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4.3 Equations of Motion

PHYSICS

AQA A Level Revision Notes

4.3 Equations of Motion

CONTENTS

Displacement, Speed, Velocity & Acceleration

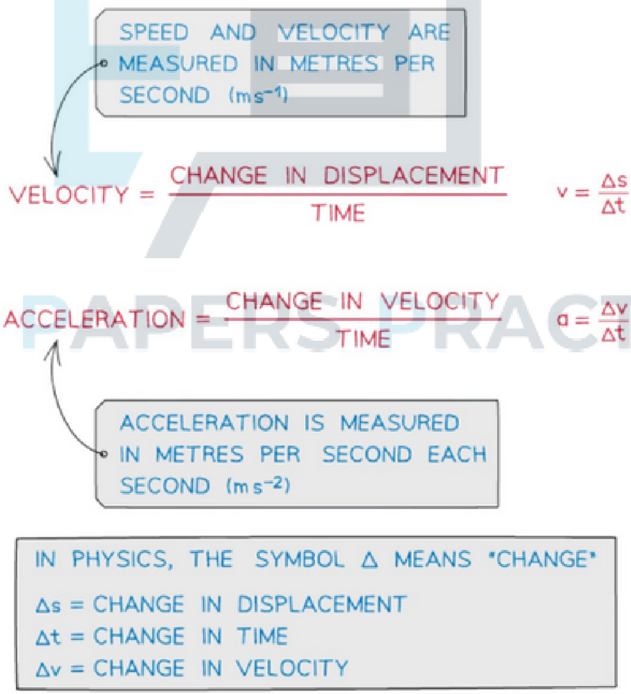
Scalar quantities

- Scalar quantities only have a magnitude (size)
  - **Distance:** the total length between two points
  - **Speed:** the total distance travelled per unit of time

Vector quantities

- Vector quantities have both magnitude and direction
  - **Displacement:** the distance of an object from a fixed point in a specified direction
  - **Velocity:** the rate of change of displacement of an object
  - **Acceleration:** the rate of change of velocity of an object

Equations for Velocity & Acceleration



Equations linking displacement, velocity and acceleration

Worked Example

A car accelerates uniformly from rest to a speed of 150 km h^{-1} in 6.2 s. Calculate the magnitude of the acceleration of the car in m s^{-2}.

Step 1: Convert the speed from km h^{-1} to m s^{-1}

$$150 \text{ km h}^{-1} = 150 \times 10^3 \text{ m h}^{-1}$$

$$3600 \text{ s} = 1 \text{ h}$$

$$\frac{150 \times 10^3}{3600} = 41.67 \text{ m s}^{-1}$$

Step 2: Write down the equation for acceleration

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

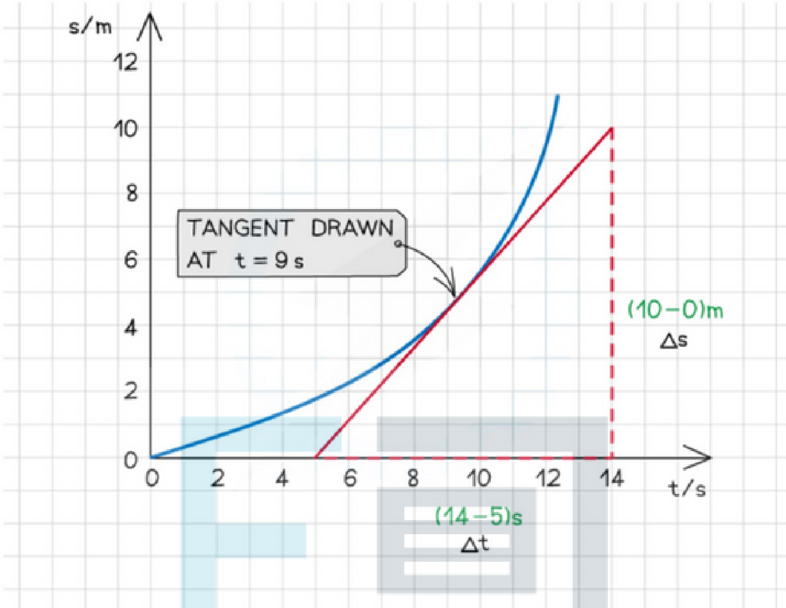
Step 3: Calculate the acceleration

$$a = \frac{41.67}{6.2} = 6.7 \text{ m s}^{-2}$$

Average & Instantaneous Speed

Instantaneous Speed / Velocity

- The instantaneous speed (or velocity) is the speed (or velocity) of an object at any given point in time
- This could be for an object moving at a constant velocity or accelerating
  - An object accelerating is shown by a **curved line** on a displacement – time graph
  - An accelerating object will have a changing velocity
- To find the instantaneous velocity on a displacement-time graph:
  - Draw a **tangent** at the required time
  - Calculate the **gradient** of that tangent



The instantaneous velocity is found by drawing a tangent on the displacement time graph

Average Speed / Velocity

- The average speed (or velocity) is the **total distance** (or displacement) divided by the **total time**
- To find the average velocity on a displacement-time graph, divide the **total displacement** (on the y-axis) by the **total time** (on the x-axis)
  - This method can be used for both a curved or a straight-line on a displacement-time graph

Worked Example

A cyclist travels a distance of 20 m at a constant speed then decelerates to a traffic light 5 m ahead. The whole journey takes 3.5 s. Calculate the average speed of the cyclist.

Step 1: Write the average speed equation

Average speed = total distance ÷ total time

Step 2: Calculate the total distance

Total distance = 20 + 5 = 25 m

Step 3: Calculate the average speed

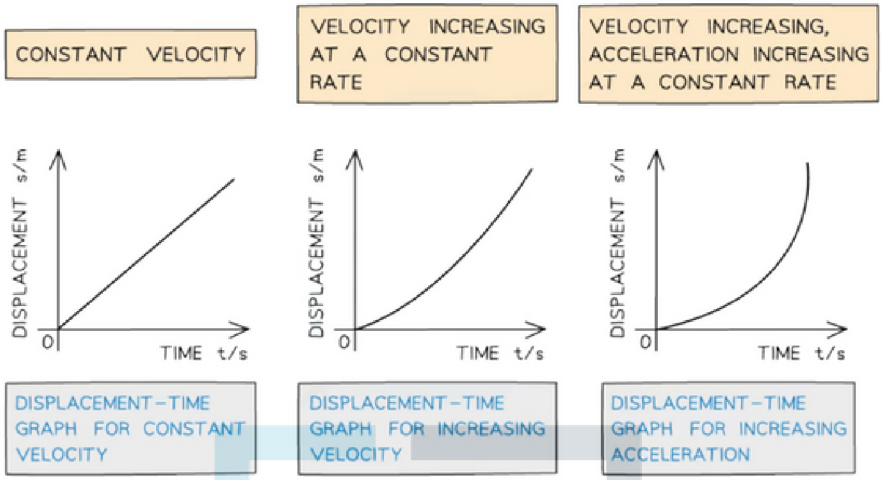
Average speed = 25 ÷ 3.5 = 7.1 m s^{-1}

Uniform & Non-Uniform Acceleration Graphs

- Three types of graph that can represent motion are displacement-time graphs, velocity-time graphs and acceleration-time graphs

