Cambridge (CIE) IGCSE Physics

Your notes

Motion

Contents

Speed

- The **speed** of an object is defined as

Distance travelled per unit time

- Speed is a **scalar** quantity
  - This is because it only contains a **magnitude** (without a direction)
- For objects that are moving at a **constant speed**, the equation for calculating speed is:

$$v = \frac{s}{t}$$

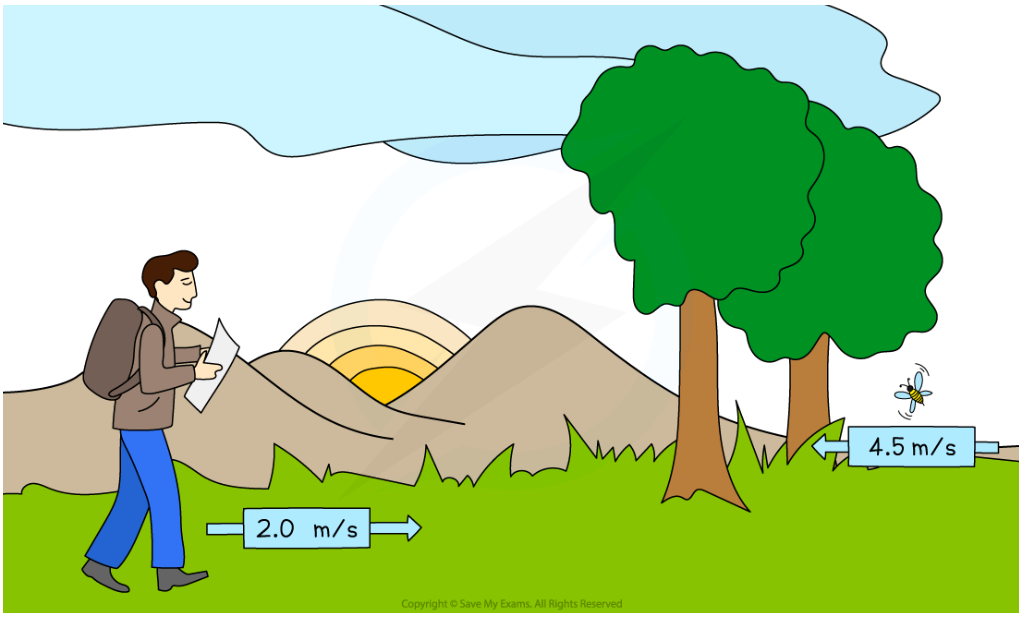
- Where:
  - v = speed, measured in metres per second (m/s)
  - s = distance travelled, measured in metres (m)
  - t = time, measured in seconds (s)

Average speed

- The **speed** of an object can **vary** throughout its journey
- Therefore, it is often more useful to know an object's **average speed**

Examples of average speeds

- Average walking speed = 1.5 m/s
- Average running speed = 3 m/s
- Average cycling speed = 6 m/s

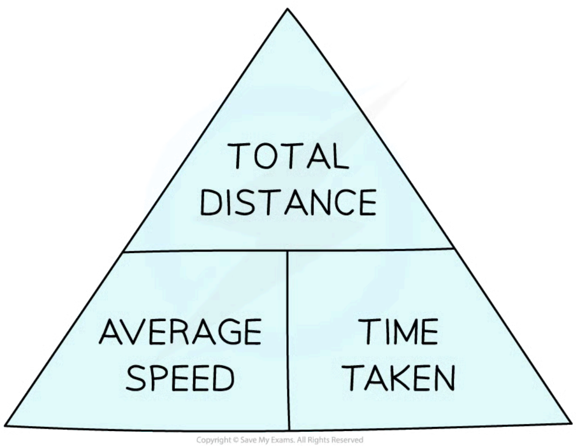


A hiker might have an average speed of 2.0 m/s, whereas a particularly excited bumble bee can have average speeds of up to 4.5 m/s

- A car travels at different instantaneous speeds throughout its journey
  - The car speeds up and slows down
  - The car may stop at junctions and traffic lights
- The average speed of the journey of the car can be found by dividing the total distance travelled by the total time taken
- The equation for calculating the **average speed** of an object is:

$$\text{Average speed} = \frac{\text{distance travelled}}{\text{time taken}}$$

- **Average speed** considers the **total distance travelled** and the **total time taken**



Your notes

Formula triangle for average speed, distance moved and time taken

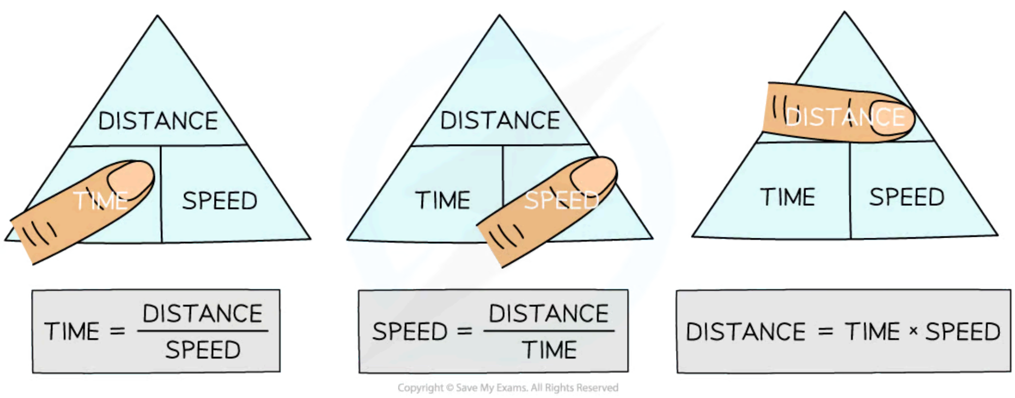
How to use formula triangles

- Formula triangles are really useful for knowing how to rearrange physics equations
- To use them:

1. Cover up the quantity to be calculated, this is known as the 'subject' of the equation
2. Look at the position of the other two quantities
    - If they are on the same line, this means they are **multiplied**
    - If one quantity is above the other, this means they are **divided** - make sure to keep the order of which is on the top and bottom of the fraction!

- In the example below, to calculate average speed, cover-up the variable speed so that only distance and time are left
    - The equation is revealed as:

$$speed = \frac{distance}{time}$$



To use a formula triangle, simply cover up the quantity you wish calculate and the structure of the equation is revealed

Worked Example

Planes fly at typical average speeds of around 250 m/s.

Calculate the distance travelled by a plane moving at this average speed for 2 hours.

