How fast can things go?

Newton's Laws of motion

- **investigate and apply theoretically and practically Newton's three laws of motion in situations where two or more coplanar forces act along a straight line and in two dimensions.**

Paper	Multiple choice	Short Answer	Idea	Marks	%	Type
2022	7		Newton's third law	1	47%	Concept
	9		Newton's third law	1	52%	Concept
		7a i	Inclined plane	2	78%	Calculation
		7a ii	Inclined plane, friction force	2	53%	Calculation
2022 NHT	7		SUVAT	1	NA	Calculation
2021		4	Newton's third law	2	9%	Explanation
		8a	$F_{net} = ma$	3	49%	Calculation
2021 NHT		8a	Inclined plane, draw forces	3	NA	Concept
		8b	$F_{net} = 0$, $a = 0$	3	NA	Calculation
2020	9		Newton's third law	1	49%	Explanation
2019	11		$F_{net} = 0$	1	62%	Calculation
2019 NHT		9	Vertical connected bodies	1	NA	Calculation
2018	5		Forces	1	74%	Calculation
	6		Graphs	1	69%	Calculation
		8a	Horizontal connected bodies	2	35%	Calculation
		8b	Horizontal connected bodies	2	75%	Concept
2018 NHT	8		Connected bodies	1	NA	Calculation
	9		Connected bodies	1	NA	Calculation
2017	7		Newton's Laws	1	95%	Calculation
	9		SUVAT	1	87%	Calculation

Straight line motion (SLM) can be grouped into the following ideas.

Forces can be grouped into the following ideas.

Vectors and Scalars

Vectors are quantities that have a magnitude and a direction.
E.g. displacement, velocity, and acceleration, force, weight, momentum, impulse, torque, Electric field, Magnetic field, gravitational field.

Scalars are quantities that only have a magnitude,
E.g. mass, speed, distance travelled, time, area, density, energy.

Change in velocity (Δv)

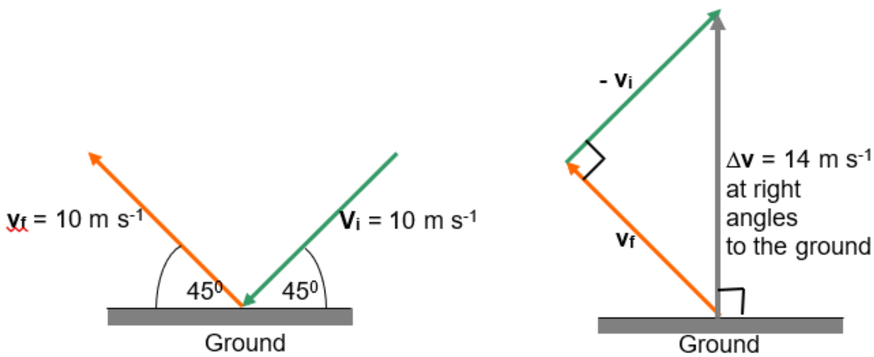
The change in anything is defined as the 'final' – 'initial'.
If the quantity that you are finding the change in is a vector, then you need to take the directions of the initial and final into consideration.
Remember, that to subtract a vector you add the negative of the vector.

When an object collides with another and changes its velocity, its change in velocity is a vector quantity found by subtracting the initial velocity from the final velocity.

Change in velocity = final velocity - initial velocity

$\Delta \mathbf{v} = \mathbf{v}_f - \mathbf{v}_i$

If a ball bounces off a wall, the change in velocity can be determined graphically in a vector diagram.



Graphical techniques

When given a graph in the exam, look at three things on the graph before even reading the question:

type of graph (s - t, v - t, etc) **the units on the axis** **the limit on each axis.**

Graph type / Found from	s - t	v - t	a - t
Direct reading	's' at any 't' 't' at any 's'	'v' at any 't' 't' at any 'v'	'a' at any 't' 't' at any 'a'
Gradient	Instantaneous velocity at any point. v_{av} between any two points	Instantaneous 'a' Average 'a'	
Area under graph		Change in position	Change in velocity

Units

Use the MKSA system of units. All values should be in **M**etres, **K**ilograms, **S**econds and **A**mperes.

To convert from km h^{-1} to m s^{-1} you need to divide by 3.6, this should be on your cheat sheet.

e.g 100 kph = 27.8 m s^{-1}

SUVAT (Equations of motion)

The following relationships hold for **straight line motion with constant acceleration**.