Displacement-Time Graph

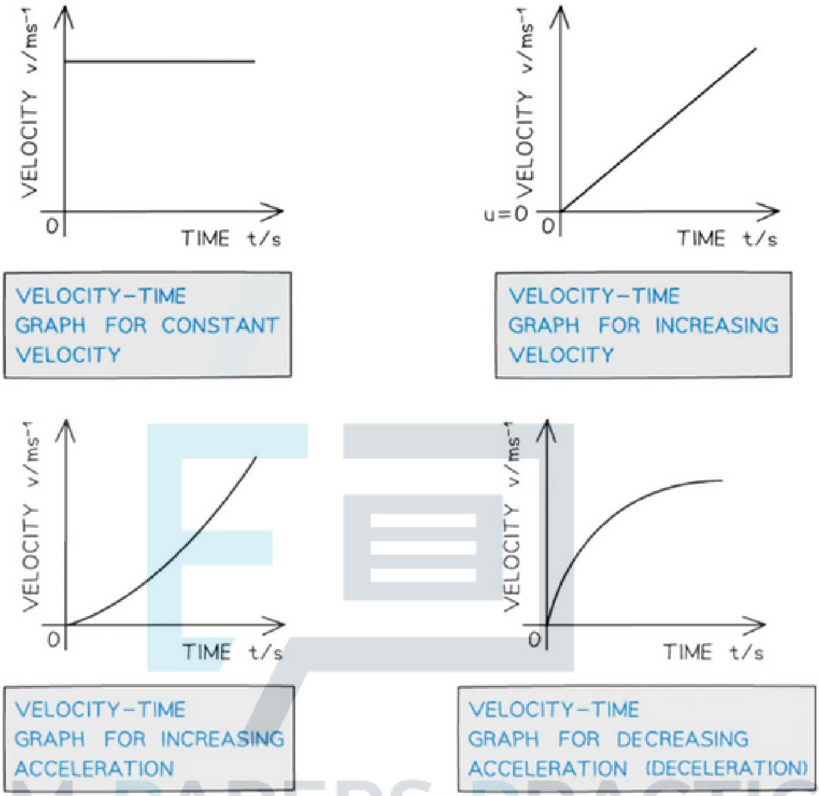
- On a **displacement-time graph:**
  - The **gradient** (or slope) equals **velocity**
  - The **y-intercept** equals the **initial displacement**
  - A diagonal **straight** line represents a **constant** velocity
    - A **positive slope** represents motion in the **positive direction**
    - A **negative slope** represents motion in the **negative direction**
  - A **curved** line represents an **acceleration**
  - A **horizontal line** (zero slope) represents a state of **rest**
  - The area under the curve is meaningless
- Remember the displacement-time graph can have positive or negative values on the displacement axis. However, a distance-time graph only has positive



Displacement-time graph for different scenarios

Velocity-Time Graph

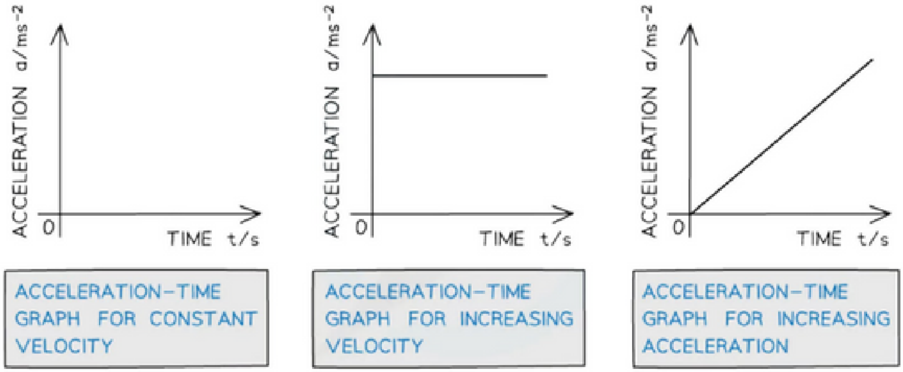
- On a **velocity-time graph**:
  - **Slope** equals **acceleration**
  - The **y-intercept** equals the **initial velocity**
  - A **straight** line represents **uniform** acceleration
    - A **positive** slope represents an **increase** in **velocity** (acceleration) in the **positive direction**
    - A **negative** slope represents an **increase** in **velocity** (acceleration) in the **negative direction**
  - A **curved** line represents the **non-uniform acceleration**
  - A **horizontal** line (zero slope) represents motion with **constant velocity**
  - The **area** under the curve equals the **displacement** or **distance** travelled
- Remember the velocity-time graph can have positive or negative values on the displacement axis. However, a speed-time graph only has positive



Velocity-time graph for different scenarios

Acceleration-Time Graph

- On an **acceleration-time graph**:
  - The slope is meaningless
  - The **y-intercept** equals the **initial acceleration**
  - A horizontal line (zero slope) represents an object undergoing **constant acceleration**
  - The **area** under the curve equals the **change in velocity**



Acceleration-time graphs for different velocity scenarios

4.3.2 Motion Graphs

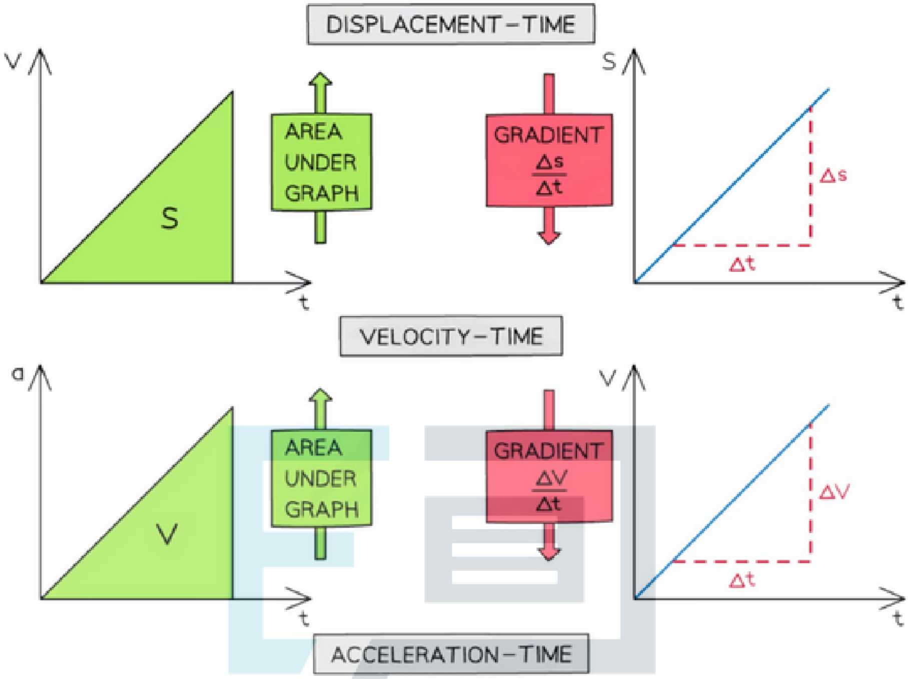
Motion Graphs

Gradients

- The gradient of a **displacement**-time graph is the **velocity**
- The gradient of a **velocity**-time graph is the **acceleration**

Area Under the Graph

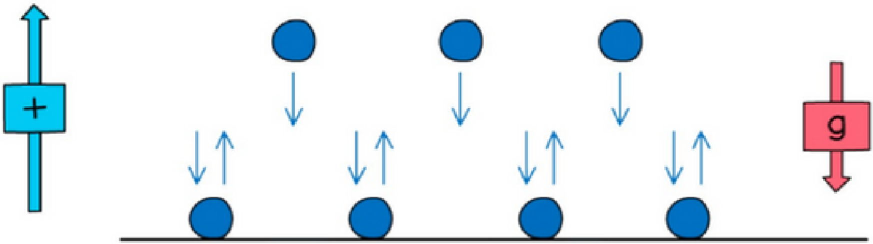
- The area under a **velocity**-time graph is the **displacement**
- The area under an **acceleration**-time graph is the **velocity**