Answer:

Step 1: List the known quantities

- Average speed = 250 m/s

Your notes

- Time taken = 2 hours

Step 2: Write the relevant equation

$$\text{average speed} = \frac{\text{distance travelled}}{\text{time taken}}$$

Step 3: Rearrange to make distance moved the subject

$$\text{distance travelled} = \text{average speed} \times \text{time taken}$$

Step 4: Convert any units

- The time given in the question is not in standard units
- Convert 2 hours into seconds:

$$2 \text{ hours} = 2 \times 60 \times 60$$

$$2 \text{ hours} = 7200 \text{ s}$$

Step 5: Substitute the values for average speed and time taken

$$\text{distance travelled} = 250 \times 7200$$

$$\text{distance travelled} = 1\ 800\ 000 \text{ m}$$

Examiner Tips and Tricks

Rearranging equations is an important skill in Physics. You can use the equation triangles to help you practice, but it is better not to rely on them because they do not work for all equations you may need to rearrange in the exam.

Velocity

- **Velocity** is a vector quantity with magnitude and direction
- Velocity is defined as:

Speed in a given direction

- The direction of a velocity can be given in **words**
  - For example, 20 m/s east
- Or the direction of velocity can be given using a **positive** or **negative value**
  - For example, –20 m/s
- A positive direction is typically in the direction of the initial motion, to the right, or upward
- A negative velocity is typically in the opposite direction to the initial velocity, to the left, or downward

Comparing speed and velocity

Your notes

The cars in the diagram above have the same speed (a scalar quantity) but different velocities (a vector quantity). Fear not, they are in different lanes!

Examiner Tips and Tricks

The positive and negative values of velocity can be assigned to any direction as long as the negative velocity is in the opposite direction to the positive value. You can decide which direction you assign to be positive as long as you are consistent throughout a question.

- The equation for velocity is very similar to the equation for speed:

$$v = \frac{s}{t}$$

- Where:
  - v = velocity in metres per second (m/s)
  - s = displacement, measured in metres (m)
  - t = time, measured in seconds (s)
- Velocity is a vector quantity, so it uses displacement, s, which is another vector quantity

Your notes

Your notes

Acceleration

Extender tier only

- **Acceleration** describes how the **velocity** of an object changes over **time**
- Acceleration is defined as:

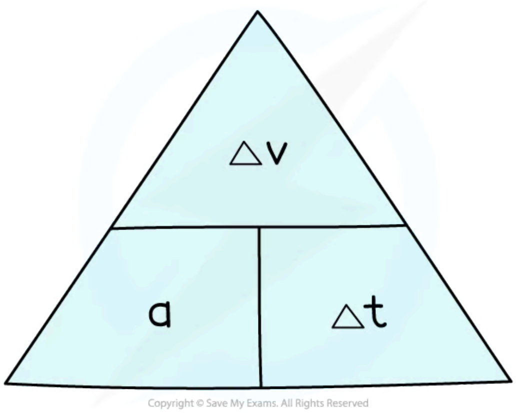
The rate of change of velocity

- In other words, acceleration is the change in velocity per unit time
- The acceleration of an object is often changing throughout an object's journey
- Therefore, is it often useful to know the **average acceleration**

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

- Where:
  - a = acceleration in metres per second squared (m/s^2)
  - Δv = change in velocity in metres per second (m/s)
  - Δt = time taken in seconds (s)

Formula triangle for acceleration, change in velocity and change in time



To use a formula triangle, simply cover up the quantity you wish calculate and the structure of the equation is revealed

- Information on how to use a formula triangle can be found in Speed & velocity

Change in velocity

Your notes

- The **change in velocity** is the **difference** between the initial and final velocity:

$$\Delta v = v - u$$

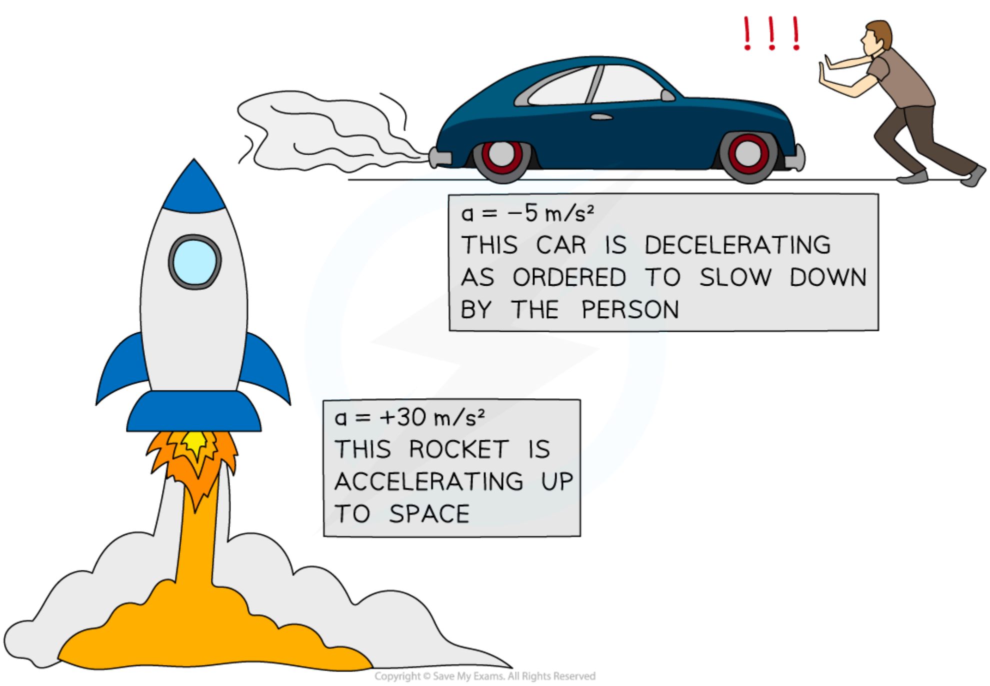
- Where:
  - Δv = change in velocity in metres per second (m/s)
  - v = final velocity in metres per second (m/s)
  - u = initial velocity in metres per second (m/s)

Speeding up & slowing down

- An object can change its velocity in several ways:
  - speeding up
  - slowing down
  - changing direction
- Any change in an object's velocity is an **acceleration**
- When an object speeds up, it is **accelerating**
  - This is **positive acceleration**
- When an object slows down, it is **decelerating**
  - This is **negative acceleration**
- Acceleration is positive if its direction is in the **same direction** as the motion of the object

Acceleration of different objects

Your notes



A rocket speeding up (accelerating) and a car slowing down (decelerating)

Worked Example

A Japanese bullet train decelerates at a constant rate in a straight line. The velocity of the train decreases from 50 m/s to 42 m/s in 30 seconds.

(a) Calculate the change in velocity of the train.

(b) Calculate the deceleration of the train, and explain how your answer shows the train is slowing down.