$v_{av} = \frac{x_2 - x_1}{\Delta t}$

$a = \frac{v - u}{t} = \frac{\Delta v}{\Delta t}$

	Includes	Omits
$v = u \pm at$	u, v, a, t	s
$v^2 = u^2 \pm 2as$	u, v, a, s	t
$s = ut \pm \frac{1}{2}at^2$	u, a, s, t	v
$s = \frac{(u + v)}{2}t$	u, v, s, t	a

Newton's 1st Law of motion

Every object remains at rest, or in uniform motion in a straight line (the velocity may be a non-zero constant), unless acted on by some external force.

Consequently, if the acceleration = 0, and therefore $F_{net} = 0$, then the velocity will remain unchanged.

Newton's 2nd Law of motion

The rate of change of momentum is equal to the resultant force causing the change.

$\mathbf{F} = \frac{mv - mu}{t}$ since $\mathbf{a} = \frac{v - u}{t}$ $\therefore$ $\mathbf{F}.t = m\mathbf{v} - m\mathbf{u}$

Impulse (change in momentum) i.e. $\mathbf{I} = \mathbf{p_2} - \mathbf{p_1}$. is always the area under F-t graph.

When the force is constant, it also equals $F\Delta t$.

Area under "**F** - t" graph = **Impulse** = Δ **momentum = F Δ t**

TOTAL MOMENTUM BEFORE IMPACT EQUALS THE TOTAL MOMENTUM AFTER IMPACT.

$\therefore$ $\mathbf{P}_{(total)}$ is constant before, during and after the collision.

Newton's 3rd Law of motion

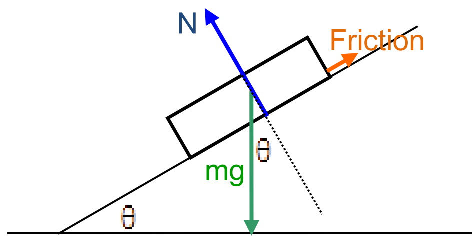
Action and reaction are equal and opposite. The force on A by B is equal and opposite to the force on B by A. This is summarised as $\mathbf{F_{on\ A\ by\ B} = -F_{on\ B\ by\ A}}$ (the minus sign is to give the direction of the force vector).For the forces to be an action reaction pair, the subjects of the two statements need to be interchanged.

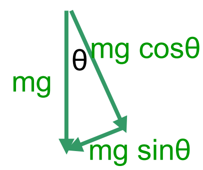
This concept is often tested using a book on a table. The action reaction pair of forces are: the weight force of the **on the book by Earth**, and the force of the **on the Earth by the book**. Many students get this incorrect, because they use the normal reaction as the other part of the pair.

Inclined planes

An example of forces acting at angles to each other is an object on an inclined plane.

The weight is resolved into two components, one perpendicular to the direction of motion (mg cosθ), and one parallel to the direction of motion (mg sinθ).





Forces perpendicular to the plane:

$$F_{net} = mg\cos\theta - N$$
$$= 0$$

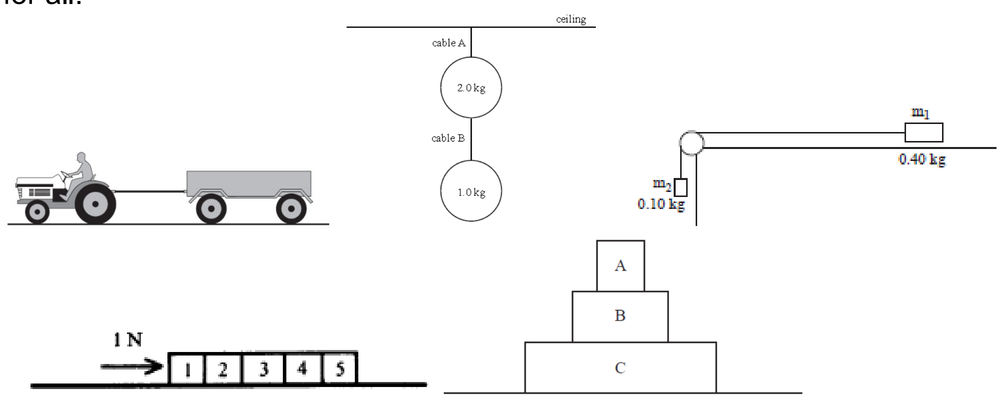
Forces parallel to the plane:

$$F_{net} = mg\sin\theta - F$$
$$= ma$$

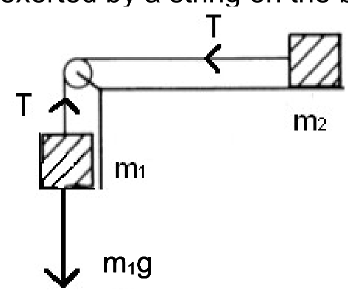
If there is no friction, then the acceleration is **g** sinθ

Connected Bodies

Connected bodies can either be linked by a string/rod etc. or they can be touching one another. They can be horizontal, vertical of both. They can be pushing or pulling. The solution process is the same for all.



