]]

✓ ✗ I have identified a method of preventing food poisoning from E. coli.[1]

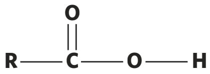
✓ ✗ I have stated how this method prevents food poisoning.[2]

6 [Temperature.[1]] [Enzyme activity decreases if the temperature rises above the optimal temperature, causing the enzyme to denature. A denatured enzyme can no longer function, therefore it would not be able to breakdown proteins.[2]]

✓ ✗ I have identified a factor that would affect the activity of an enzyme.[1]

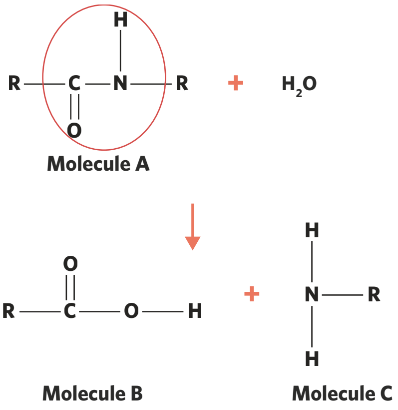
✓ ✗ I have outlined how this factor affects the breakdown of proteins.[2]

7 **a**



$R-\overset{\displaystyle O}{\overset{\|}{C}}-O-H$

b



c Peptide/Amide functional group

8 **a** [The tertiary structure[1]][because the tertiary structure is defined as the interactions and bonds between side chains within a protein, which is the target of this new drug.[2]]

✓ ✗ I have stated the level of protein structure.[1]

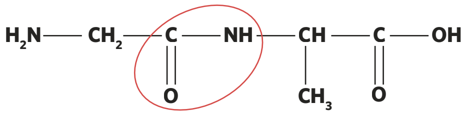
✓ ✗ I have related the protein structure to the bond type.[2]

b [The primary structure is defined by the peptide bonds between two adjacent amino acids.[1]][As the target of the new drug is the bonds between sulfur atoms, it would be unaffected.[2]]

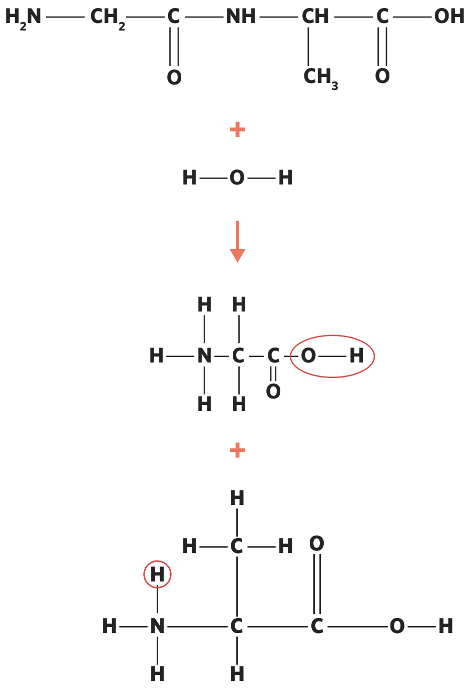
✓ ✗ I have stated what the primary structure is defined by.[1]

✓ ✗ I have stated how this differs from the target of the drug.[2]

9 **a**



b



✓ ✗ I have correctly drawn the hydrolysis reaction.

✓ ✗ I have circled where the OH was added and where the H was added to form the products.

c Glycine/2-aminoethanoic acid and alanine/2-aminopropanoic acid

10 [The heat from a hair straightener disrupts the hydrogen bonds between peptide bonds in keratin (secondary structure) as well as disrupting the tertiary and quaternary structure of keratin.[1]][Due to keratin being denatured, this causes the protein to unfold and the hair to lie flat.[2]]

✓ ✗ I have identified the structures within keratin that are disrupted by heat.[1]

✓ ✗ I have linked denaturation of this protein to hair lying flat.[2]

Multiple lessons

11 **a** [The secondary and tertiary structures of proteins are maintained, for the most part,by non-covalent bonding (excluding disulfide covalent bonds in the tertiary structure of a protein),[1]][which are weaker than the covalent peptide bonds that maintain the primary structure.[2]][As a result, it is easier to disrupt secondary and tertiary structures compared to primary structures.[3]]

✓ ✗ I have identified the type and strength of bonding in the secondary and tertiary structure of a protein.[1]

✓ ✗ I have identified the type and strength of the bonds within the primary structure of proteins, with reference to the secondary and tertiary structures.[2]

✓ ✗ I have linked the answer to the question.[3]

b [Denaturation is not strong enough to break the stronger peptide bonds in the primary structure of a protein,[1]][therefore only the weaker non-covalent linkages in the secondary and tertiary structure are disrupted, unfolding the protein.[2]]

✓ ✗ I have explained why the primary structure of a protein is unaffected by denaturation.[1]

✓ ✗ I have explained why denaturation disrupts the secondary and tertiary structures.[2]

12 **a** [In a hydrolysis reaction, water is consumed to break large molecules into their building blocks,[1]][whereas in a condensation reaction, two small molecules are linked together and water is eliminated.[2]]

✓ ✗ I have described the process of hydrolysis reactions.[1]

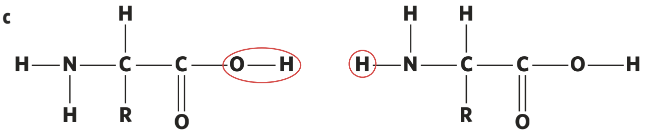
✓ ✗ I have described the process of condensation reactions.[2]

b [There are many reactions in the body that involve both condensation and hydrolysis.[1]][These include digestion (hydrolysis) and the synthesis of lipids, proteins and polysaccharides (condensation reactions).[2]]

✓ ✗ I have identified that both reaction types are important in body function.[1]

✓ ✗ I have given examples of each reaction type within the body.[2]

c



✓ ✗ I have drawn the products of the given hydrolysis reaction.

✓ ✗ I have identified where the constituents of the water molecule were added to form the products.

9C Enzymes

Theory review questions

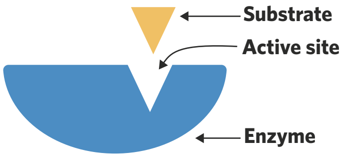
1 C **2** B **3** D

Exam-style questions

Within lesson

4 B **5** D **6** C

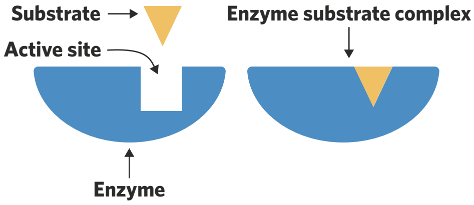
7 **a** [The lock and key model states that the substrate perfectly fits the active site of an enzyme.^{1}]



✓ ✗ I have described the lock and key model.^{1}

✓ ✗ I have drawn a labelled diagram representing the lock and key model.

b [The induced-fit model states that the active site of an enzyme can temporarily change its shape to accommodate the substrate.^{1}]



✓ ✗ I have explained the induced-fit model.^{1}

✓ ✗ I have drawn a labelled diagram representing the induced-fit model.

8 [Enzymes are specific to a certain enantiomer^{1}][because the particular three-dimensional shape of the enzyme's active site only matches one three-dimensional enantiomer.^{2}][Since the enzyme can metabolise only one of these enantiomers, half of the drug will not be metabolised by the body.^{3}]

✓ ✗ I have stated the optical specificity of enzymes.^{1}

✓ ✗ I have explained why enzymes are specific to certain enantiomers.^{2}

✓ ✗ I have justified why this will result in the chemist's findings.^{3}

Multiple lessons

9 [With elevated body temperatures, enzyme activity decreases as more and more enzymes become denatured after exceeding their optimal temperatures.^{1}][A decrease in enzyme activity is life-threatening because metabolic reactions which are necessary to sustain life will be occurring to a much slower rate.^{2}][With lower body temperatures, the rate of reactions decreases as the average kinetic energy of the reactant particles is less and there are fewer collisions per unit of time.^{3}] [This is catastrophic because with a lower rate of reaction of important metabolic reactions, the body struggles to maintain life.^{4}]

✓ ✗ I have described the effect of higher temperatures on enzyme activity.^{1}

✓ ✗ I have explained how decreased enzyme activity affects human function.^{2}

✓ ✗ I have explained the effect of lower temperatures on the rate of reaction.^{3}

✓ ✗ I have explained why a lower rate of reaction in biological systems is life-threatening.^{4}

10 **a** [Since enzyme activity operates in a narrow pH range, the test tubes 1 & 3 with a pH of 1 and 14 would result in lipase being denatured and therefore would not function.^{1}][As a result, Jasmine should observe the cube of fat still present in test tube 1 and 3 whereas it should be broken down in cube 2.^{2}].

✓ ✗ I have stated the effect of pH on enzyme activity.^{1}

✓ ✗ I have stated what Jasmine should observe.^{2}

b [A control has not been carried out because the pH of the solution around the cube of fat could be affecting the results.^{1}][This could be remedied by setting up another 3 test tubes without the enzyme lipase to see if the pH has any effect on the size of the cube of fat.^{2}]

✓ ✗ I have stated whether a control was carried out.^{1}

✓ ✗ I have explained how the experiment could be improved in light of this.^{2}

c [The enzyme alpha-amylase's optimum pH range is very close to the pH of the mouth.^{1}][Since an enzyme functions in a narrow pH range and the pH throughout the digestive tract varies, alpha-amylase can only function in the mouth.^{2}]

✓ ✗ I have identified the optimum pH range of alpha-amylase.^{1}

✓ ✗ I have explained why amylase can only function in the mouth.^{2}

d Denaturation affects the secondary, tertiary and quaternary structure of an enzyme. It does not affect its primary structure.

9D Structure and properties of vitamins

Theory review questions

1 C **2** B **3** B

Exam-style questions

Within lesson

4 D

5 From left to right: primary hydroxyl, secondary hydroxyl, secondary amide, carboxyl

6 **a** [This vitamin contains a number of hydroxyl, amine and amide functional groups,^{1}][which are capable of forming polar hydrogen bonds with water molecules.^{2}][As a result, this vitamin is water-soluble.^{3}]

✓ ✗ I have determined the functional groups present in the molecule.^{1}

✓ ✗ I have identified how these functional groups will interact with water.^{2}

✓ ✗ I have stated the solubility of the molecule.^{3}

b [Although there is one hydroxyl group present in the molecule, the major proportion of the vitamin is made up of non-polar carbon and hydrogen.[1]][As a non-polar molecule, this vitamin interacts through dispersion forces with similarly non-polar fats.[2]][As a result, this vitamin is fat-soluble.[3]]

✓ ✗ I have identified the functional groups and non-polar nature of the molecule.[1]

✓ ✗ I have described the intermolecular forces between the molecule and fats.[2]

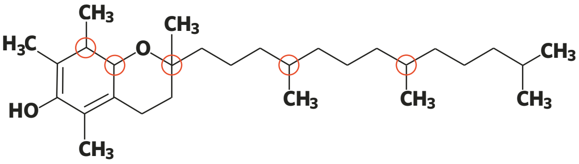
✓ ✗ I have stated the solubility of the molecule.[3]

Multiple lessons

7 A

8 $C_3H_4O_3$

9 a



b [Although there are a few electronegative atoms present in the molecule, the major proportion of the vitamin is made up of non-polar carbon and hydrogen.[1]][As a non-polar molecule, this vitamin interacts through dispersion forces and so cannot form strong intermolecular bonds with water.[2]][As a result, this vitamin is insoluble in water.[3]]

✓ ✗ I have identified the functional groups and non-polar nature of the molecule.[1]

✓ ✗ I have described the intermolecular forces between the molecule and water.[2]

✓ ✗ I have stated the solubility of the molecule.[3]

Chapter 9 review

Multiple choice

1	D	**2**	B	**3**	A	**4**	D	**5**	C
6	C	**7**	C	**8**	C	**9**	C	**10**	D

Short answer

11 a [A protein's secondary structure is determined by hydrogen bonding between the negative C=O and positive N—H of the peptide linkages in different sections of the protein's amino acid sequence.[1]][This results in the formation of either α-helices or β-pleated sheets.[2]][A protein's tertiary structure is determined by the interactions between each amino acid residue's R-group.[3]][These intermolecular forces include hydrogen bonding, ionic interactions, dispersion forces, disulfide bridges and dipole-dipole bonds.[4]]

✓ ✗ I have identified the origin of a protein's secondary structure.[1]

✓ ✗ I have described the structures that result from this hydrogen bonding.[2]

✓ ✗ I have identified the origin of a protein's tertiary structure.[3]

✓ ✗ I have specified the types of intermolecular forces present in a protein's tertiary structure.[4]

b [The addition of a highly acidic solution causes dramatic changes to any ionic interactions between charged amino acid side chains, which permanently alters the bonding patterns in the protein's tertiary structure.[1]][The protein is denatured as a result,[2]][with long protein chains folding over each other forming the 'clumps' in the solution.[3]]