Answer:

Part (a)

Step 1: List the known quantities

- Initial velocity, $u = 50 \text{ m/s}$
- Final velocity, $v = 42 \text{ m/s}$

Step 2: Write the equation for change in velocity

$$\Delta v = v - u$$

Step 3: Substitute values for final and initial velocity

$$\Delta v = 42 - 50$$

$$\Delta v = -8 \text{ m/s}$$

Your notes

Part (b)

Step 1: List the known quantities

- Change in velocity, $\Delta v = -8 \text{ m/s}$
- Time taken, $\Delta t = 30 \text{ s}$

Step 2: Write the equation for acceleration

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

Step 3: Substitute the values for change in velocity and time

$$a = \frac{-8}{30}$$

$$a = -0.27 \text{ m/s}^2$$

Step 4: Interpret the value for deceleration

- The answer is **negative**, which indicates the train is **slowing down**

Examiner Tips and Tricks

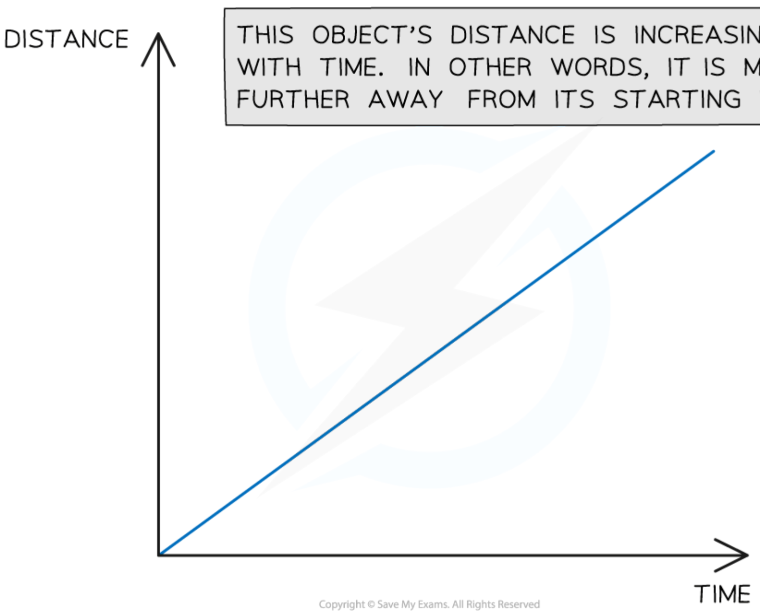
Remember, the units for acceleration are **metres per second squared**, m/s^2. In other words, acceleration measures how much the velocity (m/s) changes every second, so the units are metres per second per second (m/s/s).

Your notes

Distance-time graphs

- A **distance-time graph** is used to describe the motion of an object and calculate its speed

Distance-time graph of an object moving at a constant speed

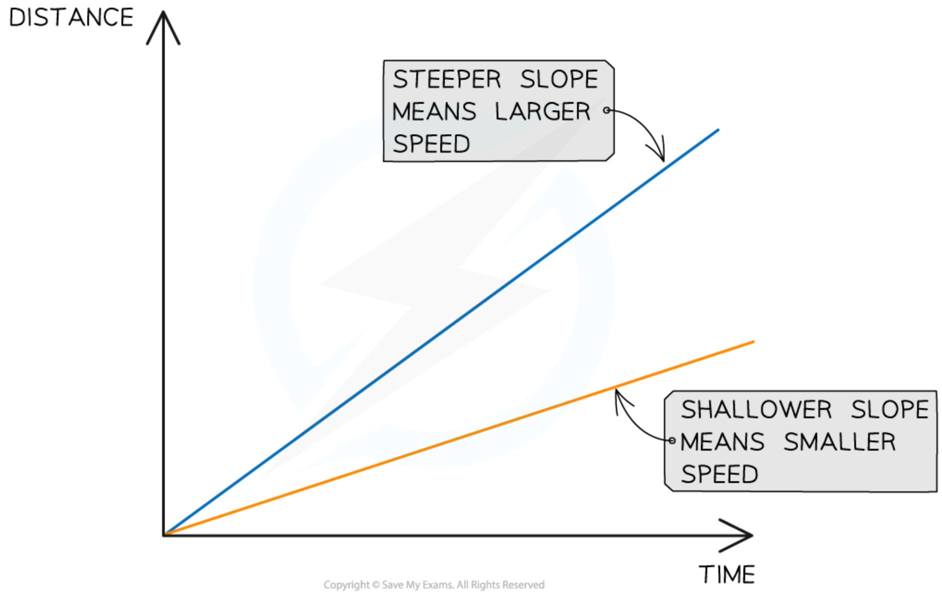


The graph shows a moving object moving further away from its origin at a constant speed

Constant speed on a distance-time graph

- If an object is moving at a **constant speed**, the distance-time graph will be a **straight line**
  - If the constant speed is **zero**, the line will be **horizontal**
  - If the constant speed is **non-zero**, the line will have a **gradient**
- If an object has a speed of zero, the object is **stationary**
  - The distance moved by the object over time is zero
- The **gradient** of a distance-time graph represents the **magnitude** of the object's **velocity**, or its **speed**
  - A **steeper slope**, or a higher gradient, represents a **greater speed**
  - A **shallower slope**, or a lower gradient, represents a **slower speed**

Different speeds on a distance-time graph



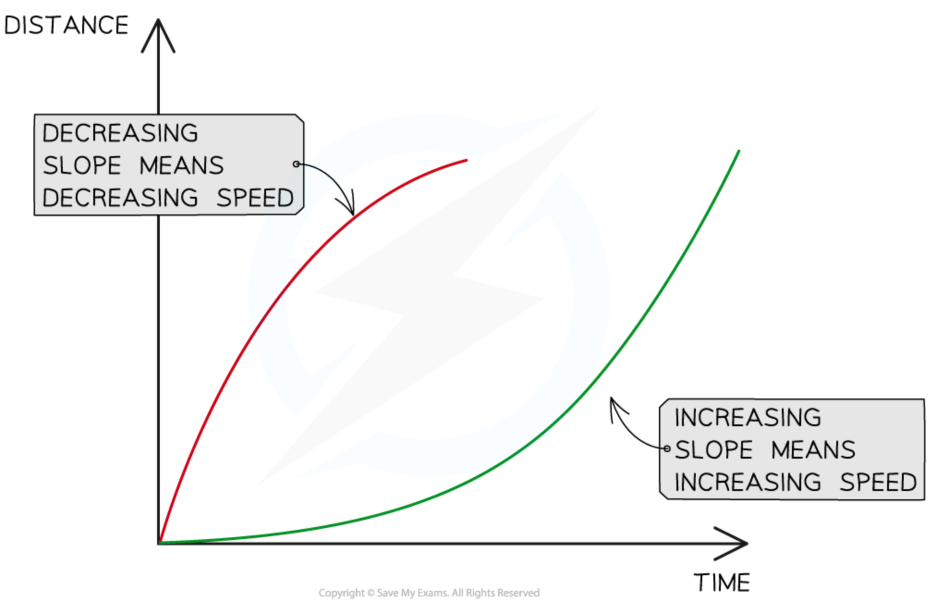
Both of these objects are moving at a constant speed, because the lines are straight. The steeper slope represents the faster speed and the shallower line represents the slower speed.