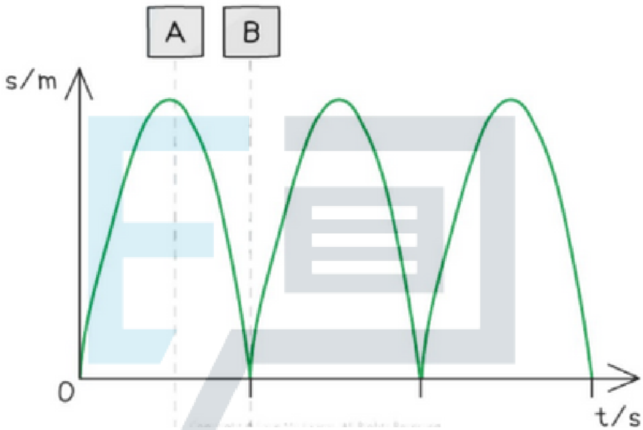


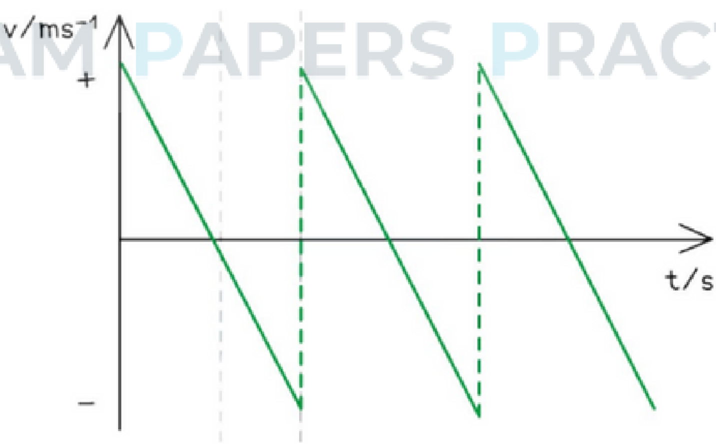
Motion of a Bouncing Ball

- For a bouncing ball, the acceleration due to gravity is **always** in the same direction (in a uniform gravitational field such as the Earth's surface)
  - This is assuming there are no other forces on the ball, such as air resistance
- Since the ball changes its direction when it reaches its highest and lowest point, the direction of the velocity will change at these points
- The vector nature of velocity means the ball will sometimes have a:
  - **Positive velocity** if it is travelling in the positive direction
  - **Negative velocity** if it is travelling in the negative direction
- An example could be a ball bouncing from the ground back upwards and back down again
  - The positive direction is taken as upwards
  - This will be either stated in the question or can be chosen, as long as the direction is consistent throughout

- Ignoring the effect of air resistance, the ball will reach the same height every time before bouncing from the ground again
- When the ball is travelling upwards, it has a positive velocity which slowly decreases (decelerates) until it reaches its highest point


+
g


A
B
s/m
0
t/s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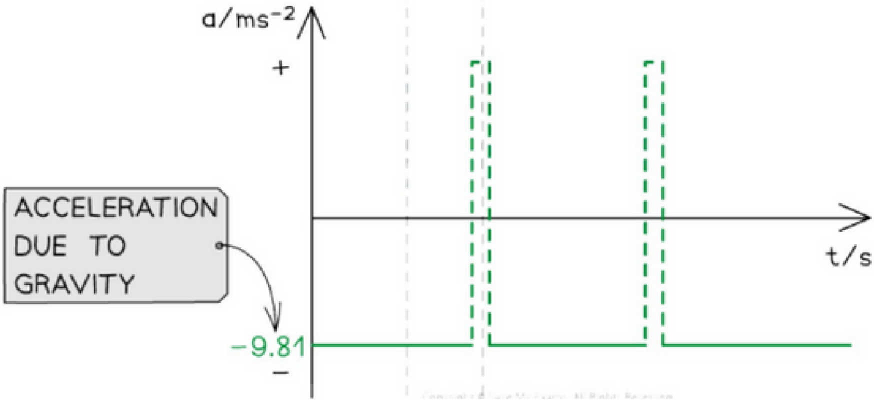
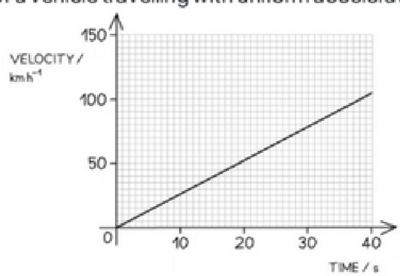
t/s



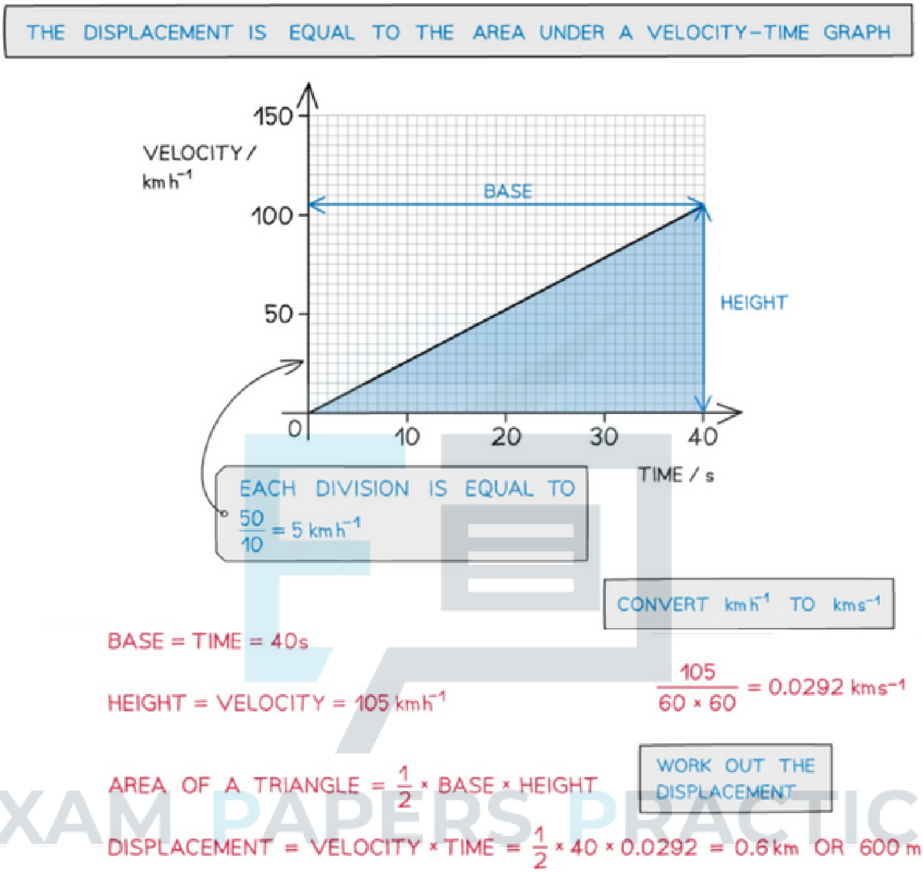
- At point **A** (the highest point):
  - The ball is at its maximum displacement
  - The ball momentarily has zero velocity
  - The velocity changes from positive to negative as the ball changes direction
  - The acceleration, *g*, is still constant and directed vertically downwards
- At point **B** (the lowest point):
  - The ball is at its minimum displacement (on the ground)
  - Its velocity changes instantaneously from negative to positive, but its speed (magnitude) **remains the same**
  - The change in direction causes a momentary acceleration (since acceleration = change in velocity / time)

Worked Example

The velocity-time graph of a vehicle travelling with uniform acceleration is shown in the diagram below.