✓ ✗ I have identified the effect of pH on a protein's tertiary structure.[1]

✓ ✗ I have linked this idea to the process of denaturation.[2]

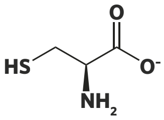
✓ ✗ I have related this theory to the observed outcome in the experiment.[3]

12 a Amide or peptide linkage

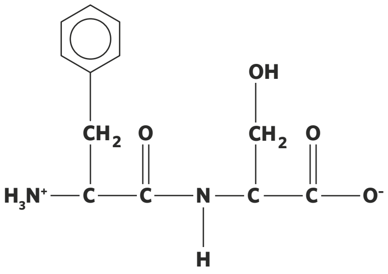
b Condensation polymerisation

c Arginine and Tyrosine

d



13 a



b +1

14 a [Enzymes have active sites that are specific to one particular substrate molecule.[1]][The 24-hydroxylase enzyme will not be able to bind to another optical isomer of vitamin D due to its different orientation in space preventing it from acting as a substrate.[2]]

✓ ✗ I have described the specificity of an enzyme's active site.[1]

✓ ✗ I have linked this specificity to the concept of optical isomerism.[2]

b [An enzyme lowers the activation energy of a reaction by providing an alternate reaction pathway.[1]][This means that a larger proportion of reactant molecules possess sufficient energy to react, [2]][leading to a higher proportion of successful collisions, which increases the overall rate of reaction.[3]]

✓ ✗ I have stated the effect of an enzyme on the activation energy of the reaction.^{1}

✓ ✗ I have explained how this affects the energy threshold of the reactant molecules.^{2}

✓ ✗ I have described how this idea links to the overall change in reaction rate.^{3}

c **i** [The lock and key model suggests that the enzyme has a very specific, rigid active site that binds with the substrate.^{1}][Under this model the substrate (vitamin D) binds to 24-hydroxylase's active site, which does not change shape in response before the reaction occurs.^{2}]

✓ ✗ I have described the key principles of the lock and key model.^{1}

✓ ✗ I have linked these principles to the reaction in the question.^{2}

ii [The induced-fit model suggests that the enzyme has a flexible active site that can alter itself slightly in order to bind with the substrate.^{1}][Under this model, the substrate (vitamin D) enters 24-hydroxylase's active site, which alters its structure to accommodate the substrate before the reaction can occur.^{2}]

✓ ✗ I have described the key principles of the induced-fit model.^{1}

✓ ✗ I have linked these principles to the reaction in the question.^{2}

d [The coenzyme would bind with the enzyme (24-hydroxylase), filling a section of the enzyme's active site.^{1}][When vitamin D binds to the enzyme complex, the coenzyme acts either as an intermediate carrier of electrons or changes the orientation of the atoms in the substrate, allowing the reaction to proceed.^{2}]

✓ ✗ I have described the process of forming the enzyme-coenzyme complex.^{1}

✓ ✗ I have explained how the coenzyme helps to catalyse the reaction in the question.^{2}

Key science skill question

15 **a** [This indicates that all the vitamin C has reacted as the iodine is now in excess, indicated by the purple colour of the starch indicator.^{1}][In order to determine the concentration of Vitamin C, she would need to create a calibration curve of the amount of iodine drops added and the concentration of vitamin C.^{2}][This could be achieved by using a few solutions of a known concentration of vitamin C and then adding the drops of iodine to them in order to see how many drops it takes for iodine to be in excess for each concentration.^{3}]

✓ ✗ I have indicated what the dark purple colour means.^{1}

✓ ✗ I have identified the need for a calibration curve to be constructed.^{2}

✓ ✗ I have suggested a method to construct this calibration curve.^{3}

b Dependent – number of iodine drops required

Independent – concentration of vitamin C present in the orange juice

Controlled – amount of iodine in each drop

10A Structure of carbohydrates

Theory review questions

1 A **2** B **3** D **4** D

Exam-style questions

Within lesson

5 C

6 $4 \times 180 - 4 \times 18 = 648$ g mol^{-1}

7 [The carbohydrate sucrose has many hydroxyl groups that allow it to readily form strong hydrogen bonds with surrounding water molecules leading to a very high solubility in this polar solvent.[1]][Pentane, however, is only capable of forming non-polar bonds through dispersion forces and so will not dissolve readily in such a polar solvent, leading to a low solubility in water.[2]]

✓ ✗ I have identified the intermolecular interactions in sucrose and how they affect its solubility.[1]

✓ ✗ I have identified the intermolecular interactions in pentane and how they affect its solubility.[2]

8 **a** **i** $650\,C_6H_{12}O_{6\,(aq)} \rightarrow C_{3900}H_{6502}O_{3251\,(aq)} + 649\,H_2O_{(l)}$

ii Condensation (polymerisation)

b Glycosidic linkage, ether

c $3900 \times 12 + 6502 \times 1 + 3251 \times 16 = 105318$ g mol^{-1}

Multiple lessons

9 **a** Starch (amylopectin, amylose), sucrose

b [The numerous hydroxyl groups from the carbohydrate contaminant allow it to form strong polar intermolecular bonds with the polar mobile phase of the HPLC column.[1]][As a result, the carbohydrate will desorb into the mobile phase to a greater extent than the carboxylic acids and it will travel most rapidly through the HPLC column.[2]][This will lead to the lowest retention time.[3]][This is given by peak A.[4]]

✓ ✗ I have identified the intermolecular bonding present in carbohydrates.[1]

✓ ✗ I have explained what effects this will have on interaction in the HPLC column with comparison to the carboxylic acids.[2]

✓ ✗ I have explained how this impacts the retention time.[3]

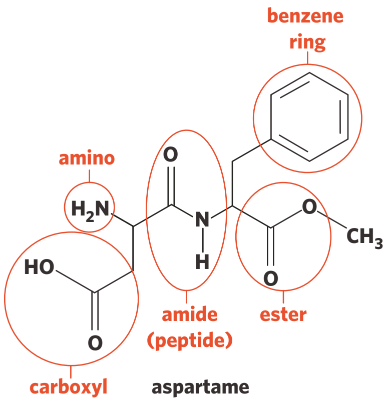
✓ ✗ I have correctly identified peak A as the contaminant peak.[4]

c [The artificial sweetener aspartame is 200 times sweeter than traditional sucrose and yet has a very similar energy content per gram.[1]][This would allow for the honey company to retain the same sweetness as their competitors but have a much more healthy product by not having to use such a high amount of sucrose.[2]]

✓ ✗ I have identified the relationship between the sweetness and energy content of aspartame.[1]

✓ ✗ I have identified the impact of the use of aspartame.[2]

10 **a**



✓ ✗ I have circled all functional groups present in the molecule.

✓ ✗ I have named all functional groups present in the molecule.

b [Although aspartame has a similar energy density to sucrose, it is a lot sweeter than sucrose.[1]][Therefore, less aspartame is required to obtain the same level of sweetness, resulting in a lower amount of kilojoules.[2]][Furthermore, aspartame is not a carbohydrate and therefore is not a sugar,[3]][and as a result products containing aspartame can be advertised as having 'no sugar'.[4]]

✓ ✗ I have identified the relative sweetness of aspartame.[1]

✓ ✗ I have described why the use of aspartame results in a lower energy content.[2]

✓ ✗ I have described why aspartame is not considered as a sugar.[3]

✓ ✗ I have linked my answer to the question.[4]

10B Breakdown and importance of carbohydrates

Theory review questions

1 D **2** A **3** D **4** C

Exam-style questions

Within lesson

5 A **6** B

7 [Although cellulose and amylose have similar structures, each requires a different enzyme to catalyse the hydrolytic reaction.[1]][The human body synthesises amylase that breaks down amylose (starch), however does not produce cellulase so cannot break down cellulose.[2]][Therefore, the body is not able to hydrolyse cellulose but can break down amylose and increase blood glucose levels.[3]]

✓ ✗ I have identified different enzymes are required to break down cellulose and amylose.[1]

✓ ✗ I have identified the inability of humans to produce cellulase.[2]

✓ ✗ I have linked my answer to the question.[3]

8 **a** Wholemeal bread

b [GI does not have a unit ^{1}][as it is a relative scale that compares the time taken to raise blood sugar level to that of pure glucose.^{2}]

✓ ✗ I have correctly identified that GI does not have a unit.^{1}

✓ ✗ I have given a reason why, with reference to the definition of GI.^{2}

c [White bread contains a higher proportion of amylopectin, which has a more branched structure compared to amylose.^{1}][As a result, amylase and water are able to access and break the glycosidic bond much easier, leading to glucose being released into the blood quicker than wholemeal bread, which has a higher proportion of amylose.^{2}] [Therefore, consuming white bread would lead to an increase in blood glucose level at a faster rate than wholemeal bread, resulting in a higher GI.^{3}]

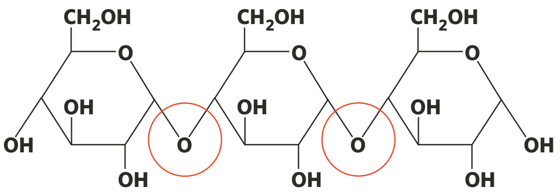
✓ ✗ I have compared the structures of amylose and amylopectin.^{1}

✓ ✗ I have compared the breakdown of the breads based on the structural differences.^{2}

✓ ✗ I have linked my answer to the question.^{3}

9 **a** 2

b

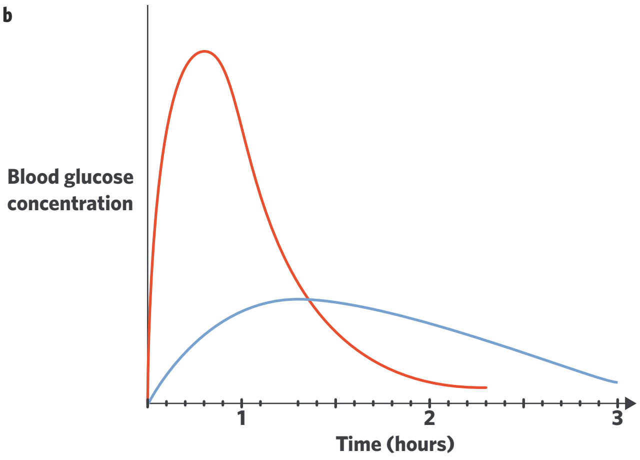


10 **a** [Low GI.^{1}][The graph shows the food increases blood sugar gradually over the course of multiple hours.^{2}]

✓ ✗ I have identified the food as low GI.^{1}

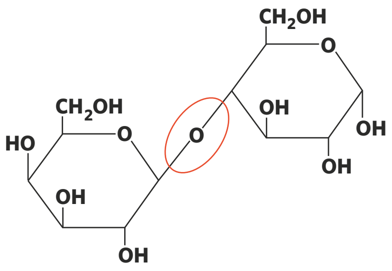
✓ ✗ I have explained how the graph provides evidence for this.^{2}

b



✓ ✗ I have drawn a peak that is more narrow and peaks earlier than the original curve.

11 **a**



α-lactose

b The molar mass of lactose will be:

M(glucose) + M(lactose) – M(water)

= 180 + 180 – 18

= 342 g mol^{-1}

c [Sally's body produces the enzyme required to break down sucrose, but does not synthesise the enzyme to digest lactose.^{1}][So, sucrose can be digested, and lactose cannot, resulting in her digestive discomfort.^{2}]

✓ ✗ I have identified lack of enzymes as the key difference.^{1}

✓ ✗ I have linked the lack of enzymes to an inability to digest.^{2}

Multiple lessons

12 B

13 **a** [Cellular respiration^{1}][converts glucose into a usable form of energy.^{2}]

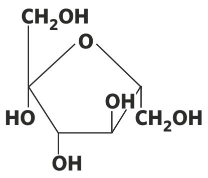
✓ ✗ I have correctly identified the name of the process.^{1}

✓ ✗ I have identified the purpose of the process.^{2}

b exothermic

c i H_2O

ii Compound Y is fructose, a 5-carbon ring, whereas glucose is a 6-carbon ring.