Changing speed on a distance–time graph

- Often, the speed of an object is **not constant**
- If the speed of an object is **changing**, the object is **accelerating**
- If an object is **accelerating**, the distance-time graph will be a **curved line**
- A **curve** on a distance-time graph is a **changing gradient**
  - If the **gradient increases** over time, the **speed is increasing** over time
  - If the **gradient decreases** over time, the **speed is decreasing** over time

Speed of an object increasing and decreasing on a distance–time graph

Your notes

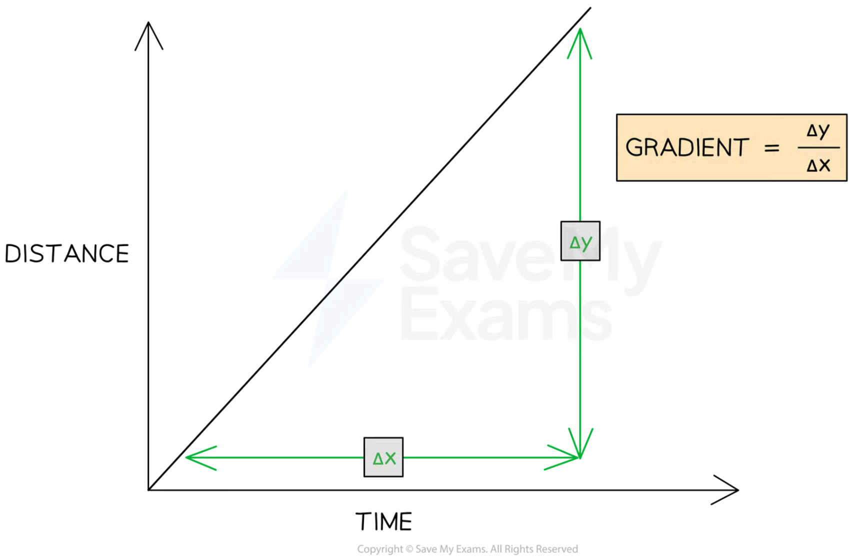


Changing speeds are represented by changing slopes, or gradients. The red line shows a decreasing gradient and represents an object slowing down, or decelerating. The green line shows an increasing gradient and represents an object speeding up, or accelerating.

Using distance–time graphs

- The **speed** of a moving object can be calculated from the **gradient** of the line on a **distance–time** graph:

$$\text{speed} = \text{gradient} = \frac{\Delta y}{\Delta x}$$



The speed of an object can be found by calculating the gradient of a distance–time graph

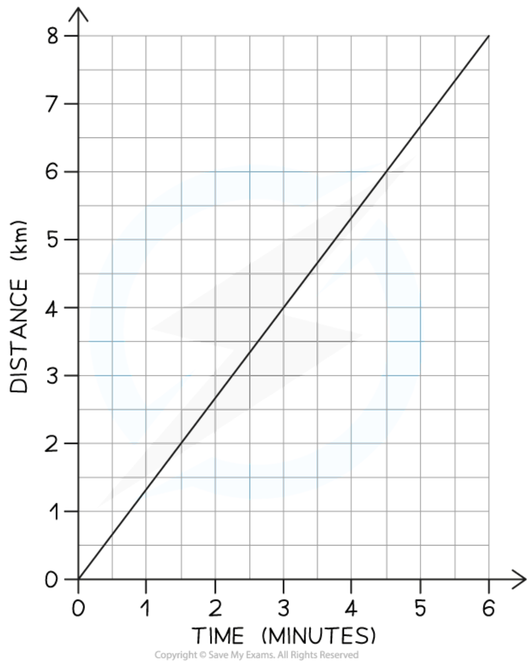
Your notes

- Δy is the **change** in y (distance) values
- Δx is the **change** in x (time) values

Your notes

Worked Example

A distance-time graph is drawn below for part of a train journey. The train is travelling at a constant speed.

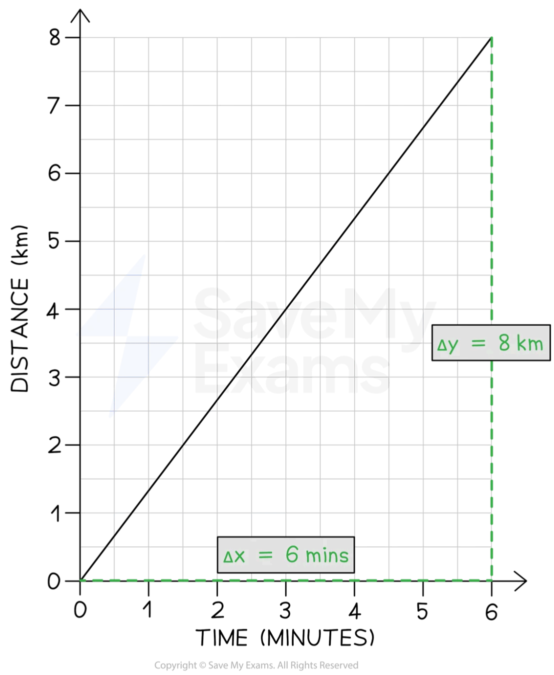


Calculate the speed of the train.

Answer:

Step 1: Draw a large gradient triangle on the graph

- The image below shows a large **gradient triangle** drawn with dashed lines
- Δy and Δx are labelled, using the **units** as stated on each axes



Step 2: Convert units for distance and time into standard units

- The distance travelled, $s = 8 \text{ km} \times 1000 \text{ m} = 8000 \text{ m}$
- The time taken, $t = 6 \text{ min} \times 60 \text{ s} = 360 \text{ s}$