Problems involving the motion of two bodies connected by strings are solved on the following assumptions: the string is assumed light and inextensible so its weight can be neglected and there is no change in length as the tension varies. Tension forces are pulls exerted by a string on the bodies to which it is attached.



To solve these problems, consider the vertical direction first.

$$m_1g - T = m_1a$$

The direction of this acceleration must be downwards.
This leads to: $T = m_1g - m_1a$

The tension in the string is the same in both directions, therefore

$$T = m_2a.$$

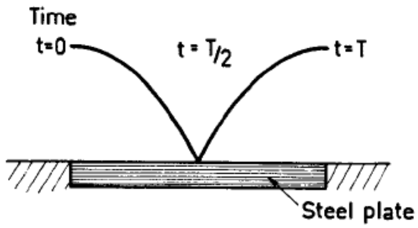
Since both bodies are connected by an inextensible string, both bodies must have the same acceleration. The vertical forces acting on m_2, (not shown) cancel each other out, and do not impact on its motion.

$$a = \frac{m_1}{m_1 + m_2}g$$

Combing these two equations gives

$$T = \frac{m_1m_2}{m_1 + m_2}g$$

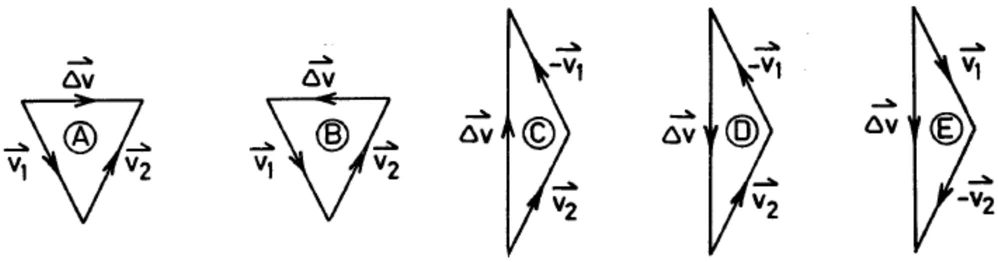
Worked example 1: Adding and subtracting vector quantities.



A steel ball is projected horizontally and makes a perfectly elastic collision with a steel plate embedded in the ground.

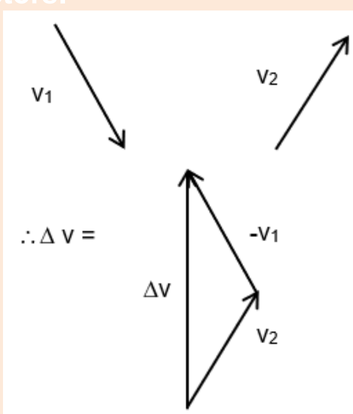
1971 Question 37, 1 mark

Which of the following vector diagrams correctly represents the relation between the velocity of the ball just before impact, v_1 , the velocity just after impact, v_2 and the change in velocity Δv?



Solution

The change in velocity is always given by $v_{final} - v_{initial}$, when treated as vectors.

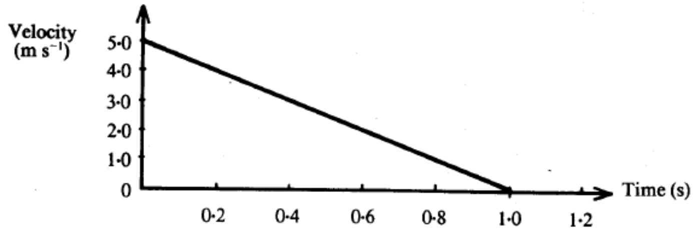


∴ C (ANS), (61%)

Current study design:

2018 Question 5 (74%)

Worked example 2: Graphing



The graph above gives the velocity-time relationship for a block of mass 4.0 kg which slides across a rough, horizontal floor, coming to rest after 1.0 s.

1986 Question 1, 1 mark

What is the magnitude of the frictional force of the floor on the block?