β-fructose

14 **a** [Amylose consists of long chains that coil into tightly packed helices,^{1}][whereas amylopectin has many branches and is therefore much more loosely packed in comparison to amylose.^{2}]

✓ ✗ I have identified the structure of amylose as linear.^{1}

✓ ✗ I have identified the structure of amylopectin as branched.^{2}

b [Due to its linear structure, amylose is able to form a tightly packed helical structure. As a result, the OH groups are less accessible to water and thereby making it not very soluble.^{1}][In contrast, the branching of amylopectin does not allow coiling to occur, exposing OH groups that can form hydrogen bonds with water, making it quite soluble.^{2}][As a result, amylopectin is more soluble than amylose.^{3}]

✓ ✗ I have identified the intermolecular forces or packing of amylose.^{1}

✓ ✗ I have identified the intermolecular forces or packing of amylopectin.^{2}

✓ ✗ I have linked the answer to the question.^{3}

c [Since amylose is tightly packed, amylose and water are not able to access and break necessary bonds.^{1}][As a result, it takes longer to digest amylose, leading to a slower release of glucose into the bloodstream over time.^{2}][Since there is a higher proportion of amylose in the biscuit, there would be a slower change in blood glucose level, leading to a lower GI.^{3}]

✓ ✗ I have described the structure of amylose.^{1}

✓ ✗ I have explained the effect of structure on digestion of amylose.^{2}

✓ ✗ I have linked my answer to the question.^{3}

10C Structure of fats and oils

Theory review questions

1 C **2** B **3** A **4** B

5 The omega carbon is the carbon atom of the methyl group at the end of the carbon chain in a fatty acid. An unsaturated fatty acid is called an omega-3 fatty acid if it has a **carbon-carbon double bond** on the **third** carbon atom counting from the omega carbon. Similarly, if an unsaturated fatty acid has a carbon-carbon double bond on the sixth carbon counting from the omega carbon, it is called an **omega-6 fatty acid**.

6 D

Exam style questions

Within lesson

7 C **8** B

9 [Arachidonic acid is classified as an omega-6 fatty acid^1][because it has a carbon-carbon double bond on the sixth carbon counting from the omega carbon in the structure.^{2}]

✓ ✗ I have determined whether the given fatty acid is an omega-3 fatty acid or an omega-6 fatty acid.^{1}

✓ ✗ I have explained my answer with reference to the position of the carbon-carbon double bond relative to the omega carbon.^{2}

10 **a** [Oleic acid is a monounsaturated fatty acid^1][because it has one carbon-carbon double bond.^{2}]

✓ ✗ I have determined whether the given fatty acid is saturated, monounsaturated or polyunsaturated.^{1}

✓ ✗ I have explained my answer with reference to the number of carbon-carbon double bonds present.^{2}

b [Palmitic acid is a saturated fatty acid^1][because it has only carbon-carbon single bonds.^{2}]

✓ ✗ I have determined whether the given fatty acid is saturated, monounsaturated or polyunsaturated.^{1}

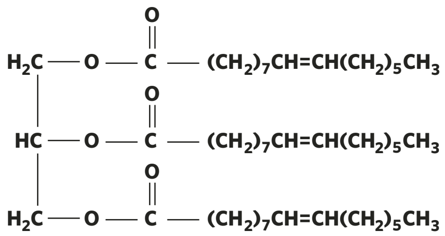
✓ ✗ I have explained my answer with reference to the type of carbon-carbon bonds present.^{2}

c [Linoleic acid is a polyunsaturated fatty acid^1][because it has two carbon-carbon double bonds.^{2}]

✓ ✗ I have determined whether the given fatty acid is saturated, monounsaturated or polyunsaturated.^{1}

✓ ✗ I have explained my answer with reference to the number of carbon-carbon double bonds present.^{2}

11 **a**



b [Palmitoleic is an unsaturated fatty acid^1][because it has one carbon-carbon double bond.^{2}]

✓ ✗ I have determined whether the given fatty acid is saturated or unsaturated.^{1}

✓ ✗ I have explained my answer with reference to the types of carbon-carbon bonds present.^{2}

c The molar mass of glycerol tripalmitate:

M(glycerol tripalmitate) = 12 × 51 + 92 + 16 × 6 = 800 g mol^{-1}

The molar mass of glycerol:

M(glycerol) = 12 × 3 + 8 + 16 × 3 = 92.0 g mol^{-1}

The number of moles of glycerol tripalmitate required:

n(glycerol tripalmitate) = $\frac{30.0}{800}$ = 0.0375 mol

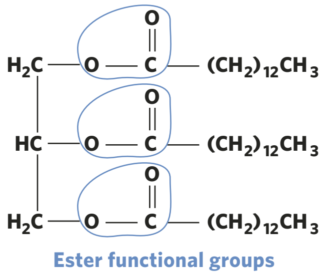
glycerol and glycerol tripalmitate are in a 1:1 ratio. Therefore, the mass of glycerol required to produce 30.0 g of glycerol tripalmitate:

m(glycerol) = 92.0 × 0.0375 = 3.45 g (3 sig figs)

Multiple lessons

12 **a** condensation reaction (or esterification)

b



✓ ✗ I have written the structural formula of the triglyceride correctly.

✓ ✗ I have circled all functional groups present.

✓ ✗ I have named the functional groups correctly.

c Triglycerides (fats or lipids are also accepted)

10D Breakdown of fats and oils

Theory review questions

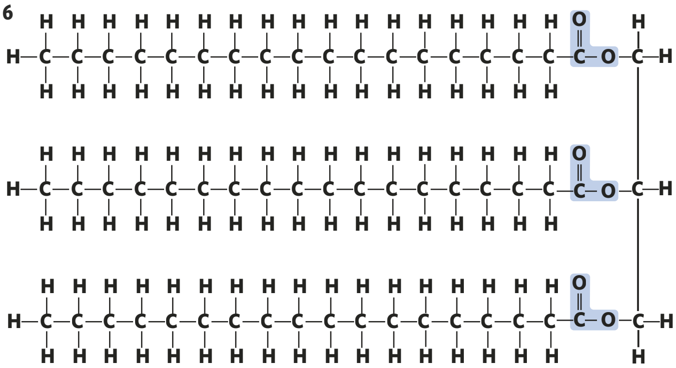
1 D **2** A **3** B **4** A

Exam-style questions

Within lesson

5 Ester

6



7 **a** [As oxidative rancidity occurs when the carbon-carbon double bonds in the fatty acids of triglycerides react with oxygen,[1]][fatty acids with more carbon-carbon double bonds would be subjected to rancidity quicker.[2]][As linolenic acid has the greatest number of C=C double bonds of the 4 fatty acids, it would undergo oxidative rancidity the quickest.[3]]

✓ ✗ I have described how oxidative rancidity occurs.[1]

✓ ✗ I have identified the relationship between bonding and oxidative rancidity.[2]

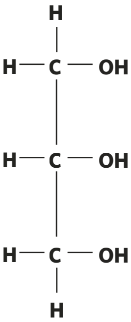
✓ ✗ I have identified the fatty acid that would undergo rancidity the quickest.[3]

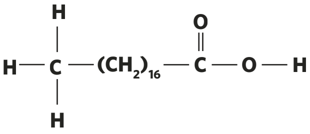
b [Oxidative rancidity is the chemical deterioration of triglycerides involving a free radical chain reaction which produces short-chain aldehydes and ketones.[1]][In hydrolysis however, the triglyceride molecule is broken down into its constituent fatty acids and glycerol molecules.[2]]

✓ ✗ I have explained the process involved in oxidative rancidity.[1]

✓ ✗ I have explained what hydrolysis does to the structure of triglycerides, in comparison to rancidity.[2]

8





$H_3C-(CH_2)_{16}-COOH$

9 **a** [Vitamin C acts as an antioxidant by donating electrons from the OH group to free radicals[1]][which slows down oxidative rancidity.[2]]

✓ ✗ I have explained how Vitamin C functions as an antioxidant.[1]

✓ ✗ I have identified the effect of Vitamin C on oxidative rancidity.[2]

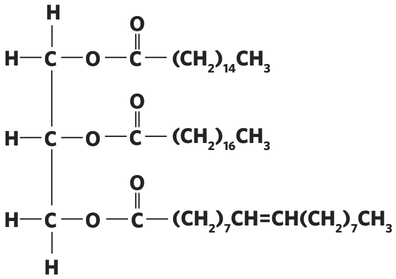
b [Vitamin C is found naturally in fruits and vegetables, so is a natural antioxidant[1]][whereas synthetic antioxidants are made by chemical synthesis to imitate a natural product.[2]]

✓ ✗ I have explained why vitamin C is a natural antioxidant.[1]

✓ ✗ I have explained what a synthetic antioxidant is.[2]

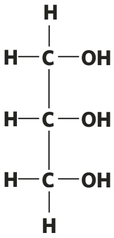
Multiple lessons

10 **a**



b $3H_2O$

c



d [The coenzyme binds to the surface of the inactive enzyme (lipase) and changes the shape of the active site of lipase.[1]][The substrate (in this case, the trigylceride/fat) is now able to attach to the active site of lipase and the reaction can be catalysed.[2]]

✓ ✗ I have identified the function of a coenzyme.[1]

✓ ✗ I have described the function of an enzyme in a chemical reaction.[2]

11 **a** Triglycerides

b [A monounsaturated fatty acid is a fatty acid that has one C=C double bond in the fatty acid chain, with the rest of the carbon-carbon bonds being only single bonds.[1]].

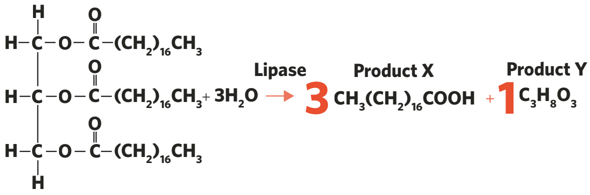
✓ ✗ I have defined monunsaturated fatty acid with reference to its structure.[1]

c $CH_3(CH_2)_7CH{=}CH(CH_2)_{11}\,COOCH_3$

d [A renewable resource can be replenished by natural processes in a relatively short period of time and therefore can be produced as quickly as it is being consumed.[1]]

✓ ✗ I have identified the definition of renewable energy.[1]

12 **a**



b Stearic acid

c $CH_3(CH_2)_{16}COOH + 26O_2 \rightarrow 18CO_2 + 18H_2O$

d [As stearic acid has a long non-polar tail that does not contain any double bonds, the triglyceride would exist in a linear form.[1]][As a result, the triglyceride molecules can stack closely together, forming strong dispersion forces[2]][and therefore result in a relatively high melting point.[3]][Consequently, it is likely that this triglyceride would exist in solid form at room temperature and therefore be considered as a fat.[4]]

✓ ✗ I have identified the structure of stearic acid.[1]

✓ ✗ I have explained how the structure of stearic acid affects the strength of the intermolecular bonds.[2]

✓ ✗ I have identified how the intermolecular bonds affect the chemical properties of the triglyceride.[3]

✓ ✗ I have linked the answer back to the question.[4]

10E Properties of fats and oils

Theory review questions

1 B

2 The strength of intermolecular forces between molecules **increases** as the size of the molecules increases. Therefore, as the number of carbon atoms present in the structure of fatty acids in saturated fats increases, the melting points **increase**.

3 As the number of carbon-carbon double bonds present in the fatty acids increases, the strength of intermolecular forces between unsaturated fats **decreases**. This means we need **less** energy to disturb the intermolecular forces between unsaturated fats. Hence, melting points **decrease** when there are more carbon-carbon double bonds in the fatty acids.

4 Fatty acids tails in saturated fats have only carbon-carbon **single** bonds and therefore they can pack closely together. This means **intermolecular forces** between saturated fat molecules are **strong**. However, in unsaturated fats, the carbon-carbon **double** bonds present in fatty acids tails prevent fat molecules from being packed tightly together due to 'kinks' in their hydrocarbon chains. As a result, the intermolecular forces between unsaturated fats are much **weaker** than between saturated fats. Therefore, it requires **more** energy to disturb the intermolecular forces between saturated fats, giving them much higher melting points than unsaturated fats.