Calculate the displacement of the vehicle at 40 s.



Exam Tip

Always check the values given on the y-axis of a motion graph - students often confuse displacement-time graphs and velocity-time graphs. The area under the graph can often be broken down into triangles, squares and rectangles, so make sure you are comfortable with calculating area!

SUVAT Equations

- The SUVAT equations are the equations of motion used for objects in constant acceleration
- They contain the following variables:
  - **s** = displacement (m)
  - **u** = initial velocity (m s^{-1})
  - **v** = final velocity (m s^{-1})
  - **a** = acceleration (m s^{-2})
  - **t** = time (s)

- The 4 SUVAT equations are:

$$v = u + at \qquad s = ut + \frac{1}{2}at^2$$

$$s = \frac{(v + u)}{2}t \qquad v^2 = u^2 + 2as$$

- These are all given on the data sheet
- All the variables, apart from **time t**, are vector quantities
  - This means they can either be positive or negative depending on their direction

- The key terms to look out for are:
  - 'Starts from rest', or if the initial velocity is not mentioned, this means ***u*** = 0
  - 'Starts from rest' means an object starts from rest at ***x*** = 0 when **t** = 0
  - If an object is only 'falling due to gravity' then ***a*** = *g* = 9.81 m s^{-2}
  - It doesn't matter which way is positive or negative for the scenario, as long as it is consistent for all the vector quantities
    - For example, if downwards is negative then for a ball travelling upwards, **s** must be positive and **a** must be negative

- SUVAT equations are used for motion with **constant acceleration** in a straight line
  - For example, an object falling in a uniform gravitational field without air resistance

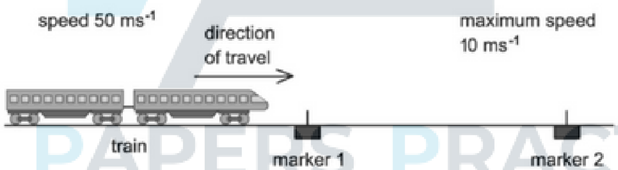
How to Use the SUVAT Equations

- **Step 1:** Write out the variables that are given in the question, both known and unknown, and use the context of the question to deduce any quantities that aren't explicitly given
  - e.g. for vertical motion $a = \pm 9.81$ m s^{-2}, an object which starts or finishes at rest will have $u = 0$ or $v = 0$
- **Step 2:** Choose the equation which contains the quantities you have listed
  - e.g. the equation that links s, u, a and t is $s = ut + ½at^2$
- **Step 3:** Convert any units to SI units and then insert the quantities into the equation and rearrange algebraically to determine the answer

- Sometimes the question may have to be split into two, where the SUVAT equations will have to be used twice
  - For example, if there are two masses connected over a pulley and one mass continues moving after the other has stopped

Worked Example

The diagram shows an arrangement to stop trains that are travelling too fast.



At marker 1, the driver must apply the brakes so that the train decelerates uniformly in order to pass marker 2 at no more than 10 m s^{-1}.

The train carries a detector that notes the times when the train passes each marker and will apply an emergency brake if the time between passing marker 1 and marker 2 is less than 20 s.

Trains coming from the left travel at a speed of 50 m s^{-1}.

Determine how far marker 1 should be placed from marker 2.

STEP 1

OUR KNOWN VARIABLES ARE

- $u = 50\ ms^{-1}$
- $v = 10\ ms^{-1}$
- $t = 20\ s$

AND WE ARE ASKED TO FIND DISTANCE, s.

STEP 2

SO THE EQUATION THAT LINKS u, v, t AND s IS

$$s = \frac{(u + v)}{2}t$$

STEP 3

NO REARRANGING IS REQUIRED SO WE SIMPLY PLUG IN THE VARIABLES:

$$s = \frac{(50 + 10)}{2} \times 20 = 30 \times 20 = 600\ m$$

Exam Tip

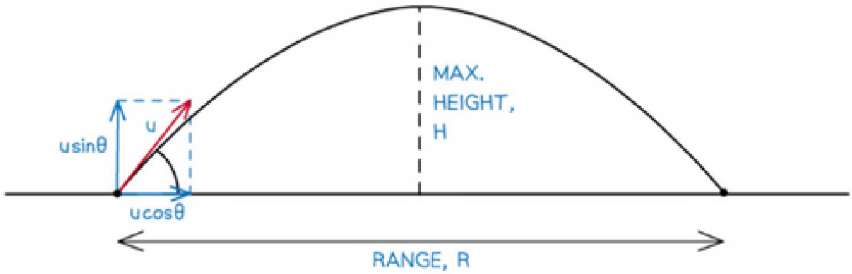
This is arguably the most important section of this topic, you can always be sure there will be one, or more, questions in the exam about solving problems with SUVAT equations

The best way to master this section is to practice as many questions as possible!

4.3.4 Projectile Motion

Projectile Motion

- The trajectory of an object undergoing projectile motion consists of a **vertical** component and a **horizontal** component
  - These need to be evaluated separately
- Some key terms to know, and how to calculate them, are:
  - **Time of flight:** how long the projectile is in the air
  - **Maximum height attained:** the height at which the projectile is momentarily at rest
  - **Range:** the horizontal distance travelled by the projectile



VERTICAL MOTION (↑)

INITIAL SPEED, $u = u\sin\theta$

ACCELERATION, $a = 9.81\ ms^{-2}$

DISPLACEMENT = 0

TIME OF FLIGHT

$u = u\sin\theta \quad v = 0 \quad a = -g \quad t = ?$

THE EQUATION THAT RELATES THESE QUANTITIES IS

$$v = u + at$$

$$0 = u\sin\theta - gt$$

$$t = \frac{u\sin\theta}{g}$$

$$2t = \frac{2u\sin\theta}{g}$$

IF THE TIME TO MAXIMUM HEIGHT IS t, THEN THE TIME OF FLIGHT IS 2t

MAXIMUM HEIGHT ATTAINED

$u = u\sin\theta \quad v = 0 \quad a = -g \quad H = ?$

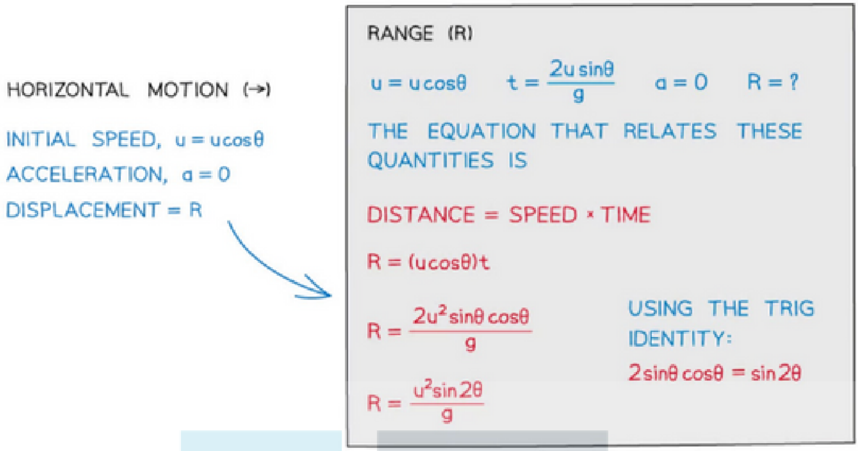
THE EQUATION THAT RELATES THESE QUANTITIES IS

$$v^2 = u^2 + 2as$$

$$0 = (u\sin\theta)^2 - 2gH$$

$$2gH = (u\sin\theta)^2$$

$$H = \frac{(u\sin\theta)^2}{2g}$$



How to find the time of flight, maximum height and range

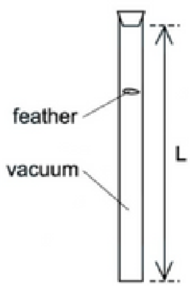
- **Remember:** the only force acting on the projectile, after it has been released, is **gravity**
- There are three possible scenarios for projectile motion:
  - **Vertical** projection
  - **Horizontal** projection
  - **Projection** at an **angle**
- Let's consider each in turn:

Worked Example

To calculate vertical projection(free fall)

A science museum designed an experiment to show the fall of a feather in a vertical glass vacuum tube.