Solution	**Current study design:**
Using $F_{net} = ma$, we need to find 'a'. The acceleration is the gradient of the velocity-time graph. The question asks for the magnitude. The gradient is: $\frac{\Delta v}{\Delta t} = \frac{-5}{1}$ $\therefore a = -5$ $\therefore$ magnitude of a = 5 $\therefore F = 4 \times 5$ $\therefore F = 20$ N (ANS)	2018 Question 6 (69%)

Worked example 3: Newton's 3rd Law.

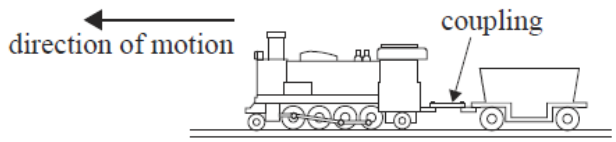
1986 Question 2, 1 mark

What is the magnitude of the frictional force of the block on the floor?

Solution	**Current study design:**
This is equal to (in magnitude), but in the opposite direction to the force of the floor on the block. $\therefore F = 20$ N (ANS)	**2022 Question 7 (47%)** **2022 Question 9 (52%)** 2021 Question 4 (9%)

Worked example 4: $v^2 = u^2 + 2as$

A train consists of an engine of mass 20 tonnes (20 000 kg) towing one wagon of mass 10 tonnes (10 000 kg), as shown below.



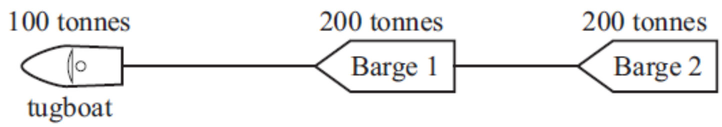
2016 Question 1a, 2 marks

The train accelerates from rest with a constant acceleration of 0.10 m s^{-2}.
Calculate the speed of the train after it has moved 20 m. Show your working.

Solution	**Current study design:**
Use: $v^2 = u^2 + 2as$ where u = 0, a = 0.1, s = 20 **∴ $v^2 = 0 + 2 \times 0.1 \times 20$** **∴ $v^2 = 4$** **∴ v = 2 m s^{-1} (ANS), (87%)**	**2022 NHT Question 7** **2018 NHT Question 9**

Worked example 5: v = u + at, straight substitution

A tugboat is towing two barges (unpowered boats) connected by cables, as shown below. The tugboat has a mass of 100 tonnes and each barge has a mass of 200 tonnes.



The tugboat starts from rest and accelerates at 0.50 m s^{-2}.

2017 NHT Question 1a, 2 marks

Calculate the distance that the tugboat and its barges travel in the first 10 s.

Solution	**Current study design:**
Use: $s = ut + \frac{1}{2}at^2$ Starts from rest, $\therefore u = 0, a = 0.50, t = 10$ $\therefore s = 0 + \frac{1}{2} \times 0\ 05. \times 10^2$ $\therefore s = 25$ m (ANS)	2017 Question 9 (87%)

Worked example 6: Newton's 2nd Law

2017 NHT Question 1b, 2 marks

Calculate the force applied by the tugboat's engine. Ignore any friction.

Solution	**Current study design:**
Use F = ma (on the system) $F_{total} = (100\times10^3 + 200\times10^3 + 200\times10^3) \times 0.50$ $\therefore F_{total} = 2.50 \times 10^5$ N (ANS)	2021 Question 8a (49%) **2017 Question 7 (95%)**

Worked example 7: Connected bodies, (horizontal, driving force)

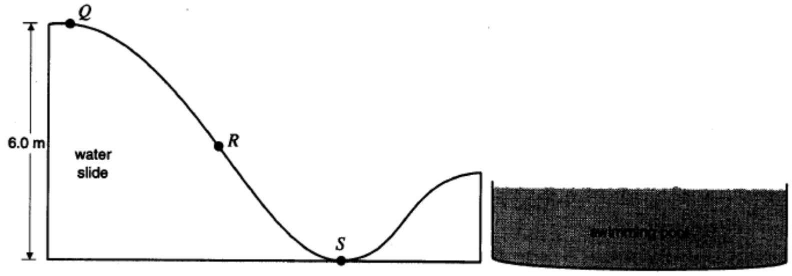
2017 NHT Question 1c, 2 marks

Calculate the tension in the cable connecting the tugboat and Barge 1.