Step 3: State that speed is equal to the gradient of a distance-time graph

- The **gradient** of a **distance-time** graph is equal to the **speed** of a moving object:

$$\text{gradient} = v = \frac{\Delta y}{\Delta x} = \frac{s}{t}$$

Step 4: Substitute values to calculate the speed

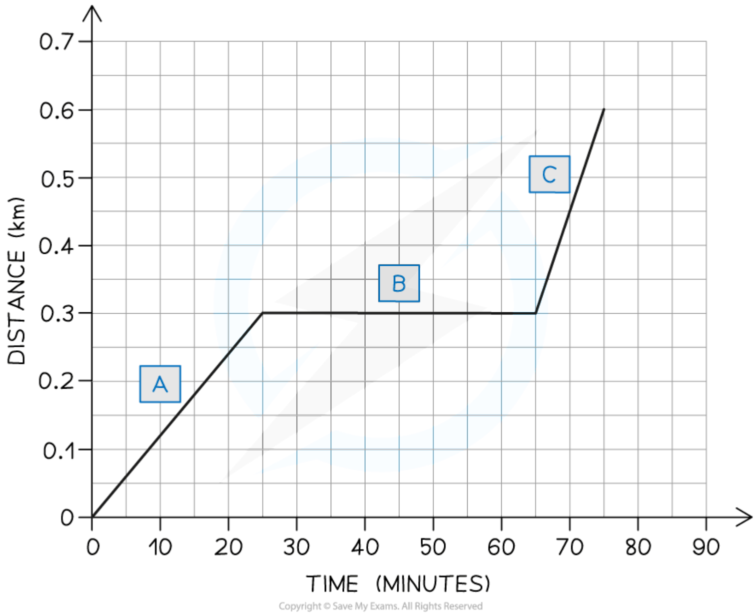
$$v = \frac{8000}{360}$$

$$v = 22.2 \text{ m/s}$$

Worked Example

A student decides to take a stroll to the park. They find a bench in a quiet spot, take a seat, and read a book on black holes. After some time reading, the student realises they lost track of time and runs home.

A distance-time graph for the trip is drawn below.



(a) How long does the student spend reading the book?

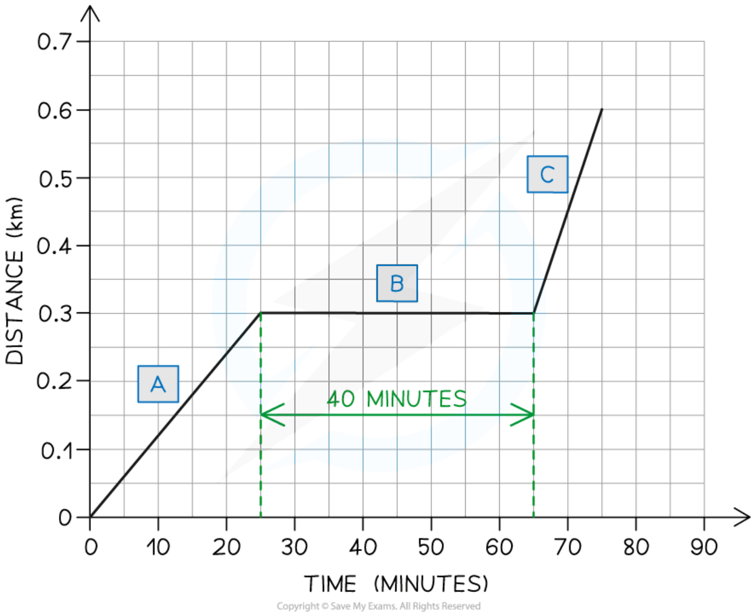
(b) Which section of the graph represents the student running home?

(c) What is the total distance travelled by the student?

Answer:

Part (a)

- The student spends **40 minutes** reading his book
- The **flat** section of the line (section B) represents an object which is **stationary**, so section B represents the student sitting on the bench reading
- This section lasts for **40 minutes**

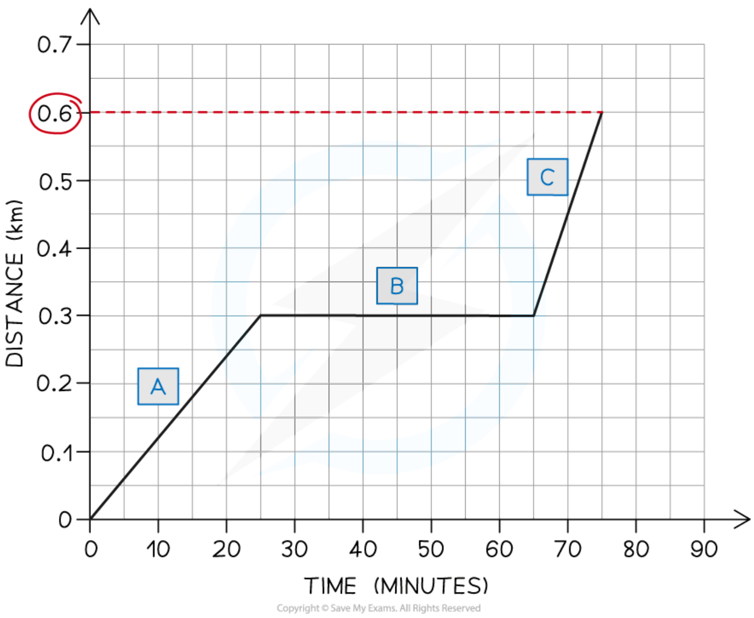


Part (b)

- **Section C** represents the student running home
- The **slope** of the line in section C is **steeper** than the slope in section A
- This means the student was moving at a **faster** speed (running) in section C

Part (c)

- The total distance travelled by the student is **0.6 km**
- The total **distance** travelled by an object is given by the final point on the line; in this case, the line ends at **0.6 km** on the **distance** axis



Your notes

Your notes

Examiner Tips and Tricks

When calculating a gradient, use the **entire line** where possible. Examiners tend to award credit if they see a **large gradient triangle** used, so you need to actually draw the lines directly on the graph itself!

Remember to check the **units** on each axis. These may not always be in standard units; in our example, the unit of distance was **km** and the unit of time was **minutes**. Double-check which units to use in your answer.

You could also be asked to plot a distance time graph from data given to you in a question, or be asked to describe the motion of an object from the data given.