The time of fall from rest is 0.5 s.



What it the length of the tube, L?

IN THIS PROBLEM, WE ONLY NEED TO CONSIDER VERTICAL MOTION. FIRST WE MUST LIST THE KNOWN VARIABLES.

$a = 9.81\ ms^{-2}$ $\quad u = 0$ $\quad t = 0.5\ s$ $\quad L = ?$

THE EQUATION THAT LINKS THESE VARIABLES IS

$$s = ut + \frac{1}{2}at^2$$

$$L = \frac{1}{2}gt^2$$

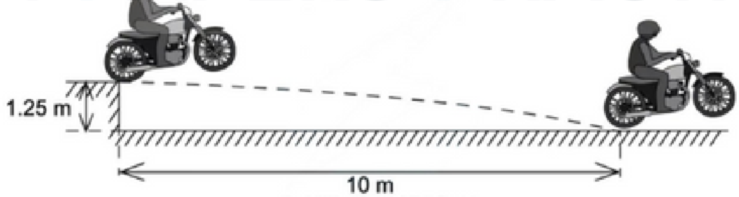
$$L = \frac{1}{2} \times 9.81 \times 0.5^2 = 1.2\ m$$

Worked Example

To calculate horizontal projection

A motorcycle stunt-rider moving horizontally takes off from a point 1.25 m above the ground, landing 10 m away as shown.

What was the speed at take-off?



IN THIS PROBLEM, WE NEED TO CONSIDER BOTH VERTICAL AND HORIZONTAL MOTION. LET'S CONSIDER THE VERTICAL MOTION FIRST. THE KNOWN VARIABLES ARE

$s = 1.25$ m $a = 9.81$ ms^{-2} $u = 0$ $t = ?$

THE EQUATION THAT LINKS THESE VARIABLES IS

$$s = ut + \frac{1}{2}at^2$$

$$s = \frac{1}{2}gt^2$$

$$t = \sqrt{\frac{2s}{g}}$$

$$t = \sqrt{\frac{2 \times 1.25}{9.81}} = 0.5\text{s}$$

NEXT LET'S CONSIDER THE HORIZONTAL MOTION. THE KNOWN VARIABLES ARE

$s = 10$ m $a = 0$ $t = 0.5$ s $u = ?$

SINCE THE ACCELERATION IS ZERO, WE CAN USE

$$\text{VELOCITY} = \frac{\text{DISPLACEMENT}}{\text{TIME}}$$

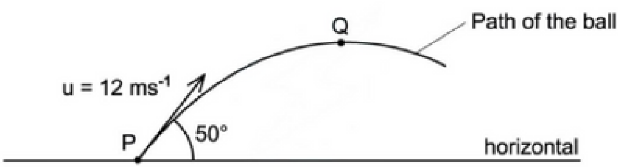
$$v = \frac{10}{0.5} = 20 \text{ ms}^{-1}$$

Worked Example

To calculate projection at an angle

A ball is thrown from a point P with an initial velocity u of 12 m s^{-1} at 50° to the horizontal.

What is the value of the maximum height at Q?



IN THIS PROBLEM, WE ONLY NEED TO CONSIDER VERTICAL MOTION UP TO THE POINT Q. FIRST WE MUST LIST THE KNOWN VARIABLES

$u = 12\sin(50)$ $a = -9.81\ ms^{-2}$ $v = 0$ $H = ?$

THE EQUATION THAT LINKS THESE VARIABLES IS

$$v^2 = u^2 + 2as$$

$$2as = v^2 - u^2$$

$$s = \frac{(v^2 - u^2)}{2a}$$

$$H = \frac{0 - (12\sin 50)^2}{2 \times (-9.81)}$$

$$H = \frac{(12\sin 50)^2}{19.62} = 4.3\ m$$

Exam Tip

Make sure you don't make these common mistakes:

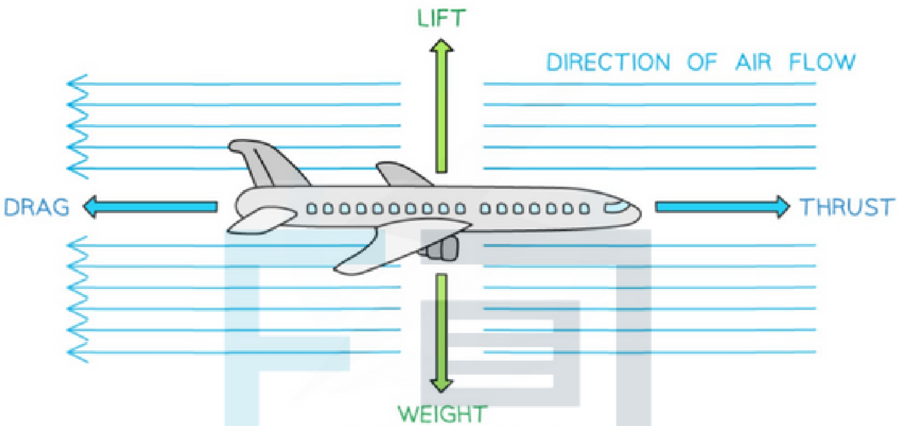
- Forgetting that deceleration is negative as the object rises
- Confusing the direction of $\sin\theta$ and $\cos\theta$
- Not converting units (mm, cm, km etc.) to metres

4.3.5 Drag Forces

Drag Forces

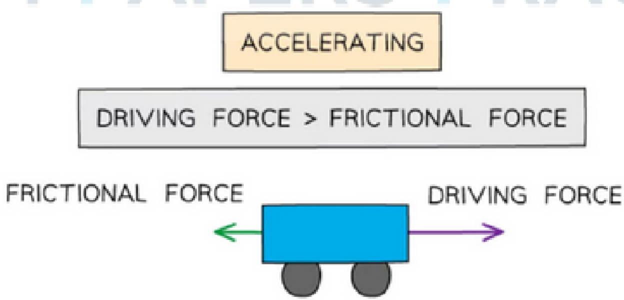
- Drag forces are forces that oppose the motion of an object moving through a fluid (gas or liquid)
- Examples of drag forces are **friction** and **air resistance**
- Drags forces:
  - Are always in the **opposite** direction to the motion of the object
  - Never speed an object up or start them moving
  - Slow down an object or keeps them moving at a constant speed
  - Convert kinetic energy into heat and sound