Solution	**Current study design:**
Use F = ma (on the barges) $\therefore F_{total} = (200 \times 10^3 + 200 \times 10^3) \times 0.50$ $\therefore F_{total} = 2.0 \times 10^5$ N (ANS)	2020 Question 9 (49%)

Worked example 8: Inclined plane, (Draw/label forces acting)

Jessica moves down a water slide of vertical height 6.0 m into a swimming pool as shown below. Jessica starts from rest at Q and you may assume that friction and air resistance are negligible.

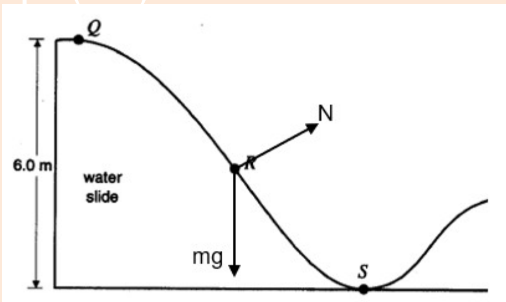


1996 Question 2, 1 mark

On the figure above, sketch and label the individual forces on Jessica at the point R.

Solution

The only two forces acting are the weight, mg, downwards, and the normal force, N, perpendicular to the slope. (42%)



Current study design:

2021 NHT Question 8a

Worked example 9: Newton's 1st Law

A cyclist pedals up a 15° slope at a constant speed as shown. The total mass of rider and bicycle is 100 kg.

2001 Question 1, 2 marks

What is the magnitude of the **net** force on the bicycle and rider when travelling up the slope?

Solution

This question is designed to be a nice starter, so don't fall into the trap of making it too complicated. As you were reading the question, you should have highlighted the words "constant speed". This means that acceleration = 0.

∴ net force = 0 (ANS) (46%)

Current study design:

2021 NHT Question 8b

2019 Question 11 (62%)

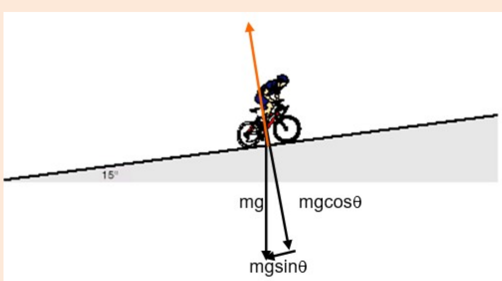
Worked example 10: Inclined plane, (Resolve forces)

2001 Question 1, 2 marks

Calculate the magnitude of the normal reaction force acting on the bicycle when travelling up the slope.(g = 9.8 m s^{-2})

Solution

Always use a diagram to solve these questions.



Here the normal is equal in value, but in the opposite direction to mgcosθ.

∴ N = mgcosθ

∴ N = 100 × 9.8 × cos15°

= 946.6

= 947 N (ANS), (56%)

Current study design:

2022 Question 7a i (78%)

Worked example 11: Inclined plane, (Including friction)

Sometime later the rider turns around and rolls at constant speed down the slope.

2001 Question 3, 3 marks

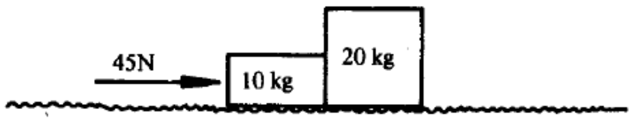
Calculate the magnitude of the total frictional forces that are acting on the rider and bicycle while travelling down the slope.

Solution	**Current study design:**
When the rider is going down the hill at a constant speed, then the sum of the forces is again zero. So, the frictional forces opposing the motion (acting up the slope) must be equal to the weight component acting down the slope. **∴ Frictional forces = mg sinθ** **= 100 × 9.8 × $\sin 15^0$** = 253.6 **= 254 N (ANS), (47%)**	**2022 Question 7a ii (53%)**

Worked example 12: Connected bodies, (horizontal)

Two masses, 10 kg and 20 kg, are placed in contact on a rough surface as shown. A person exerts a force of 45 N on the 10 kg mass.

The magnitude of the frictional force acting on the 10 kg mass is 10 N and the magnitude of the frictional force acting on the 20 kg mass is 20 N.



1984 Question 28, 1 mark

What is the acceleration of the system of two masses?

Solution

$F_{net} = ma$

The net force = $45 - F_{friction}$

$= 45 - 30$

$= 15$

$\therefore 15 = (10 + 20)a$

$\therefore a = \frac{15}{30}$

$= 0.5$ m s^{-2} (ANS), (90%)

Current study design:

2018 Question 8a (35%)

Worked example 13: Connected bodies, (horizontal, using Newton 3)

1984 Question 29, 1 mark

What is the force exerted by the 20 kg mass on the 10 kg mass while they are in motion?