Exam style questions

Within lesson

5 C **6** D

7 **a** [Arachidic acid and myristic acid are saturated, while linoleic acid and arachidonic acid are unsaturated.[1]][Arachidic acid and myristic acid contain only carbon-carbon single bonds, and therefore, have stronger intermolecular dispersion forces, as compared to linoleic acid and arachidonic acid. Therefore, arachidic acid and myristic acid have higher melting points than linoleic acid and arachidonic acid.[2]][Arachidic acid has 20 carbon atoms while myristic acid has 14 carbon atoms.[3]][Since intermolecular dispersion forces strengthen as molecular size increases, arachidic acid has a higher melting point than myristic acid.[4]][Linoleic acid has 2 carbon-carbon double bonds, while arachidonic acid has 4 carbon-carbon double bonds.[5]][As the number of carbon-carbon double bonds increases, the strength of the intermolecular forces decreases, meaning arachidonic acid has a lower melting point than linoleic acid.[6]] [Hence, arachidonic acid < linoleic acid < myristic acid < arachidic acid in terms of melting points.[7]]

✓ ✗ I have categorised each fatty acid as saturated or unsaturated.[1]

✓ ✗ I have used the structure and intermolecular bonding of saturated fatty acids and unsaturated fatty acids to compare their relative melting points.[2]

✓ ✗ I have compared the number of carbon atoms present in the saturated fatty acids.[3]

✓ ✗ I have used the structure and intermolecular bonding of the saturated fatty acids to compare their relative melting points.[4]

✓ ✗ I have compared the number of carbon-carbon double bonds present in the unsaturated fatty acids.[5]

✓ ✗ I have used the structure and intermolecular bonding of unsaturated fatty acids to compare their relative melting points.[6]

✓ ✗ I have put the given fatty acids in order of increasing melting point.[7]

b

Meal	Fatty acid
A	arachidic
B	linoleic
C	arachidonic
D	myristic

8 **a** [Lauric acid is a saturated fatty acid with only carbon-carbon single bonds while oleic acid is an unsaturated fatty acid with one carbon-carbon double bond.[1]][The double bond in oleic acid prevents molecules from being packed closely together. Therefore, the intermolecular forces are weaker in oleic acid and we need less energy to disturb the intermolecular forces between oleic acid molecules.[2]] [Hence, oleic acid has a lower melting point than lauric acid.[3]]

✓ ✗ I have categorised each fatty acid as saturated or unsaturated.[1]

✓ ✗ I have used the difference in structure and intermolecular forces to compare the relative energy required to disturb the intermolecular forces between the molecules of each fatty acid.[2]

✓ ✗ I have concluded that oleic acid has a lower melting point than lauric acid.[3]

b [Lauric acid and stearic acid are both saturated fatty acids.[1]] [However, stearic acid has 18 carbon atoms while lauric only has 12 carbon atoms.[2]] [As the strength of intermolecular forces increase when molecular size increases, stearic acid has greater intermolecular forces than lauric acid.[3]] [Therefore, stearic acid has a higher melting point than lauric acid.[4]]

✓ ✗ I have categorised each fatty acid as saturated or unsaturated.[1]

✓ ✗ I have compared the number of carbon atoms in each fatty acid.[2]

✓ ✗ I have compared the strength of the intermolecular forces of the fatty acids.[3]

✓ ✗ I have concluded that stearic acid has a higher melting point than lauric acid.[4]

c [Arachidonic acid and palmitoleic acid are both unsaturated fatty acids.[1]] [However, arachidonic has 4 carbon-carbon double bonds while palmitoleic has 1 carbon-carbon double bond.[2]] [As intermolecular dispersion forces weaken as the number of carbon-carbon double bonds increases, arachidonic acid has weaker intermolecular forces than palmitoleic acid.[3]] [Therefore, arachidonic acid has a lower melting point than palmitoleic acid.[4]]

✓ ✗ I have categorised each fatty acid as saturated or unsaturated.[1]

✓ ✗ I compared the number of carbon-carbon double bonds in the fatty acids.[2]

✓ ✗ I have compared the strength of the intermolecular forces of the fatty acids.[3]

✓ ✗ I have concluded that arachidonic has a lower melting point than palmitoleic.[4]

Multiple lessons

9 **a** [Triglyceride A has 2 saturated fatty acid tails and 1 unsaturated fatty acid tail, while triglyceride B has 1 saturated fatty acid tail and 2 unsaturated fatty acids tails.[1]] [The carbon-carbon double bonds in fatty acids prevent triglyceride molecules from being packed tightly together. Therefore, the more carbon-carbon double bonds present, the weaker the intermolecular dispersion forces between molecules.[2]] [We need less energy to disturb the intermolecular forces between triglyceride B, as compared to triglyceride A.[3]] [Hence, triglyceride B has a lower melting point.[4]]

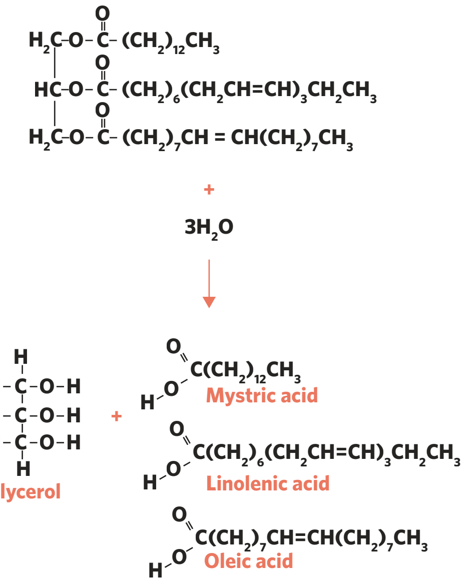
✓ ✗ I have determined the number of saturated and unsaturated fatty acid tails in each triglyceride.[1]

✓ ✗ I have explained the relationship between the number of carbon-carbon double bonds and the strength of the intermolecular dispersion forces.[2]

✓ ✗ I have compared the energy required to disturb the intermolecular forces in triglycerides A and B.[3]

✓ ✗ I have concluded that triglyceride B has a lower melting point.[4]

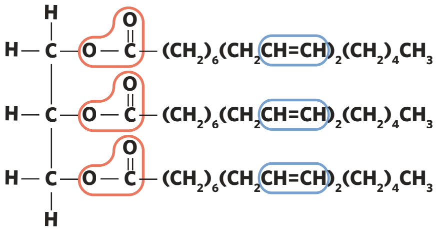
b



✓ ✗ I have written the hydrolysis reaction of triglyceride B.[1]

✓ ✗ I have included correct names for all products including glycerol and 3 fatty acids.[2]

10 **a**



[The biomolecule is a triglyceride.[1]]

✓ ✗ I have circled the COO groups and carbon-carbon double bonds present in the biomolecule.

✓ ✗ I have stated that the biomolecule is a triglyceride.[1]

b [Linoleic acid is a polyunsaturated fatty acid[1]] [because it has two carbon-carbon double bonds.[2]]

✓ ✗ I have determined whether the fatty acid is saturated, monounsaturated or polyunsaturated.[1]

✓ ✗ I have explained my answer with reference to the structure of the fatty acid.[2]

c [Linoleic is an omega-6 fatty acid[1]] [because it has a carbon-carbon double bond on the sixth carbon from the omega carbon.[2]]

✓ ✗ I have determined whether the fatty acid is omega-3 or omega-6.[1]

✓ ✗ I have explained my answer with reference to the position of the carbon-carbon double bonds relative to the omega carbon.[2]

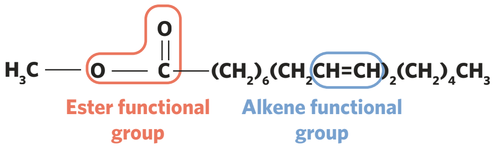
d [Linoleic acid is unsaturated while lauric acid is saturated.[1]] [If we replace three linoleic tails with three lauric tails, the melting point of the biomolecule will increase.[2]] [Lauric acid has only carbon-carbon single bonds allowing the triglyceride molecules to be packed more closely together. Intermolecular forces between molecules become stronger, therefore, it requires more energy to break down the biomolecule.[3]]

✓ ✗ I have identified the type of fatty acid to which each fatty acid belongs.[1]

✓ ✗ I have concluded that the melting point of the biomolecule will increase.[2]

✓ ✗ I have explained my conclusion with reference to structure, intermolecular forces and energy required to disturb the intermolecular forces in the biomolecule.[3]

e



$H_3C-O-\overset{\overset{\displaystyle O}{||}}{C}-(CH_2)_6(CH_2CH{=}CH)_2(CH_2)_4CH_3$

✓ ✗ I have written the semi-structural formula of the biodiesel molecule correctly.

✓ ✗ I have circled the COO group and the carbon-carbon double bond.

✓ ✗ I have named the functional groups present.

10F Calorimetry

Theory review questions

1 A **2** D **3** C

Exam-style questions

Within lesson

4 $q = mC\Delta T = 7.00 \times 0.900 \times 17.0 = 107$ J

5 $n = \frac{m}{M} = \frac{3.4}{298} = 0.0114$ mol

$E = \text{CF} \times \Delta T = 4.42 \times 2.17 = 9.59$ kJ

Energy released per mole

$= \frac{E}{n} = \frac{9.59}{0.0114} = 841 \text{ kJ mol}^{-1} = 8.4 \times 10^2 \text{ kJ mol}^{-1}$

$\Delta H_c = -8.4 \times 10^2 \text{ kJ mol}^{-1}$

6 **a** $n(C_{14}H_{28}O_2) = \frac{1.72}{228.0} = 7.54 \times 10^{-3}$ mol

Energy released $= 4.85 \times 13.2 = 64.02$ kJ

$\Delta H_C = \frac{-64.02}{(7.54 \times 10^{-3})} = -8.49 \times 10^3 \text{ kJ mol}^{-1}$

b $C_{14}H_{28}O_{2(l)} + 20O_{2(g)} \rightarrow 14CO_{2(g)} + 14H_2O_{(g)}$

$\Delta H = -8.5 \times 10^3 \text{ kJ mol}^{-1}$

7 **a** $E = VIt = 5.5 \times 1.5 \times (2.5 \times 60) = 1237.5 = 1.24 \times 10^3$ J

$\text{CF} = \frac{E}{\Delta T}$

$= \frac{1.24 \times 10^3}{1.7}$

$= 7.3 \times 10^2 \text{ J °C}^{-1}$

$= 0.73 \text{ kJ °C}^{-1}$

b Energy released by ethanol

$= \text{CF} \times \Delta T = 0.73 \times 10 = 7.3$ kJ

$n(C_2H_5OH) = \frac{m}{M} = \frac{1.5}{46.0} = 0.033$ mol

Energy from 1 mole of ethanol $= \frac{7.3}{0.033}$

$= 2.2 \times 10^2 \text{ kJ mol}^{-1}$

$\Delta H = -2.2 \times 10^2 \text{ kJ mol}^{-1}$

c The calculated energy released in combustion is lower due to loss of heat to the surrounding environment during combustion.

Multiple lessons

8 **a** Energy in serving size of 56 g $= ((9.3 \times 37) + (1.7 \times 17) + (12 \times 16))$

$= 565$ kJ

Energy in 5.6 g $= \frac{565}{10}$

$= 57$ kJ

b $\text{CF} = \frac{E}{\Delta T} = \frac{56.5}{18} = 3.1 \text{ kJ °C}^{-1}$

9 **a** $n(C_{10}H_8) = \frac{0.212}{128.0} = 0.00166$ mol

$E = 0.00166 \times 5133 = 8.52$ kJ

$\text{CF} = \frac{E}{\Delta T} = \frac{8.52}{4.0}$ (from graph) $= 2.1 \text{ kJ °C}^{-1}$

b [Only one set of values was used.[1]][Therefore, it was not a reliable experiment.[2]]

✓ ✗ I have commented on the data collection.[1]

✓ ✗ I have stated whether this means the data is reliable or not.[2]

10 **a** $E = 2.3 \times 22.7$ (value from data book) $= 52.21$ kJ

$q = mC\Delta T$

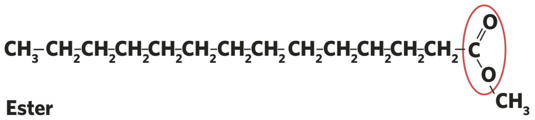
$52210 = 200 \times 4.18 \times \Delta T$

$\Delta T = 62$°C

Final temperature = 16°C + 62°C = 78°C

b Put a lid on the container holding the water.

c **i**



✓ ✗ I have drawn the semi-structural formula of the molecule.[1]

✓ ✗ I have circled the functional group.[2]

✓ ✗ I have named the functional group.[3]

ii [Canola oil is a mixture, and therefore does not have a specific formula,[1]][so the number of moles cannot be determined.[2]]

✓ ✗ I stated that canola oil is a mixture.[1]

✓ ✗ I have explained why this means the number of moles cannot be determined.[2]

11 **a** $q = mC\Delta T = 100 \times 0.997 \times (54 - 27) \times 4.18 = 11252$ J

$n(CaCl_2) = \frac{m}{M} = \frac{25}{111.1} = 0.2250$ mol

$\Delta H = \frac{-q}{n} = \frac{-11.25 \text{ kJ}}{0.225 \text{ mol}} = -50 \text{ kJ mol}^{-1}$

This reaction is exothermic.

b [The experimental value is less than the literature value.[1]]
[One reason could be heat loss to the surrounding environment.[2]]

✓ ✗ I have compared the experimental value and the literature value.[1]

✓ ✗ I have explained why the values are different.[2]

c $E = \Delta H \times n = 83 \times 0.225 = 18.7$ kJ

$$\% \text{ heat loss} = \frac{(\text{theoretical energy released} - \text{actual energy released})}{\text{theoretical energy released}} \times 100$$

$$= \frac{(18.7 - 11.25) \times 100}{18.7}$$

$$= 40\%$$

d [Chris could add a lid to the polystyrene cup to minimise heat loss.[1]] [He could also add a stirrer so that he ensures all $CaCl_{2(s)}$ is dissolved.[2]]

✓ ✗ I have suggested one improvement.[1]

✓ ✗ I have suggested another improvement.[2]