You can read more about the use of graphs in exams in the article Graph skills for GCSE Physics

Your notes

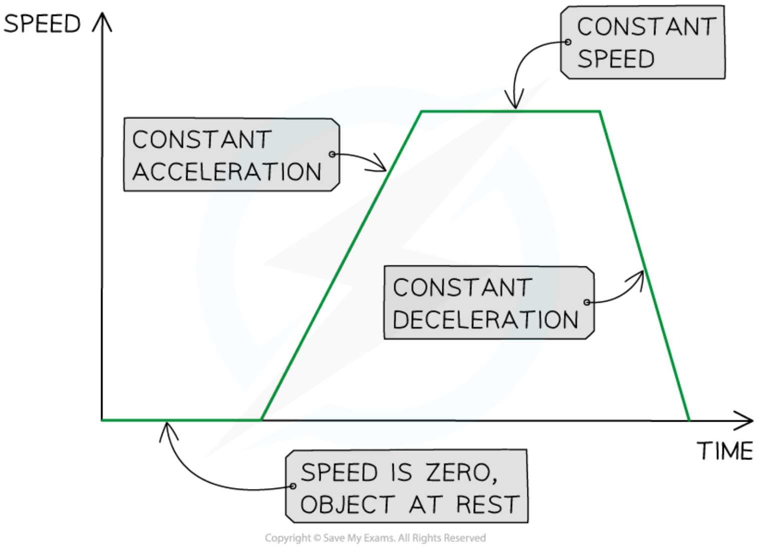
Speed-time graphs

- A **speed-time graph** is used to describe the speed of an object and calculate its acceleration

Constant acceleration on a speed-time graph

- If an object is moving at a **constant acceleration**, the speed-time graph will be a **straight line**
  - If the constant acceleration is **zero**, the line will be **horizontal**
  - If the constant speed is **non-zero**, the line will have a **gradient**
- If an object has an **acceleration** of **zero**, the object is travelling at a **constant velocity**
  - Its velocity is not changing over time
  - If the **constant speed** is **zero**, then the object is **stationary**

Motion on a speed-time graph

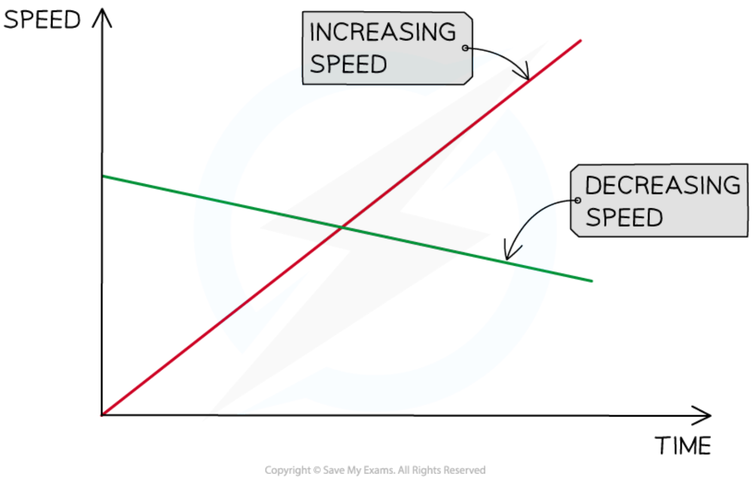


This image shows how to interpret the slope of a speed-time graph

- The **gradient** of a speed-time graph represents the object's **acceleration**
  - A **steeper slope**, or a higher gradient, represents a **greater acceleration**
  - A **shallower slope**, or a lower gradient, represents a **slower acceleration**
- If the gradient is positive, the line slopes upward

- A **positive gradient** represents an increasing speed, or **acceleration**
- If the gradient is negative, the line slopes downward
    - A **negative gradient** represents a decreasing speed, or **deceleration**

Speeding up and slowing down on a speed-time graph



Both of these objects are moving at a constant acceleration, because the lines are straight. The positive gradient represents an increasing speed or positive acceleration. The negative gradient represents a decreasing speed or negative acceleration.

Examiner Tips and Tricks

For CIE IGCSE Physics, you may be asked plot a graph of your own, or to interpret information given to you in a graph. You may also be asked to describe the motion of an object from data given in a question. You can read more about graph skills in the article Graph skills in GCSE Physics

Using speed-time graphs

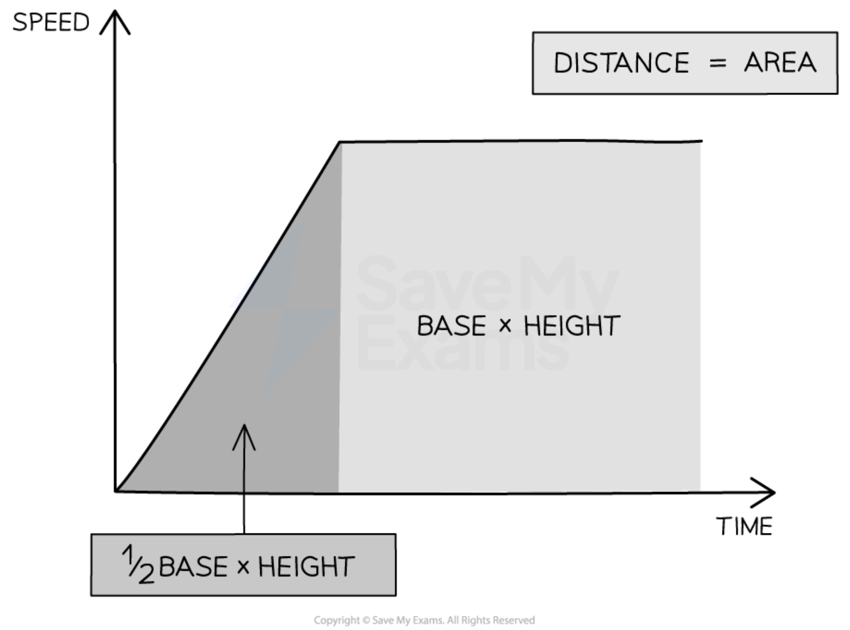
- **Speed-time graphs** can also be used to determine the distance travelled by an object

The area under a speed-time graph

- The **area** under a speed-time graph represents the **distance travelled**

Your notes

Your notes



The area under a speed-time graph represents the distance travelled

- If the area of a section of the speed-time graph forms a **triangle**, the area can be calculated using:

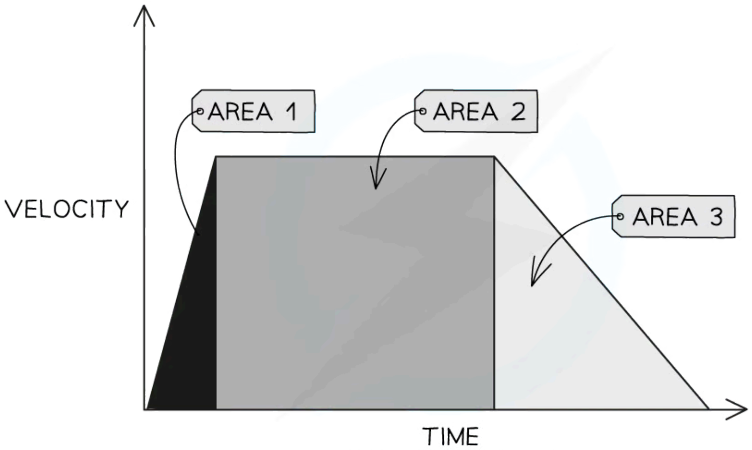
$$A_T = \frac{1}{2}bh$$

- If the area of a section of the speed-time graph forms a **rectangle**, the area can be determined using:

$$A_R = bh$$

- Where:
  - A_T = area of a triangle
  - A_R = area of a rectangle
  - b = base
  - h = height
- The **total distance travelled** can be determined by finding the **total area** under the speed-time graph
- The distance travelled for **part of the journey** can be determined by finding the area under the graph for a specific **time interval**