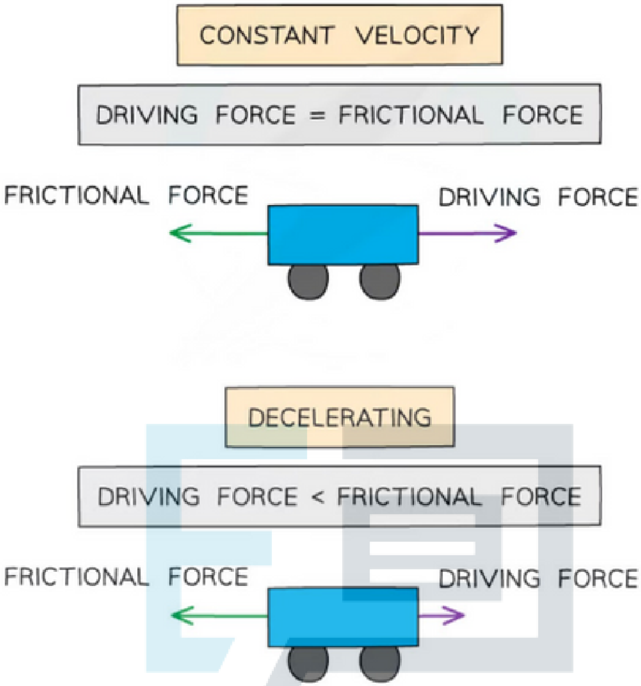
- Lift is an upwards force on an object moving through a fluid. It is perpendicular to the fluid flow
  - For example, as an aeroplane moves through the air, it pushes down on the air to change its direction
  - This causes an equal and opposite reaction upwards on the wings (lift) due to Newton's third law



Drag forces are always in the opposite direction to the thrust (direction of motion). Lift is always in the opposite direction to the weight

- A key component of drag forces is it increases with the speed of the object
- This is shown in the diagram below:





Frictional forces on a car increase with speed

Worked Example

A car of mass 800 kg has a horizontal driving force of 3 kN acting on it.Its acceleration is 2.0 m s^{-2}.What is the frictional force acting on the car?

STEP 1

CALCULATE THE RESULTANT FORCE FROM NEWTON'S SECOND LAW

$F = ma = 800 \times 2.0 = 1600$ N

1600 N = DRIVING FORCE − FRICTIONAL FORCE

1600 = 3000 − FRICTIONAL FORCE

STEP 2

REARRANGE FOR THE FRICTIONAL FORCE

FRICTIONAL FORCE = 3000 N − 1600 N = 1400 N

Air Resistance

- Air resistance is an example of a drag force that objects experience when moving through the air
    - At a walking pace, a person rarely experiences the effects of air resistance
- However, a person swimming at the same pace uses up much more energy - this is because air is 800 times **less dense** than water
- Air resistance **increases with the speed** of an object, such as a vehicle
- However, there are other factors that also affect the maximum speed, such as:
    - Cross-sectional area
    - Shape
    - Altitude
    - Temperature
    - Humidity

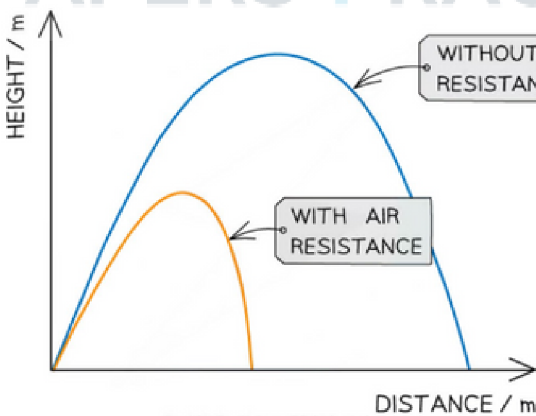
- Air resistance must be carefully considered in vehicle design, for example in racing cars, bicycles and aeroplanes:
- Racing cars have a streamlined design with a curve, angled front to experience less air resistance and travel faster
- Aeroplanes travel at high altitudes where there is less air resistance (since the air is less dense)
    - However, they also travel through a variety of extreme temperatures and at very high speeds
    - Therefore, aeroplane design is focused on producing the fastest, but also smoothest, journey possible

- A racing cyclist adopts a more streamlined posture to reduce the effects of air resistance
  - Also, the bicycle, clothing and helmet are designed to allow them to go as fast as possible

Many factors such as posture, clothes and bicycle shape must be considered when trying to reduce air resistance

Air Resistance & Projectile Motion

- Air resistance decreases the **horizontal** component of the velocity of a projectile
  - This means both its range and maximum height is decreased compared to no air resistance



A projectile with air resistance travels a smaller distance and has a lower maximum height than one without air resistance

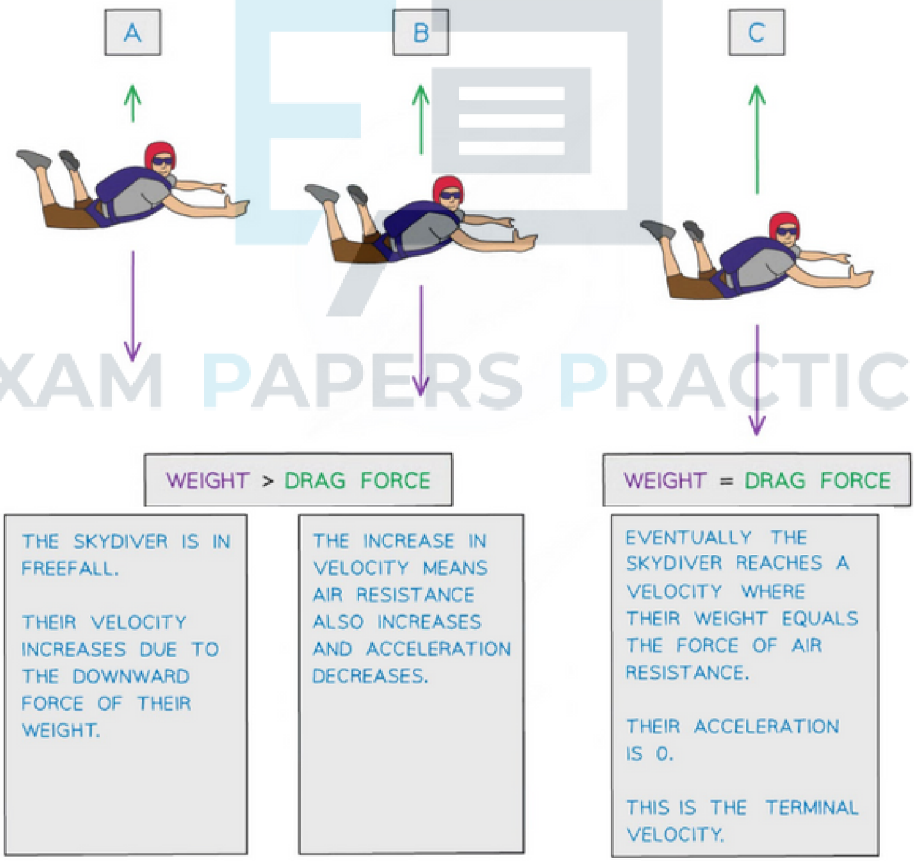
- The angle and speed of release of a projectile is varied to produce either a longer flight path or cover a larger distance, depending on the situation
  - For sports such as the long jump or javelin, an optimum angle against air resistance is used to produce the greatest distance
  - For gymnastics or a ski jumper, the initial vertical velocity is made as large as possible to reach a greater height and longer flight path
- The perfect angle and speed for a projectile can be difficult to achieve
  - For example, a footballer tries to kick a ball as high as possible but also with great speed to score a goal from a long distance

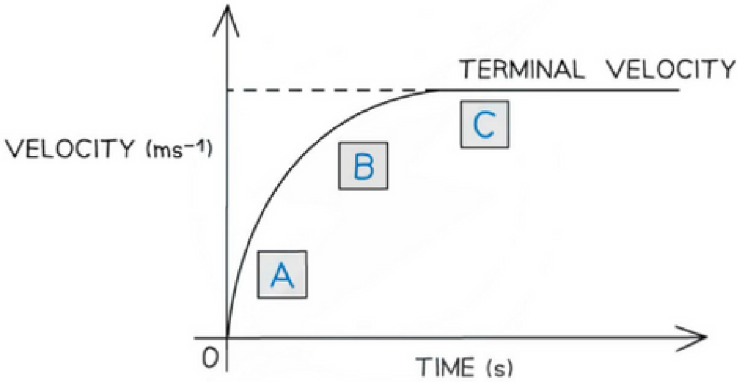
Exam Tip

If a question considers air resistance to be '**negligible**' this means in that question, air resistance is taken to be so small it will not make a difference to the motion of the body. You can take this to mean there are no drag forces acting on the body.