Solution

The force exerted by the 20 kg mass on the 10 kg mass is equal and opposite to the force exerted by the 10 kg mass on the 20 kg mass.

Since the 20 kg mass is accelerating at 0.5 m s^{-2}, the net force on it must be $F_{net} = ma$.

$\therefore F_{net} = 20 \times 0.5 = 10$ N.

The frictional force of 20 N still needs to be overcome, so $F_{10\ on\ 20} = 10 + 20 = 30$ N

$\therefore$ The force exerted by the 20 kg mass on the 10 kg mass

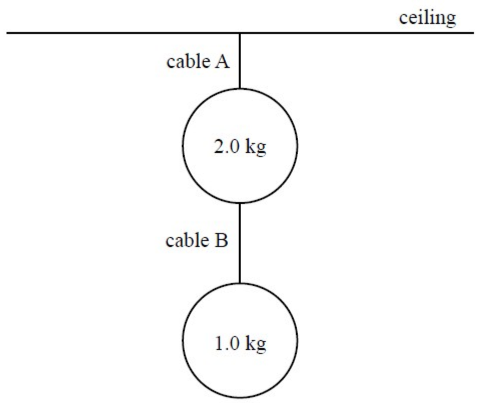
= 30 N (ANS), (21%)

Current study design:

2018 Question 8b (75%)

Worked example 14: Connected bodies, (vertical, using Newton 3)

Two metal spheres hang from the ceiling as shown below. Cable A runs between the ceiling and the upper sphere of mass 2.0 kg. Cable B runs between the 2.0 kg sphere and the 1.0 kg sphere. Assume that the cables have no mass.



2012 Question 4b, 2 marks

Newton's third law is sometimes stated as 'To every action there is an equal and opposite reaction'.

If the weight (the gravitational force by Earth) of the 2.0 kg sphere is taken as the 'action' force, identify the corresponding 'reaction' force and give its direction.

Solution

Newton's third law can be written in the form;

$F_{A\ on\ B} = -F_{B\ on\ A}$

Then the weight of sphere is

$F_{Earth\ on\ Sphere}$

In terms of Newtons action and reaction pairs, the 'reaction' will be

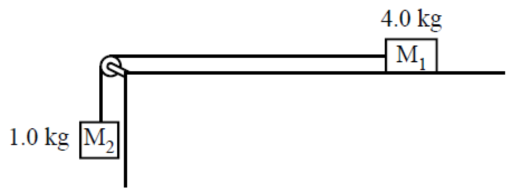
$F_{Sphere\ on\ Earth}$, UP (ANS), (15%)

Current study design:

2019 NHT Question 9

Worked example 15: Connected bodies, (in two dimensions)

Students set up an experiment as shown below. M_1, of mass 4.0 kg, is connected by a light string (assume it has no mass) to a hanging mass, M_2, of 1.0 kg.
The system is initially at rest. Ignore mass of string and friction.



The masses are released from rest.

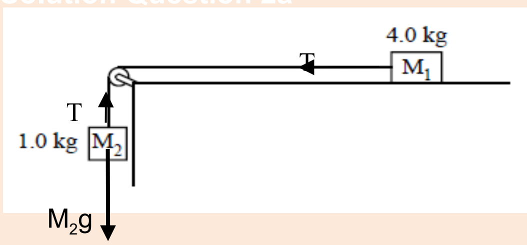
2015 Question 2a, 2 marks

Calculate the acceleration of M_1.

2015 Question 2b, 2 marks

Calculate the magnitude of the tension in the string as the masses accelerate.

Solution Question 2a



For M_2, use $F_{net} = ma$

$\therefore M_2g - T = m_2a$

$\therefore 1 \times 10 - T = 1 \times a$

For M_1, use $F_{net} = ma$

$\therefore T = M_1a$

$\therefore T = 4 \times a$

Combine the two equations to get

$10 - 4a = a$

$\therefore 10 = 5a$

$\therefore a = 2 \text{ m s}^{-2}$ (ANS), (52%)

Solution Question 2b

Consider M_1,

$T = 4 \times a$

$\therefore T = 4 \times 2$

$\therefore T = 8$ N (ANS), (54%)

Current study design:

2018 NHT Question 8

VCAA physics exams and exam reports

These papers are all available on the VCAA website.
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You need to scroll down the page to find the Physics exams.