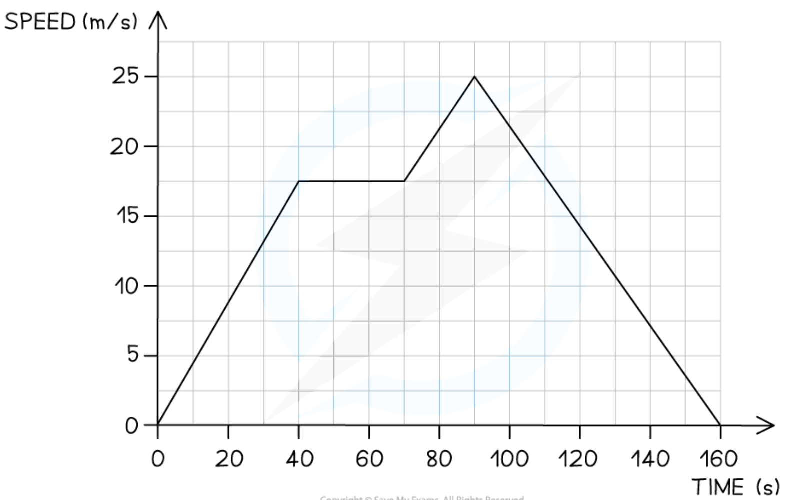
Area under a speed-time graph split into sections



The area under a speed-time graph can split into triangular and rectangular sections

Worked Example

The speed-time graph below shows a car journey that lasts for 160 seconds.



Calculate the total distance travelled by the car on this journey.

Answer:

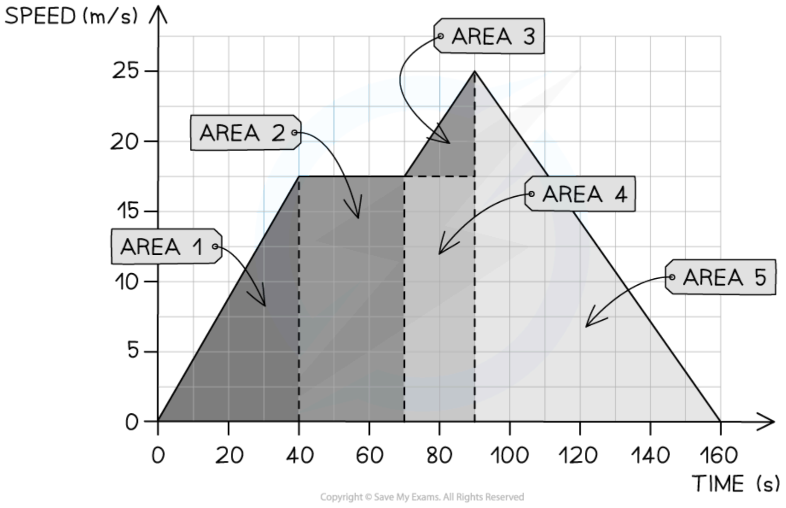
Step 1: Recall that the area under a speed-time graph represents the distance travelled

- In order to calculate the total distance travelled, the total area underneath the line must be determined

Step 2: Identify each enclosed area

Your notes

- In this example, there are **five** enclosed areas under the line
- These can be labelled as areas 1, 2, 3, 4 and 5, as shown in the image below:



Step 3: Calculate the area of each enclosed shape under the line

- Area 1 = area of a triangle

$$A_1 = \frac{1}{2}bh$$

$$A_1 = \frac{1}{2} \times 40 \times 17.5$$

$$A_1 = 350 \text{ m}$$

- Area 2 = area of a rectangle

$$A_2 = bh$$

$$A_2 = 30 \times 17.5$$

$$A_2 = 525 \text{ m}$$

- Area 3 = area of a triangle

$$A_3 = \frac{1}{2}bh$$

$$A_3 = \frac{1}{2} \times 20 \times 7.5$$

$$A_3 = 75 \text{ m}$$

- Area 4 = area of a rectangle

$$A_4 = bh$$

Your notes

$$A_4 = 20 \times 17.5$$

$$A_4 = 350 \text{ m}$$

- Area 5 = area of a triangle

$$A_5 = \frac{1}{2}bh$$

$$A_5 = \frac{1}{2} \times 70 \times 25$$

$$A_5 = 875 \text{ m}$$

Step 4: Calculate the total distance travelled by finding the total area under the line

- Add up each of the five areas enclosed:

$$\text{total distance} = A_1 + A_2 + A_3 + A_4 + A_5$$

$$\text{total distance} = 350 + 525 + 75 + 350 + 875$$

$$\text{total distance} = 2175 \text{ m}$$

Examiner Tips and Tricks

Some areas will need to be split into a triangle and a rectangle to determine the area for a specific time interval, like areas 3 & 4 in the worked example above.

If you are asked to find the distance travelled for a specific time interval, then you just need to find the area of the section above that time interval.

For example, the distance travelled between 70 s and 90 s is the sum of Area 3 + Area 4