10G Energy in food

Theory review questions

1 C **2** D

Exam-style questions

Within lesson

3 C

4 **a** (21.3 × 16) + (16.5 × 37) = 951 kJ

Energy supplied by protein = 1022.7− 951.3 = 71.4 kJ

Mass of protein = $\frac{71.4}{17}$ = 4.2 g

[Based on the calculations, there is only 4.2 g of protein in the bar.[1]] [Therefore, the company's statement is inaccurate.[2]]

✓ ✗ I have used data to support my answer.[1]

✓ ✗ I have identified the accuracy of the company's statement.[2]

✓ ✗ I have included working out.

b kJ / g

5 **a** **i** Energy in the bar = (9.8 × 17) +(20.0 × 16) + (7.0 × 37) = 745.6 kJ

[Based on the calculations, there would be 745.6 kJ of energy produced using this recipe.[1]] [As this is under 800 kJ, this would meet her energy requirements.[2]]

✓ ✗ I have used data to support my answer.[1]

✓ ✗ I have identified the appropriateness of the bar with respect to energy content.[2]

✓ ✗ I have included working out.

ii Energy content in 100 g = 745.6 × $\frac{100}{40}$ = 1864 kJ per 100 g

b $\frac{7.0 \times 37}{745.6} \times 100 = 35\%$

Multiple lessons

6 **a** Glycosidic bond

b Glucose

c 45 × 16 = 720 kJ

7 **a** $C_6H_{12}O_{6(aq)} + 6O_{2(g)} \rightarrow 6CO_{2(g)} + 6H_2O_{(l)}$

b Glycogen

c 4.3 × 16 = 68.8 kJ

8 **a** Energy in biscuit 1 = (22 × 16) + (6.8 × 17) + (18.7 × 37) = 1159.5 kJ

Energy in biscuit 2 = (22 × 16) + (7.3 × 17) + (19.1 × 37) = 1182.2 kJ

Biscuit 2 has more energy per serving.

b [Due to the branching of amylopectin compared to amylose, substances containing a higher percentage of amylopectin would result in a higher GI level.[1]] [This is because amylopectin is more readily digested compared to amylose, leading to a faster increase in blood glucose levels.[2]] [As a result, biscuit 2 would be considered lower GI compared to biscuit 1 as it has a lower percentage of amylopectin.[3]]

✓ ✗ I have described the relationship between structure and GI.[1]

✓ ✗ I have explained how the different structures affect blood glucose levels.[2]

✓ ✗ I have identified the biscuit with the lower GI value.[3]

9 **a** [Fats are able to supply more energy per gram than protein.[1]] [As a result, a high-fat meal would provide the athlete with more energy compared to a high protein meal.[2]] [As a result, it would be best for the athlete to consume a high-fat meal.[3]]

✓ ✗ I have compared the energy content of fats and proteins .[1]

✓ ✗ I have compared the meal options.[2]

✓ ✗ I have related the answer to the question.[3]

b Hydrolysis

c 1 glycerol and 3 fatty acids

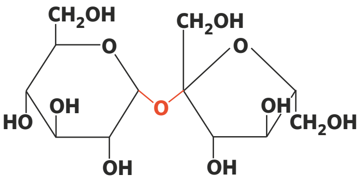
Chapter 10 review

Multiple choice

1	C	**2**	B	**3**	B	**4**	D	**5**	A
6	D	**7**	D	**8**	A	**9**	B	**10**	B

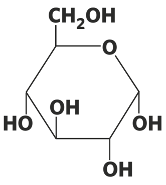
Short answer

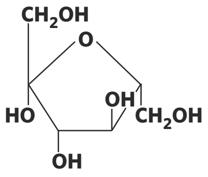
11 **a**



b Hydrolysis reaction

c





d [Alpha glucose has the hydroxyl (OH) group on the first carbon oriented downwards while beta glucose has the hydroxyl (OH) group pointing upwards.[1]]

✓ ✗ I have identified the key difference between the structure of alpha and beta glucose.^{1}

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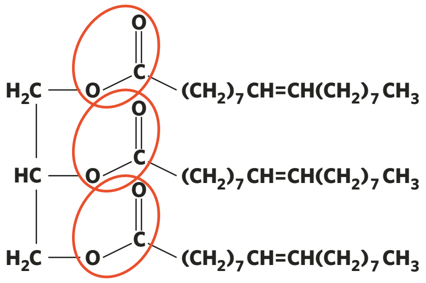
12 **a**



b Hydrolysis will produce one glycerol and three fatty acids.

$n(\text{glycerol}) = n(\text{triglyceride})$

$= \frac{m(\text{triglyceride})}{M(\text{triglyceride})}$

$= \frac{15.0 \text{ g}}{884 \text{ g mol}^{-1}} = 0.0170 \text{ mol}$

The mass of glycerol produced:

$m(\text{glycerol}) = 0.0170 \times 92.0 = 1.56 \text{ g}$

The number of moles of oleic acid produced:

$n(\text{oleic acid}) = 0.0170 \text{ x } 3 = 0.0510 \text{ mol}$

The mass of oleic acid produced:

$m(\text{oleic acid}) = M(\text{oleic acid}) \text{ x } n(\text{oleic acid}) = 282 \text{ x } 0.0510 = 14.4 \text{ g}$

13 **a** Triglyceride or lipid

b Lipase, a hydrolytic reaction

c [The general formula for a saturated fatty acid tail is $-C_nH_{2n+1.}$ For every double carbon-carbon bond the fatty acid gains, the molecule loses two hydrogens from the above ratio and gains two bromine. The first tail is $C_{17}H_{29}$, which has lost 6 hydrogens from the saturated ratio, and gained six bromine, the second tail is $C_{17}H_{33}$ so has one double bond and has gained two bromine, and the third tail is $C_{17}H_{31}$ and so has two double bonds and gained four bromine.^{1}] [Since bromine gas exists as Br_2, a total of 6 bromine molecules have reacted with a single triglyceride molecule.^{2}]

✓ ✗ I have calculated the number of double bonds in each fatty acid tail.^{1}

✓ ✗ I have determined the number of bromine molecules that reacted with the overall molecule.^{2}

d [The molecules formed are linoleic acid, oleic acid and linolenic acid.^{1}][Of the three fatty acids, oleic acid has the fewest double bonds. As a result, oleic acid molecules will be able to pack more tightly than the other two fatty acids without 'kinks' in the hydrocarbon chain and therefore have the strongest intermolecular dispersion forces.^{2}][Consequently, oleic acid would have the highest boiling point.^{3}]

✓ ✗ I have identified the three molecules formed.^{1}

✓ ✗ I have described the effect of double bonds on the strength of intermolecular forces.^{2}

✓ ✗ I have linked information from part b to the boiling point.^{3}

e [$n(\text{triglyceride}) = \frac{m(\text{triglyceride})}{M(\text{triglyceride})}$

$n = \frac{1756 \text{ g}}{878 \text{ g mol}^{-1}} = 2$ mol of triglyceride reacted.^{1}]

[For each triglyceride molecule hydrolysed, three water molecules are required, so for two mol of the triglyceride, 6 mol of water is required.^{2}][As a result, 108 grams of water is required.^{3}]

✓ ✗ I have calculated the number of moles of the triglyceride reacted.^{1}

✓ ✗ I have determined the number of water molecules required.^{2}

✓ ✗ I have converted the number of moles of water to mass.^{3}

14 **a** [Calibration factor = energy released by combustion / change in temperature

Using the data book, we know the heat of combustion of methanol is 22.7 kJ/g.^{1}]

[Calibration factor = $\frac{50.6 \times 22.7}{(25.7 - 22.3)}$

$= 338 \text{ kJ °C}^{-1}$.^{2}]

✓ ✗ I have identified the formula for calibration factor and substituted the correct values.^{1}

✓ ✗ I have calculated the calibration factor.^{2}

b Energy = CF x ΔT so energy = 337.8 × (28.9 – 24.8) = 1385 kJ.

If 47.7 g released 1385 kJ of energy, then the energy content is:

$= \frac{1385}{47.7} = 29.0 \text{ kJ g}^{-1}$.

c [A calibration factor reduces error in calculating the energy content.^{1}][because it takes into account the energy lost to the surroundings by the combustion reaction.^{2}]

✓ ✗ I have identified the function of the calibration factor.^{1}

✓ ✗ I have identified how the calibration factor reduces error.^{2}

15 **a** [Amylose packs more tightly than amylopectin because of its linear structure and so has stronger intermolecular forces.^{1}][Therefore with a lower GI, it is expected that there would be a higher proportion of amylose in the structure.^{2}]

✓ ✗ I have compared the structure and intermolecular bonding of amylose and amylopectin.^{1}

✓ ✗ I have linked my answer to the question.^{2}

b [Lucy does not have lactase in her digestive system, the enzyme that hydrolyses lactose, whereas Jessie does.^{1}]

✓ ✗ I have identified the lack of the specific enzyme required for digestion of lactose.^{1}

c [Unsaturated triglycerides have weaker intermolecular bonding than saturated triglycerides because of the kinks caused by double bonds in their structure.^{1}][Olive oil has a greater proportion of unsaturated fats and so has weaker intermolecular bonds between its molecules compared to sunflower oil.^{2}][So, sunflower oil will be more viscous at room temperature and therefore be the preferred substance.^{3}]

✓ ✗ I have identified the difference in intermolecular bonding between saturated and unsaturated triglycerides.[1]

✓ ✗ I have related the proportion of saturated and unsaturated triglycerides in each of the oils to the relative intermolecular bonding strengths.[2]

✓ ✗ I have linked the intermolecular bonding to the viscosity.[3]

Key science skill question

16 **a** **i** Extrapolation of the calibration curve shows that the

$\Delta T = (70 - 23) = 47$

$E = 2.00 \times 1.50 \times 100$

$= 300\text{ J}$

$CF = \frac{300}{47}$

$= 6.38\text{ J °C}^{-1}$

ii [A well insulated calorimeter is able to maintain a constant temperature after the energy source is turned off.[1]][However, as shown by the calibration graph, the temperature began to decrease immediately after the energy source was turned off, [2]] [which suggests that the bomb calorimeter used was not well insulated.[3]][As a result, Kael's statement is inaccurate.[4]]

✓ ✗ I have described the characteristics of a well insulated calorimeter.[1]

✓ ✗ I have referred to the graph to support my answer.[2]

✓ ✗ I have identified how well insulated the calorimeter is.[3]

✓ ✗ I have linked my answer to the question.[4]

b [In this experiment, the heat capacity of water is used to calculate the calibration factor for the calorimeter, which is then used to determine the energy change as a result of the reaction involving glucose.[1]][Given that the specific heat capacity of the liquid used is smaller than that of water, there is less energy required to raise the temperature of the liquid and therefore for the given amount of energy released in 1.50 g of glucose, there would be a greater temperature change.[2]][Based on these values, the energy change as a result of the combustion of 1.50 g of glucose would be calculated to be higher than the true value.[3]]

✓ ✗ I have identified the relationship between heat capacity and overall energy change.[1]

✓ ✗ I have explained how using a liquid with a lower heat capacity would affect the overall reaction.[2]

✓ ✗ I have identified the effect of the use of a different liquid on the calculations and on the overall energy change of the reaction.[3]

GLOSSARY

A

2-amino acid (α-amino acid) amino acid whose carboxyl and amino group are bonded to the same central carbon atom p. 346

Accuracy how close measured values are to their true value p. 18

Achiral compounds compounds that can be superimposed onto their mirror image p. 257

Acidic amino acid amino acid with a carboxyl group in its side chain p. 361

Activation energy minimum amount of energy required for a reaction to proceed p. 68, 151

Active site region of an enzyme where the substrate molecule binds to the enzyme and undergoes a chemical reaction p. 359

Actual yield amount of product that is actually produced as a result of a chemical reaction p. 277

Addition reaction reaction where one molecule combines with another to form a larger molecule with no other products p. 270

Adsorption component adheres to the stationary phase (in the context of chromatography) p. 323

Aim purpose/objective of an experiment p. 3

Alcohols compounds that contain a hydroxyl functional group (OH) bonded to a carbon atom in the carbon chain p. 238

Aldehydes compounds that contain an aldehyde functional group (CHO). p. 239

Aliquot portion of sample solution that is to be analysed during titration p. 329

Alkyl groups groups formed by removing one hydrogen atom from the equivalent alkane chain p. 237

Amide compound that has the amide functional group (CON) p. 238

Amperes (A) unit used to measure the amount of current p. 209

Amylase enzyme that catalyses the hydrolysis of starch p. 383

Amylopectin highly branched form of starch p. 379

Amylose tightly coiled, unbranched form of starch p. 379

Analyte substance being analysed in a titration reaction p. 329

Anode negatively charged electrode in a galvanic cell where oxidation occurs p. 110

Anode positively charged electrode in an electrolytic cell where oxidation occurs p. 200