Terminal Velocity

- For a body in free fall, the only force acting is its weight and its acceleration *g* is only due to gravity.
- The drag force increases as the body accelerates
  - This increase in velocity means the drag force also increases
- Due to Newton's Second Law, this means the resultant force and therefore acceleration decreases (recall ***F* = *ma***)
- When the drag force is equal to the gravitational pull on the body, the body will no longer accelerate and will fall at a constant velocity
  - This the **maximum** velocity that the object can have and is called the **terminal velocity**





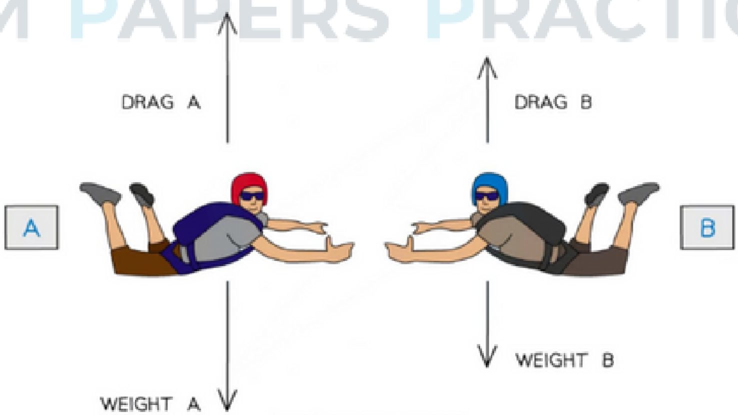
A skydiver in freefall reaching terminal velocity

- The graph shows how the velocity of the skydiver varies with time
- Since the acceleration is equal to the gradient of a velocity-time graph, the acceleration decreases and eventually becomes zero when terminal velocity is reached

Worked Example

Skydivers jump out of a plane at intervals of a few seconds.

Skydivers A and B want to join up as they fall.



If A is heavier than B, who should jump first?

- Skydiver **B** should jump first since he will have a lower terminal velocity
- This is because skydiver **A** has a greater mass, and hence, weight
- Terminal velocity is reached when weight is equal to air resistance
- Therefore, a higher terminal velocity means that skydiver **A** will have a greater speed, and will reach terminal velocity faster than skydiver **B**

Exam Tip

- Exam questions about terminal velocity tend to involve the motion of skydivers as they fall
- A common misconception is that skydivers move upwards when their parachutes are deployed - however, this is not the case, they are in fact **decelerating** to a lower terminal velocity
- What do you think this would look like on the graph above?

4.3.7 Required Practical: Determination of g

Required Practical: Determination of g

Aims of the Experiment

- The overall aim of the experiment is to calculate the value of the acceleration due to gravity, *g*
- This is done by measuring the time it takes for a ball-bearing to fall a certain distance. The acceleration is then calculated using an equation of motion

Variables

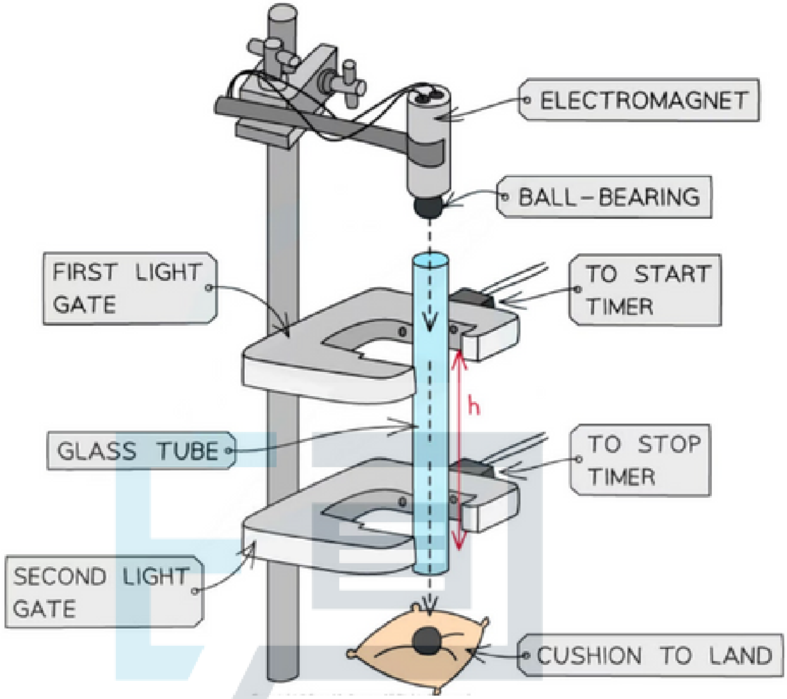
- Independent variable = height, *h*
- Dependent variable = time, *t*
- Control variables:
  - Same steel ball-bearing
  - Same electromagnet
  - Distance between ball-bearing and top of the glass tube

Equipment List

Equipment	Purpose
Metre ruler	To measure the distance between the light gates
Steel ball–bearing	To measure the distance and time taken to drop. The ball must be made from a magnetic material (iron, steel etc.)
Electromagnet	To drop the ball–bearing through the glass tube at specific height every time
Two light gates	To determine the time taken to drop a certain distance
Timer	To measure the time taken for the ball to drop between the light–gates. The timer must be activated to start when the ball passes the first light gate and stop when it passes the second
Tall clamp stand (retort stand)	To hold the glass tube and electromagnet in line with each other
Glass tube	To guide the ball–bearing vertically downwards
Cushion	To stop the ball–bearing from being damaged or damaging the surface when landing

- Resolution of measuring equipment:
  - Metre ruler = 1 mm
  - Timer = 0.01 s

Method



Apparatus set up to measure the distance and time for the ball bearing to drop

This method is an example of the procedure for varying the height the ball-bearing falls and determining the time taken – this is just one possible relationship that can be tested

1. Set up the apparatus by attaching the electromagnet to the top of a tall clamp stand. Do not switch on the current till everything is set up
2. Place the glass tube directly underneath the electromagnet, leaving space for the ball-bearing. Make sure it faces directly downwards and not at an angle
3. Attach both light gates around the glass tube at a starting distance of around 10 cm
4. Measure this distance between the two light gates as the height, *h* with a metre ruler
5. Place the cushion directly underneath the end of the glass tube to catch the ball-bearing when it falls through
6. Switch the current on the electromagnet and place the ball-bearing directly underneath so it is attracted to it

7. Turn the current to the electromagnet off. The ball should drop
8. When the ball drops through the first light gate, the timer starts
9. When the ball drops through the second light gate, the timer stops
10. Read the time on the timer and record this as time, *t*
11. Increase *h* (eg. by 5 cm) and repeat the experiment. At least 5 – 10 values for *h* should be used
12. Repeat this method at least 3 times for each value of *h* and calculate an average *t* for each

- An example of a table with some possible heights would look like this:

Example Table of Results

HEIGHT h/m	TIME t_1/s	TIME t_2/s	TIME t_3/s	AVERAGE TIME t/s
0.10				
0.15				
0.20				
0.25				
0.30				
0.35				

Analysis of Results

- The acceleration is found by using one of the SUVAT equations
- The known quantities are
  - Displacement $s = h$
  - Time taken = t
  - Initial velocity $u = u$
  - Acceleration $a = g$