Antioxidant compound that prevents oxidative rancidity of fats and oils p. 400

Aqueous electrolyte dissolved ionic compound with ions that are free to move and in the aqueous state p. 195

Aspartame powerful artificial sweetener used instead of sucrose p. 378

Atom economy extent to which the reactants are used to make the desired product(s) p. 276

Autoxidation spontaneous oxidation of a compound in the presence of oxygen p. 400

B

Base peak peak formed from ion fragment with the greatest relative intensity p. 293

Basic amino acid amino acid with an amino group in its side chain p. 361

Batteries devices consisting of cells that convert chemical energy to electrical energy p. 216

Bias difference between the average of a large set of measurements and the true value p. 19

Bile fluid secreted by the liver that aids digestion p. 398

Biodiesel fuel produced by the esterification of fats and oils in organic matter p. 46

Bioethanol fuel produced by the fermentation of glucose in organic matter p. 46

Biofuel fuel sourced from organic matter p. 46

Biogas gaseous fuel produced by the anaerobic breakdown of organic matter p. 46

Boiling point temperature required to turn a substance from a liquid to its gaseous state p. 262

Bond energy measurement used to indicate the amount of energy needed to break bonds, measured in kJ/mol p. 235

Bond length length of a bond p. 235

Bond strength how strongly bonds hold atoms together p. 235

Bond vibration bond movement including stretching and bending p. 300

C

C environment atoms and bonds surrounding a particular C atom p. 307

Calibration curve curve that is developed from a set of known standards and is used to identify the concentration of a sample p. 324

Calibration factor joules of energy required to raise the temperature of the calorimeter by one degree celsius p. 410

Calibration graph plot of temperature as a function of time p. 411

Calorimetry method used to determine the amount of heat energy transferred in a system p. 409

Carbohydrate molecule made up of carbon, hydrogen and oxygen with the general formula of $C_a(H_2O)_b$ p. 376

Carbon neutral fuel which does not result in a net production of carbon dioxide from sourcing or consumption p. 47

Carboxylic acids compounds that contain a carboxyl functional group (COOH) p. 239

Catalyst substance that increases the reaction rate without itself being consumed or permanently changed p. 151

Cathode negatively charged electrode in an electrolytic cell where reduction occurs p. 200

Cathode positively charged electrode in a galvanic cell where reduction occurs p. 110

Cellular respiration metabolic process by which glucose is converted into energy for cells p. 387

Cellulase enzyme that catalyses the hydrolysis of cellulose p. 385

Cellulose polysaccharide composed of β-glucose that is indigestible to humans and found in the cell walls of plants p. 379

Chemical energy energy stored in the bonds of chemical compounds p. 64

Chemical shift energy frequency required for the spin flip of a nucleus in comparison to the reference compound TMS (tetramethylsilane) p. 307

Chiral centre an atom that has four different groups bonded to it p. 259

Chiral compounds compounds that cannot be superimposed onto their mirror image p. 257

Chromatogram visual output of chromatography which can be analysed p. 324

Chromatography analytical technique used to determine the identity of components in a mixture as well as their concentration p. 322

Coal seam gas natural gas sourced from coal deposits p. 40

Coal combustible fossil fuel formed by the partial decay of plant matter p. 40

Coenzyme organic molecule that attaches to the active site of an enzyme and changes the surface shape to enable the substrate to bind p. 362

Collision theory theory which states that for a chemical reaction to occur, the reactant particles have to collide with sufficient energy and with the correct orientation p. 140

Competing equilibria multiple equilibrium reactions competing with one another because they involve either the same reactants or products p. 180

Complete combustion reaction of a substance with oxygen to produce carbon dioxide and water p. 62

Concentration-time graph representation of the concentration of reactants and products over time p. 159

Concordant titres volume of three or more titres that fall within approximately 0.1 mL of each other p. 330

Condensation reaction chemical reaction where two molecules combine with the release of a water molecule p. 272

Conjugate redox pair electron donor (reducing agent) and its corresponding electron acceptor (oxidising agent) p. 99

Controlled variable(s) variable(s) held constant throughout the experiment p. 4

Coulomb (C) unit used to measure the amount of electrical charge p. 209

Current (I) rate of flow of electric charge p. 208

D

Denaturation process where proteins lose their quarternary, tertiary and/or secondary structure due to factors such as pH and temperature change p. 355

Dependent variable variable that is measured by the experimenter p. 3

Deprotonation loss of a proton p. 361

Desorption a component is released from the stationary phase and dissolves into the mobile phase (in the context of chromatography) p. 323

Dipeptide product of a condensation reaction between two 2-amino acids p. 348

Direct redox reaction reactions where chemical species react in the same vessel p. 122

Disaccharide carbohydrate formed from a condensation reaction between two monosaccharides and joined by a glycosidic linkage p. 377

Discharge conversion of chemical energy to electrical energy as a result of spontaneous redox reactions p. 217

Dynamic equilibrium system in which the forwards and backwards reaction are occurring at the same rate with reactants and products continuously being formed and used up p. 158

E

Electric charge (Q) amount of charge (usually measured in coulombs) p. 208

Electrochemical series arrangement of chemical species in order of their reducing and oxidising strength p. 106

Electrode electrical conductor that is either unreactive or involved in a reaction p. 110

Electrolyte chemical compound that allows the flow of electric charge within a cell p. 200

Electrolytic half-equation one of two equations (oxidation or reduction) which describes one half of an electrolytic reaction p. 192

Electrolytic reaction non-spontaneous redox reaction that requires electricity for it to occur p. 192

Electronegativity tendency of an atom to attract a pair of bonding electrons p. 235

Electroplating application of electrolysis used to coat a substance with a metallic layer p. 210

Eluent combination of the mobile phase and sample that moves through the HPLC column p. 323

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Fatty acid carboxylic acid with a long hydrocarbon chain p. 392

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G

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Heterogeneous catalyst catalyst whose physical state differs from the phase of the reactants p. 152

Homogeneous catalyst catalyst whose physical state is the same as the phase of p. 152

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HPLC (High performance liquid chromatography) type of chromatography technique which pumps the mobile phase through a very tightly packed stationary phase under high pressure p. 323

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L

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Lipid biomolecule commonly found in food which has two main types, fats and oils p. 391

Lock and key model theory of enzyme activity where the substrate perfectly fits the active site of the enzyme p. 359

M

Mass spectrometer an instrument used to measure the mass-to-charge ratio of ions p. 292

Mass spectrometry an analytical technique used to measure the mass-to-charge ratio of ions p. 292

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Mass-to-charge ratio equal to the mass of a cation divided by its charge p. 292

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Monounsaturated fatty acid fatty acid which contains only one carbon-carbon double bond p. 393

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Non-essential fatty acid fatty acid that can be produced by the human body p. 394

Non-essential vitamin vitamin that can be manufactured by the human body p. 365

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O

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Oxidation number number assigned to an element, representing the number of electrons lost or gained by an atom of that element to form a chemical bond with another species p. 97

Oxidation chemical reaction where a species increases its oxidation number by losing electrons p. 96

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P

Parent carbon chain longest continuous chain of carbon-carbon bonds. This needs to include any carbon double/triple bonds if present. p. 247

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Personal error result of mistakes or misinterpretations of methods and/or readings by the experimenter p. 19

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Qualitative data non-numerical (descriptive) data collected based on observations taken during the experiment p. 9

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Random error error in measurement that differs in amount / proportion each time experiment is conducted and is usually a 'one-off' error p. 19

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T

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VICTORIAN CURRICULUM
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2021

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Written examination

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Instructions

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A question and answer book is provided with this data book.

Students are NOT permitted to bring mobile phones and/or any other unauthorised electronic devices into the examination room.

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1. Periodic table of the elements

atomic number — **79**
relative atomic mass — 197 0
symbol of element — **Au**
name of element — gold

1 **H** 1 0 hydrogen																	**2** **He** 4 0 helium
3 **Li** 6 9 lithium	**4** **Be** 9 0 beryllium											**5** **B** 10 8 boron	**6** **C** 12 0 carbon	**7** **N** 14 0 nitrogen	**8** **O** 16 0 oxygen	**9** **F** 19 0 fluorine	**10** **Ne** 20 2 neon
11 **Na** 23 0 sodium	**12** **Mg** 24 3 magnesium											**13** **Al** 27 0 aluminium	**14** **Si** 28 1 silicon	**15** **P** 31 0 phosphorus	**16** **S** 32 1 sulfur	**17** **Cl** 35 5 chlorine	**18** **Ar** 39 9 argon
19 **K** 39 1 potassium	**20** **Ca** 40 1 calcium	**21** **Sc** 45 0 scandium	**22** **Ti** 47 9 titanium	**23** **V** 50 9 vanadium	**24** **Cr** 52 0 chromium	**25** **Mn** 54 9 manganese	**26** **Fe** 55 8 iron	**27** **Co** 58 9 cobalt	**28** **Ni** 58 7 nickel	**29** **Cu** 63 5 copper	**30** **Zn** 65 4 zinc	**31** **Ga** 69 7 gallium	**32** **Ge** 72 6 germanium	**33** **As** 74 9 arsenic	**34** **Se** 79 0 selenium	**35** **Br** 79 9 bromine	**36** **Kr** 83 8 krypton
37 **Rb** 85 5 rubidium	**38** **Sr** 87 6 strontium	**39** **Y** 88 9 yttrium	**40** **Zr** 91 2 zirconium	**41** **Nb** 92 9 niobium	**42** **Mo** 96 0 molybdenum	**43** **Tc** (98) technetium	**44** **Ru** 101 1 ruthenium	**45** **Rh** 102 9 rhodium	**46** **Pd** 106 4 palladium	**47** **Ag** 107 9 silver	**48** **Cd** 112 4 cadmium	**49** **In** 114 8 indium	**50** **Sn** 118 7 tin	**51** **Sb** 121 8 antimony	**52** **Te** 127 6 tellurium	**53** **I** 126 9 iodine	**54** **Xe** 131 3 xenon
55 **Cs** 132 9 caesium	**56** **Ba** 137 3 barium	**57–71** lanthanoids	**72** **Hf** 178 5 hafnium	**73** **Ta** 180 9 tantalum	**74** **W** 183 8 tungsten	**75** **Re** 186 2 rhenium	**76** **Os** 190 2 osmium	**77** **Ir** 192 2 iridium	**78** **Pt** 195 1 platinum	**79** **Au** 197 0 gold	**80** **Hg** 200 6 mercury	**81** **Tl** 204 4 thallium	**82** **Pb** 207 2 lead	**83** **Bi** 209 0 bismuth	**84** **Po** (210) polonium	**85** **At** (210) astatine	**86** **Rn** (222) radon
87 **Fr** (223) francium	**88** **Ra** (226) radium	**89–103** actinoids	**104** **Rf** (261) rutherfordium	**105** **Db** (262) dubnium	**106** **Sg** (266) seaborgium	**107** **Bh** (264) bohrium	**108** **Hs** (267) hassium	**109** **Mt** (268) meitnerium	**110** **Ds** (271) darmstadtium	**111** **Rg** (272) roentgenium	**112** **Cn** (285) copernicium	**113** **Nh** (280) nihonium	**114** **Fl** (289) flerovium	**115** **Mc** (289) moscovium	**116** **Lv** (292) livermorium	**117** **Ts** (294) tennessine	**118** **Og** (294) oganesson

57 **La** 138 9 lanthanum	**58** **Ce** 140 1 cerium	**59** **Pr** 140 9 praseodymium	**60** **Nd** 144 2 neodymium	**61** **Pm** (145) promethium	**62** **Sm** 150 4 samarium	**63** **Eu** 152 0 europium	**64** **Gd** 157 3 gadolinium	**65** **Tb** 158 9 terbium	**66** **Dy** 162 5 dysprosium	**67** **Ho** 164 9 holmium	**68** **Er** 167 3 erbium	**69** **Tm** 168 9 thulium	**70** **Yb** 173 1 ytterbium	**71** **Lu** 175 0 lutetium

89 **Ac** (227) actinium	**90** **Th** 232 0 thorium	**91** **Pa** 231 0 protactinium	**92** **U** 238 0 uranium	**93** **Np** (237) neptunium	**94** **Pu** (244) plutonium	**95** **Am** (243) americium	**96** **Cm** (247) curium	**97** **Bk** (247) berkelium	**98** **Cf** (251) californium	**99** **Es** (252) einsteinium	**100** **Fm** (257) fermium	**101** **Md** (258) mendelevium	**102** **No** (259) nobelium	**103** **Lr** (262) lawrencium

The value in brackets indicates the mass number of the longest-lived isotope.

2. Electrochemical series

Reaction	**Standard electrode potential (E^0) in volts at 25 °C**
$F_2(g) + 2e^- \rightleftharpoons 2F^-(aq)$	+2.87
$H_2O_2(aq) + 2H^+(aq) + 2e^- \rightleftharpoons 2H_2O(l)$	+1.77
$Au^+(aq) + e^- \rightleftharpoons Au(s)$	+1.68
$Cl_2(g) + 2e^- \rightleftharpoons 2Cl^-(aq)$	+1.36
$O_2(g) + 4H^+(aq) + 4e^- \rightleftharpoons 2H_2O(1)$	+1.23
$Br_2(l) + 2e^- \rightleftharpoons 2Br^-(aq)$	+1.09
$Ag^+(aq) + e^- \rightleftharpoons Ag(s)$	+0.80
$Fe^{3+}(aq) + e^- \rightleftharpoons Fe^{2+}(aq)$	+0.77
$O_2(g) + 2H^+(aq) + 2e^- \rightleftharpoons H_2O_2(aq)$	+0.68
$I_2(s) + 2e^- \rightleftharpoons 2I^-(aq)$	+0.54
$O_2(g) + 2H_2O(l) + 4e^- \rightleftharpoons 4OH^-(aq)$	+0.40
$Cu^{2+}(aq) + 2e^- \rightleftharpoons Cu(s)$	+0.34
$Sn^{4+}(aq) + 2e^- \rightleftharpoons Sn^{2+}(aq)$	+0.15
$S(s) + 2H^+(aq) + 2e^- \rightleftharpoons H_2S(g)$	+0.14
$2H^+(aq) + 2e^- \rightleftharpoons H_2(g)$	0.00
$Pb^{2+}(aq) + 2e^- \rightleftharpoons Pb(s)$	–0.13
$Sn^{2+}(aq) + 2e^- \rightleftharpoons Sn(s)$	–0.14
$Ni^{2+}(aq) + 2e^- \rightleftharpoons Ni(s)$	–0.25
$Co^{2+}(aq) + 2e^- \rightleftharpoons Co(s)$	–0.28
$Cd^{2+}(aq) + 2e^- \rightleftharpoons Cd(s)$	–0.40
$Fe^{2+}(aq) + 2e^- \rightleftharpoons Fe(s)$	–0.44
$Zn^{2+}(aq) + 2e^- \rightleftharpoons Zn(s)$	–0.76
$2H_2O(l) + 2e^- \rightleftharpoons H_2(g) + 2OH^-(aq)$	–0.83
$Mn^{2+}(aq) + 2e^- \rightleftharpoons Mn(s)$	–1.18
$Al^{3+}(aq) + 3e^- \rightleftharpoons Al(s)$	–1.66
$Mg^{2+}(aq) + 2e^- \rightleftharpoons Mg(s)$	–2.37
$Na^+(aq) + e^- \rightleftharpoons Na(s)$	–2.71
$Ca^{2+}(aq) + 2e^- \rightleftharpoons Ca(s)$	–2.87
$K^+(aq) + e^- \rightleftharpoons K(s)$	–2.93
$Li^+(aq) + e^- \rightleftharpoons Li(s)$	–3.04

3. Chemical relationships

Name	Formula
number of moles of a substance	$n = \frac{m}{M}; \quad n = cV; \quad n = \frac{V}{V_m}$
universal gas equation	$pV = nRT$
calibration factor (CF) for bomb calorimetry	$\mathrm{CF} = \frac{VIt}{\Delta T}$
heat energy released in the combustion of a fuel	$q = mc\Delta T$
enthalpy of combustion	$\Delta H = \frac{q}{n}$
electric charge	$Q = It$
number of moles of electrons	$n(e\ \ ) = \frac{Q}{F}$
% atom economy	$\frac{\text{molar mass of desired product}}{\text{molar mass of all reactants}} \times \frac{100}{1}$
% yield	$\frac{\text{actual yield}}{\text{theoretical yield}} \times \frac{100}{1}$

4. Physical constants and standard values

Name	Symbol	Value
Avogadro constant	N_A or L	6.02×10^{23} mol^{-1}
charge on one electron (elementary charge)	e	-1.60×10^{-19} C
Faraday constant	F	96 500 C mol^{-1}
molar gas constant	R	8.31 J mol^{-1} K^{-1}
molar volume of an ideal gas at SLC (25 °C and 100 kPa)	V_m	24.8 L mol^{-1}
specific heat capacity of water	c	4.18 kJ kg^{-1} K^{-1} or 4.18 J g^{-1} K^{-1}
density of water at 25 °C	d	997 kg m^{-3} or 0.997 g mL^{-1}

TURN OVER

5. Unit conversions

Measured value	Conversion
0 °C	273 K
100 kPa	750 mm Hg or 0.987 atm
1 litre (L)	1 dm^3 or 1×10^{-3} m^3 or 1×10^3 cm^3 or 1×10^3 mL

6. Metric (including SI) prefixes

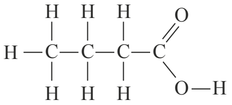
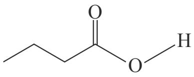
Metric (including SI) prefixes	Scientific notation	Multiplying factor
giga (G)	10^9	1 000 000 000
mega (M)	10^6	1 000 000
kilo (k)	10^3	1000
deci (d)	10^{-1}	0.1
centi (c)	10^{-2}	0.01
milli (m)	10^{-3}	0.001
micro (μ)	10^{-6}	0.000001
nano (n)	10^{-9}	0.000000001
pico (p)	10^{-12}	0.000000000001

7. Acid-base indicators

Name	pH range	Colour change from lower pH to higher pH in range
thymol blue (1st change)	1.2–2.8	red → yellow
methyl orange	3.1–4.4	red → yellow
bromophenol blue	3.0–4.6	yellow → blue
methyl red	4.4–6.2	red → yellow
bromothymol blue	6.0–7.6	yellow → blue
phenol red	6.8–8.4	yellow → red
thymol blue (2nd change)	8.0–9.6	yellow → blue
phenolphthalein	8.3–10.0	colourless → pink

8. Representations of organic molecules

The following table shows different representations of organic molecules, using butanoic acid as an example.

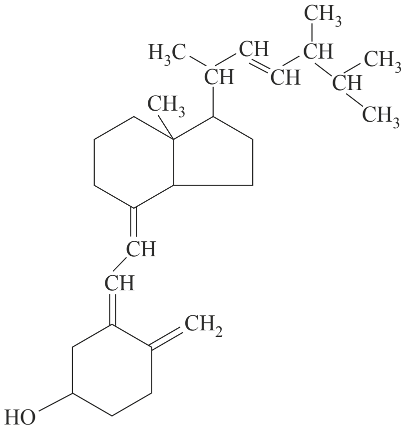
Formula	Representation
molecular formula	$C_4H_8O_2$
structural formula	
semi-structural (condensed) formula	$CH_3CH_2CH_2COOH$ or $CH_3(CH_2)_2COOH$
skeletal structure	

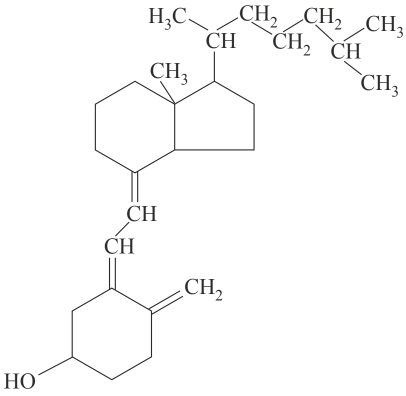
9. Formulas of some fatty acids

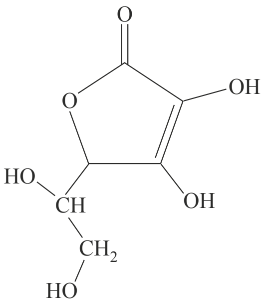
Name	Formula	Semi-structural formula
lauric	$C_{11}H_{23}COOH$	$CH_3(CH_2)_{10}COOH$
myristic	$C_{13}H_{27}COOH$	$CH_3(CH_2)_{12}COOH$
palmitic	$C_{15}H_{31}COOH$	$CH_3(CH_2)_{14}COOH$
palmitoleic	$C_{15}H_{29}COOH$	$CH_3(CH_2)_4CH_2CH{=}CHCH_2\ (CH_2)_5CH_2COOH$
stearic	$C_{17}H_{35}COOH$	$CH_3(CH_2)_{16}COOH$
oleic	$C_{17}H_{33}COOH$	$CH_3(CH_2)_7CH{=}CH(CH_2)_7COOH$
linoleic	$C_{17}H_{31}COOH$	$CH_3(CH_2)_4(CH{=}CHCH_2)_2(CH_2)_6COOH$
linolenic	$C_{17}H_{29}COOH$	$CH_3CH_2(CH{=}CHCH_2)_3(CH_2)_6COOH$
arachidic	$C_{19}H_{39}COOH$	$CH_3(CH_2)_{17}CH_2COOH$
arachidonic	$C_{19}H_{31}COOH$	$CH_3(CH_2)_4(CH{=}CHCH_2)_3CH{=}CH(CH_2)_3COOH$

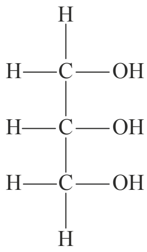
TURN OVER

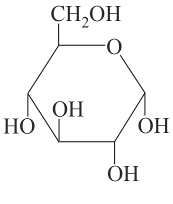
10. Formulas of some biomolecules

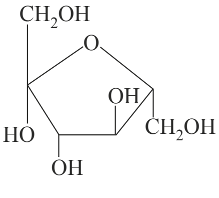

vitamin D_2 (ergocalciferol)

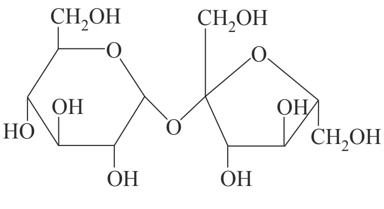

vitamin D_3 (cholecalciferol)

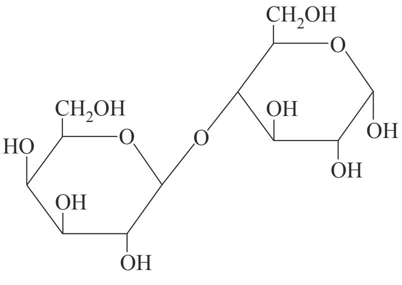

vitamin C (ascorbic acid)

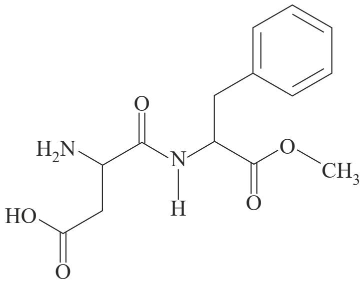

glycerol


α-glucose

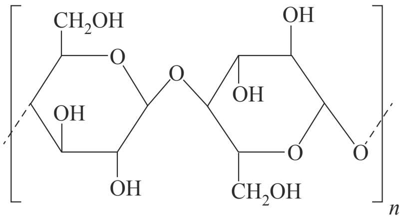

β-fructose


sucrose

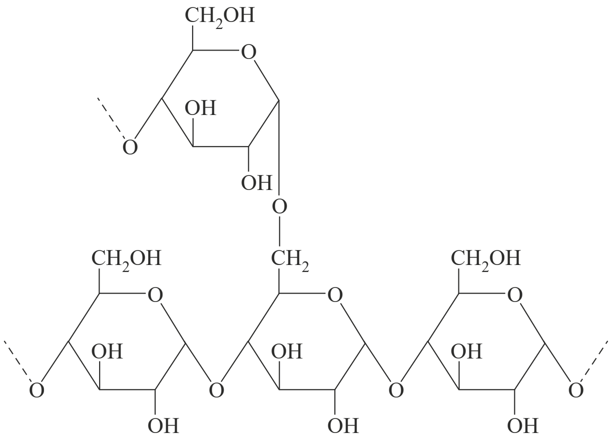

α-lactose



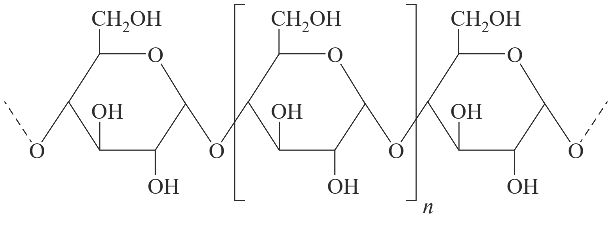
aspartame



cellulose



amylopectin (starch)



amylose (starch)

TURN OVER

11. Heats of combustion of common fuels

The heats of combustion in the following table are calculated at SLC (25 °C and 100 kPa) with combustion products being CO_2 and H_2O. Heat of combustion may be defined as the heat energy released when a specified amount of a substance burns completely in oxygen and is, therefore, reported as a positive value, indicating a magnitude. Enthalpy of combustion, ΔH, for the substances in this table would be reported as negative values, indicating the exothermic nature of the combustion reaction.