- The following SUVAT equation can be rearranged:

$$s = ut + \frac{1}{2}at^2$$

$$2s = 2ut + at^2$$

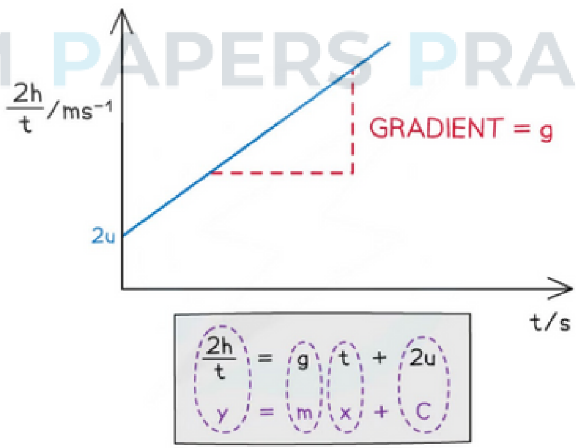
$$\frac{2s}{t} = 2u + at$$

- Substituting in the values and rearranging it as a straight line equation gives:

$$\frac{2h}{t} = gt + 2u$$

- Comparing this to the equation of a straight line: $y = mx + c$
  - $y = 2h/t$ ($m\ s^{-1}$)
  - $x = t$
  - Gradient, $m = a = g$ ($m\ s^{-2}$)
  - y-intercept = $2u$

1. Plot a graph of the $2h/t$ against t
2. Draw a line of best fit
3. Calculate the gradient - this is the acceleration due to gravity g
4. Assess the uncertainties in the measurements of h and t. Carry out any calculations needed to determine the uncertainty in g due to these



The graph of 2h/t against t produces a straight-line graph where the acceleration is the gradient

Evaluating the Experiment

Systematic Errors:

- Residue magnetism after the electromagnet is switched off may cause *t* to be recorded as longer than it should be

Random Errors:

- Large uncertainty in *h* from using a metre rule with a precision of 1 mm
- Parallax error from reading *h*
- The ball may not fall accurately down the centre of each light gate
- Random errors are reduced through repeating the experiment for each value of *h* at least 3–5 times and finding an average time, *t*

Safety Considerations

- The electromagnetic requires current
  - Care must be taken to not have any water near it
  - To reduce the risk of electrocution, only switch on the current to the electromagnet once everything is set up
- A cushion or a soft surface must be used to catch the ball-bearing so it doesn't roll off / damage the surface
- The tall clamp stand needs to be attached to a surface with a G clamp so it stays rigid

Worked Example

A student investigates the relationship between the height that a ball-bearing is dropped between two light gates and the time taken for it to drop.

Height h/m	Time t_1/s	Time t_2/s	Time t_3/s	Average time t/s
0.10	0.14	0.15	0.14	
0.20	0.18	0.20	0.21	
0.30	0.25	0.25	0.26	
0.40	0.29	0.28	0.30	
0.50	0.32	0.31	0.32	
0.60	0.34	0.35	0.34	

Calculate the value of g from the table.

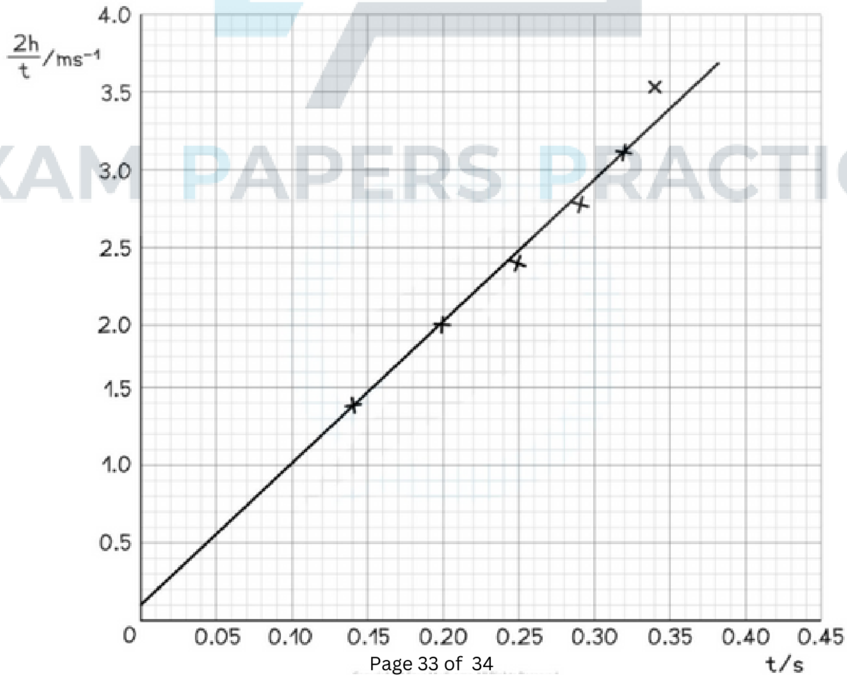
Step 1: Complete the table

Calculate the average time for each height

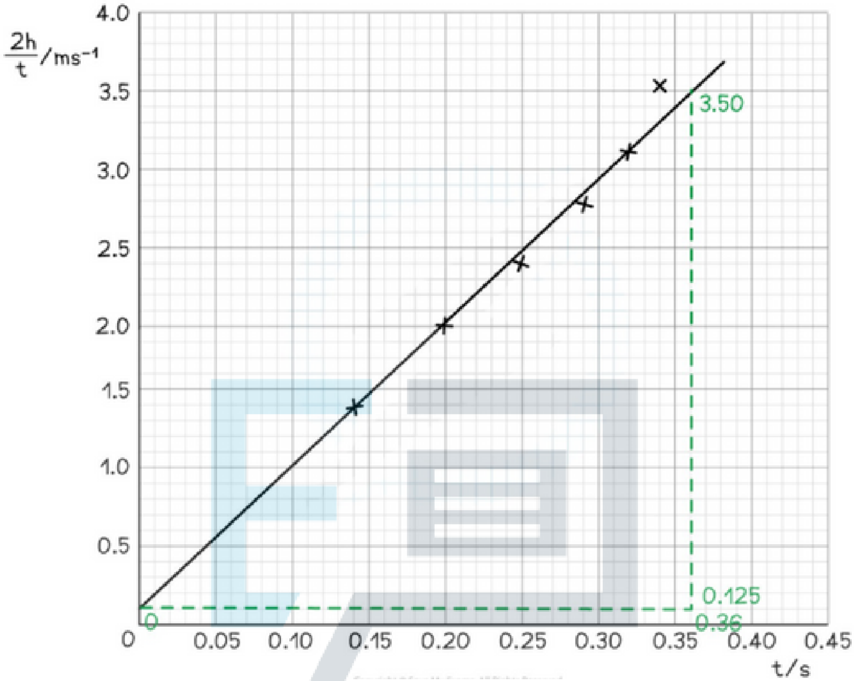
Add an extra column 2h / t

Height h/m	Time t_1/s	Time t_2/s	Time t_3/s	Average time t/s	$\frac{2h}{t}$ /ms^{-1}
0.10	0.14	0.15	0.14	0.14	1.43
0.20	0.18	0.20	0.21	0.20	2.00
0.30	0.25	0.25	0.26	0.25	2.40
0.40	0.29	0.28	0.30	0.29	2.76
0.50	0.32	0.31	0.32	0.32	3.13
0.60	0.34	0.35	0.34	0.34	3.53

Step 2: Draw graph of 2h/t against time t



Step 3: Calculate the gradient of the graph



The gradient is calculated by:

$$g = \frac{3.50 - 0.125}{0.36 - 0} = 9.375 = \mathbf{9.38\ m\ s^{-2}}$$