Fuel	Formula	State	Heat of combustion ($kJ\ g^{-1}$)	Molar heat of combustion ($kJ\ mol^{-1}$)
hydrogen	H_2	gas	141	282
methane	CH_4	gas	55.6	890
ethane	C_2H_6	gas	51.9	1560
propane	C_3H_8	gas	50.5	2220
butane	C_4H_{10}	gas	49.7	2880
octane	C_8H_{18}	liquid	47.9	5460
ethyne (acetylene)	C_2H_2	gas	49.9	1300
methanol	CH_3OH	liquid	22.7	726
ethanol	C_2H_5OH	liquid	29.6	1360

12. Heats of combustion of common blended fuels

Blended fuels are mixtures of compounds with different mixture ratios and, hence, determination of a generic molar enthalpy of combustion is not realistic. The values provided in the following table are typical values for heats of combustion at SLC (25 °C and 100 kPa) with combustion products being CO_2 and H_2O. Values for heats of combustion will vary depending on the source and composition of the fuel.

Fuel	State	Heat of combustion ($kJ\ g^{-1}$)
kerosene	liquid	46.2
diesel	liquid	45.0
natural gas	gas	54.0

13. Energy content of food groups

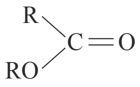
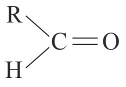
Food	Heat of combustion ($kJ\ g^{-1}$)
fats and oils	37
protein	17
carbohydrate	16

14. Characteristic ranges for infra-red absorption

Bond	**Wave number (cm^{-1})**	**Bond**	**Wave number (cm^{-1})**
C–Cl (chloroalkanes)	600–800	C=O (ketones)	1680–1850
C–O (alcohols, esters, ethers)	1050–1410	C=O (esters)	1720–1840
C=C (alkenes)	1620–1680	C–H (alkanes, alkenes, arenes)	2850–3090
C=O (amides)	1630–1680	O–H (acids)	2500–3500
C=O (aldehydes)	1660–1745	O–H (alcohols)	3200–3600
C=O (acids)	1680–1740	N–H (amines and amides)	3300–3500

15. ^{13}C NMR data

Typical ^{13}C shift values relative to TMS = 0
These can differ slightly in different solvents.

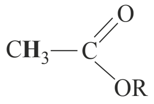
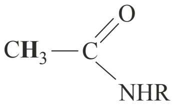
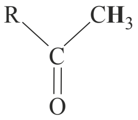
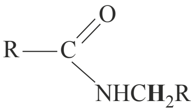
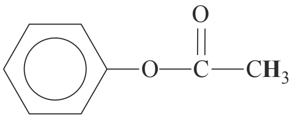
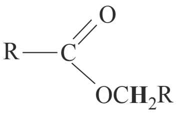
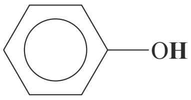
Type of carbon	**Chemical shift (ppm)**
R–CH_3	8–25
R–CH_2–R	20–45
R_3–CH	40–60
R_4–C	36–45
R–CH_2–X	15–80
$R_3C–NH_2$, $R_3C–NR$	35–70
R–CH_2–OH	50–90
RC≡CR	75–95
$R_2C=CR_2$	110–150
RCOOH	160–185
	165–175
	190–200
$R_2C=O$	205–220

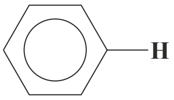
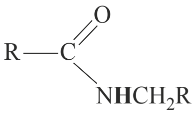
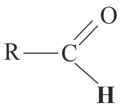
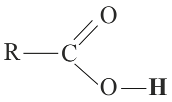
TURN OVER

16. ^{1}H NMR data

Typical proton shift values relative to TMS = 0

These can differ slightly in different solvents. The shift refers to the proton environment that is indicated in bold letters in the formula.

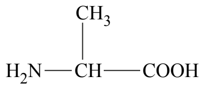
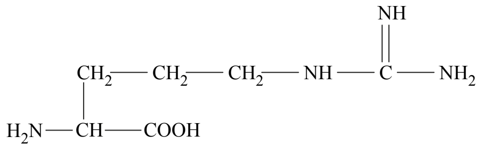
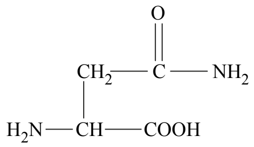
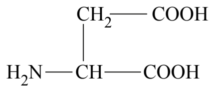
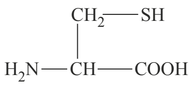
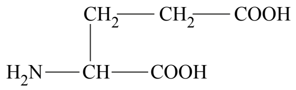
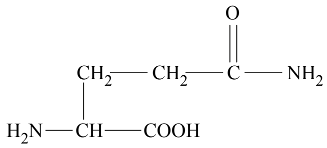
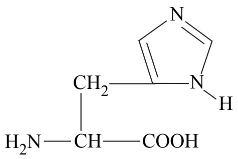
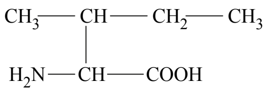
Type of proton	Chemical shift (ppm)
$\mathrm{R{-}C}\mathbf{H}_3$	0.9–1.0
$\mathrm{R{-}C}\mathbf{H}_2\mathrm{{-}R}$	1.3–1.4
$\mathrm{RCH{=}CH{-}C}\mathbf{H}_3$	1.6–1.9
$\mathrm{R_3{-}C}\mathbf{H}$	1.5
 or 	2.0
	2.1–2.7
$\mathrm{R{-}C}\mathbf{H}_2\mathrm{{-}X}$ (X = F, Cl, Br or I)	3.0–4.5
$\mathrm{R{-}C}\mathbf{H}_2\mathrm{{-}OH}$, $\mathrm{R_2{-}C}\mathbf{H}\mathrm{{-}OH}$	3.3–4.5
	3.2
$\mathrm{R{—}O{—}C}\mathbf{H}_3$ or $\mathrm{R{—}O{—}C}\mathbf{H}_2\mathrm{R}$	3.3–3.7
	2.3
	3.7–4.8
$\mathrm{R{-}O{-}}\mathbf{H}$	1–6 (varies considerably under different conditions)
$\mathrm{R{-}N}\mathbf{H}_2$	1–5
$\mathrm{RHC{=}C}\mathbf{H}\mathrm{R}$	4.5–7.0
	4.0–12.0

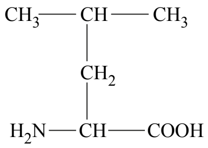
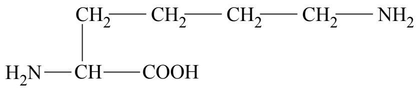
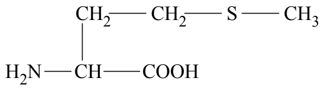
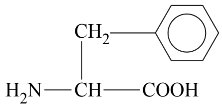
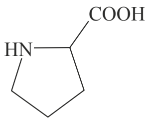
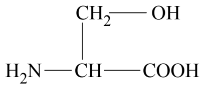
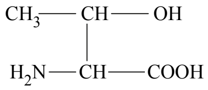
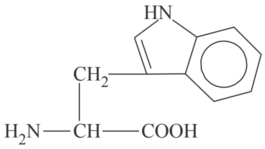
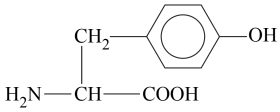
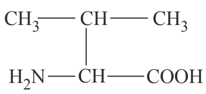
Type of proton	**Chemical shift (ppm)**
	6.9–9.0
	8.1
	9.4–10.0
	9.0–13.0

TURN OVER

17. 2-amino acids (*α*-amino acids)

The table below provides simplified structures to enable the drawing of zwitterions, the identification of products of protein hydrolysis and the drawing of structures involving condensation polymerisation of amino acid monomers.

Name	Symbol	Structure
alanine	Ala	 $\begin{array}{l} \quad CH_3 \\ \quad \vert \\ H_2N-CH-COOH \end{array}$
arginine	Arg	 $\begin{array}{l} \qquad\qquad\qquad\qquad\qquad\qquad\quad NH \\ \qquad\qquad\qquad\qquad\qquad\qquad\quad \Vert \\ \quad CH_2-CH_2-CH_2-NH-C-NH_2 \\ \quad \vert \\ H_2N-CH-COOH \end{array}$
asparagine	Asn	 $\begin{array}{l} \qquad\quad\; O \\ \qquad\quad\; \Vert \\ \quad CH_2-C-NH_2 \\ \quad \vert \\ H_2N-CH-COOH \end{array}$
aspartic acid	Asp	 $\begin{array}{l} \quad CH_2-COOH \\ \quad \vert \\ H_2N-CH-COOH \end{array}$
cysteine	Cys	 $\begin{array}{l} \quad CH_2-SH \\ \quad \vert \\ H_2N-CH-COOH \end{array}$
glutamic acid	Glu	 $\begin{array}{l} \quad CH_2-CH_2-COOH \\ \quad \vert \\ H_2N-CH-COOH \end{array}$
glutamine	Gln	 $\begin{array}{l} \qquad\qquad\qquad\; O \\ \qquad\qquad\qquad\; \Vert \\ \quad CH_2-CH_2-C-NH_2 \\ \quad \vert \\ H_2N-CH-COOH \end{array}$
glycine	Gly	H_2N-CH_2-COOH
histidine	His	
isoleucine	Ile	 $\begin{array}{l} CH_3-CH-CH_2-CH_3 \\ \qquad\; \vert \\ H_2N-CH-COOH \end{array}$

Name	Symbol	Structure
leucine	Leu	 $H_2N-CH(CH_2-CH(CH_3)-CH_3)-COOH$
lysine	Lys	 $H_2N-CH(CH_2-CH_2-CH_2-CH_2-NH_2)-COOH$
methionine	Met	 $H_2N-CH(CH_2-CH_2-S-CH_3)-COOH$
phenylalanine	Phe	
proline	Pro	
serine	Ser	 $H_2N-CH(CH_2-OH)-COOH$
threonine	Thr	 $H_2N-CH(CH(CH_3)-OH)-COOH$
tryptophan	Trp	
tyrosine	Tyr	
valine	Val	 $H_2N-CH(CH(CH_3)-CH_3)-COOH$

END OF DATA BOOK

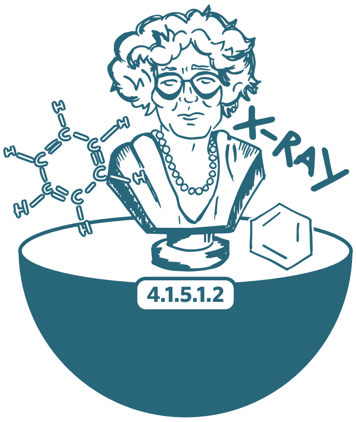
BONUS CHALLENGE

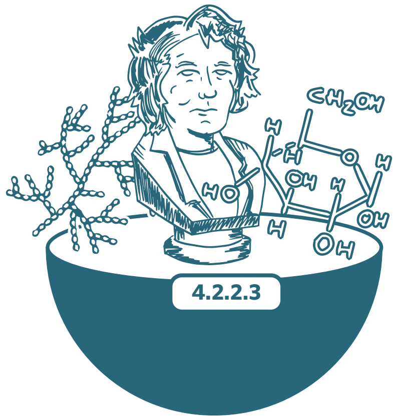
‘Joining your learning together’

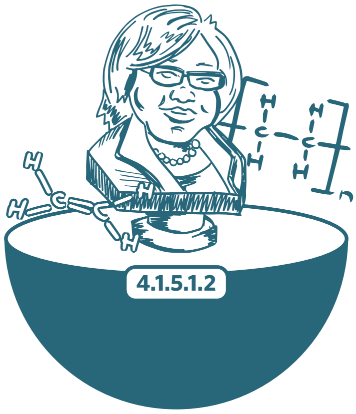
Some of the most difficult concepts from recent VCE exams are represented in the hemispheres below. Writing is a great way to test your knowledge and consolidate your understanding – especially when you’re bringing new ideas together! Here’s a challenge for you…

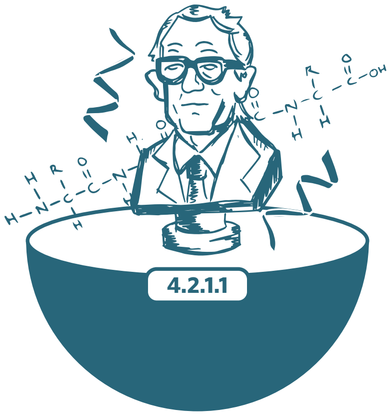
Can you name these famous scientists, what they contributed to our understanding of chemistry and join them all together to form a 200 word or less narrative?

If so, we’d love you to send them through to us at **contentteam@edrolo.com**.









Pssst… The image labelled 3.2.8.1 represents Unit 3, AOS 2, study design dot point 8, key knowledge unit 1, and features Henri Le Châtelier’s principle of changes to equilibrium. However, you might need to research a little further to discover some of the others. Good luck finding the others and joining them together!