Your notes

Interpreting speed-time graphs

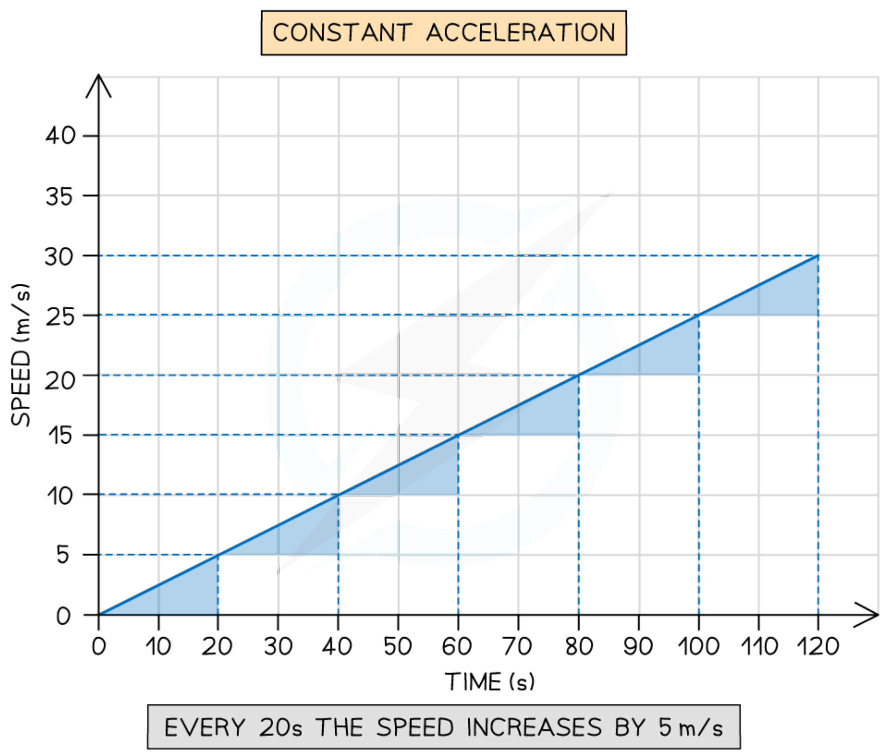
Extended tier only

- When interpreting speed-time graphs, the shape of the graph can show:
  - constant acceleration
  - changing acceleration
- The **gradient** of a speed-time graph shows the **acceleration** of a moving object
  - The gradient is **positive** if the object is accelerating (speed increases with time)
  - The gradient is **negative** if the object is decelerating (speed decreases with time)

Interpreting constant positive acceleration on a speed-time graph

- When the acceleration is **constant** and **non-zero**:
  - the graph is a **straight line**
  - velocity is **increasing** at a **constant** rate, i.e. speed changes by the same amount in equal intervals of time

Constant positive acceleration on a speed-time graph



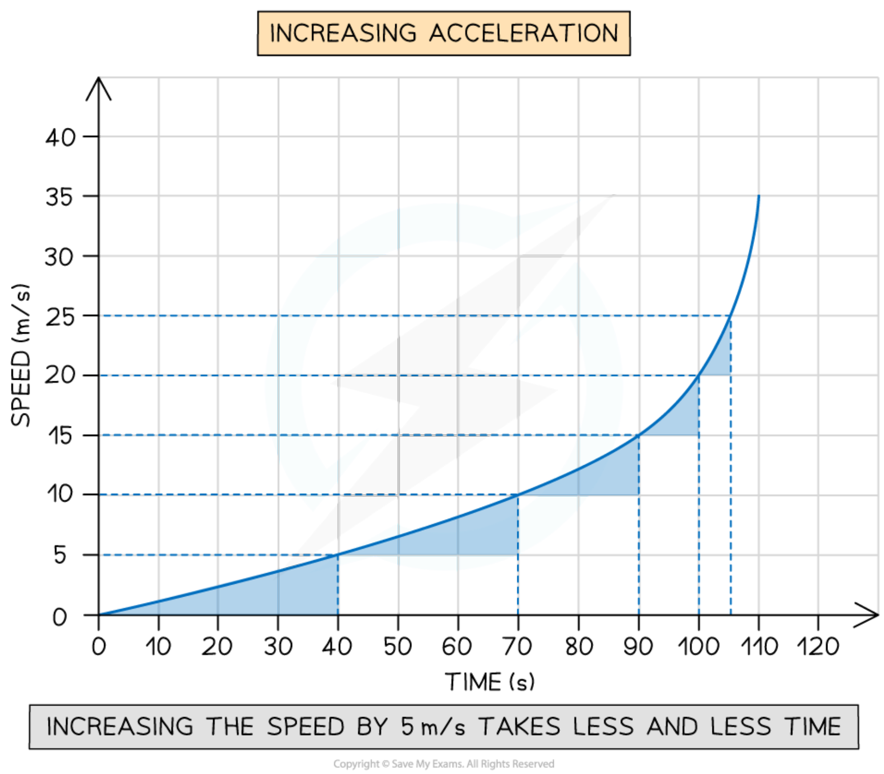
A speed-time graph for an object with constant positive acceleration. Its speed increases by 5 m/s every 20 s, showing that the rate at which the speed increases is constant.

Your notes

Interpreting increasing positive acceleration on a speed-time graph

- When the acceleration is **increasing**:
  - the graph is a **curve**
  - velocity is **increasing** at an **increasing** rate, i.e. the speed changes by the same amount in increasingly shorter time intervals

Increasing positive acceleration on a speed-time graph



A speed-time graph for an object with changing positive acceleration. The time taken for the speed to increase by 5 m/s decreases over time, showing that acceleration is increasing.

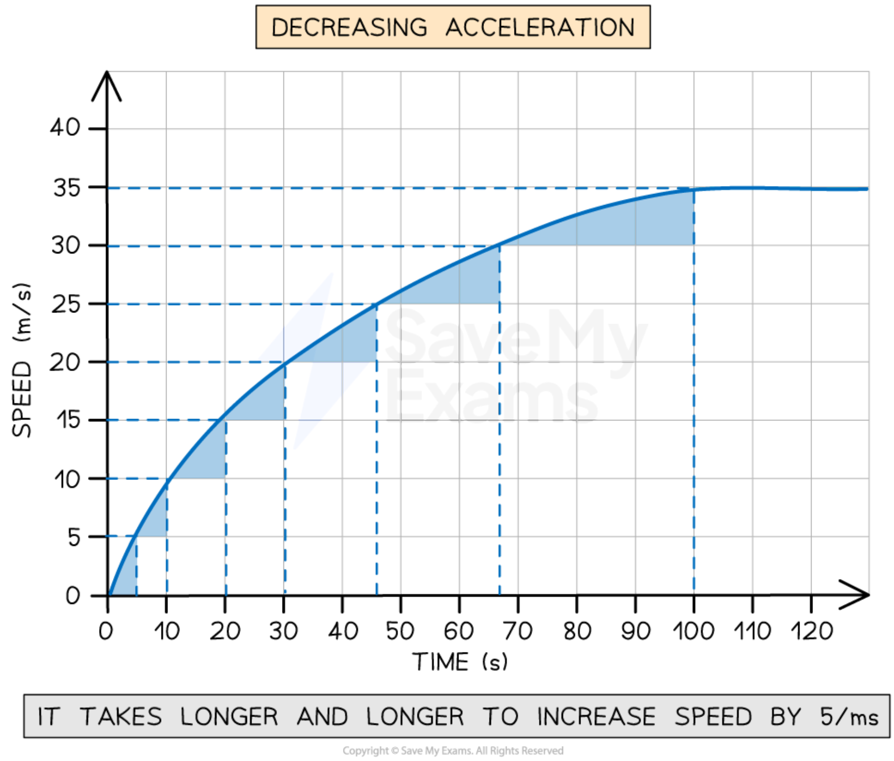
Interpreting decreasing positive acceleration on a speed-time graph

- When the acceleration is **decreasing**:
  - the graph is a **curve**

- velocity is **increasing** at a **decreasing** rate, i.e. the speed changes by the same amount in increasingly longer time intervals

Your notes

Decreasing positive acceleration on a speed-time graph

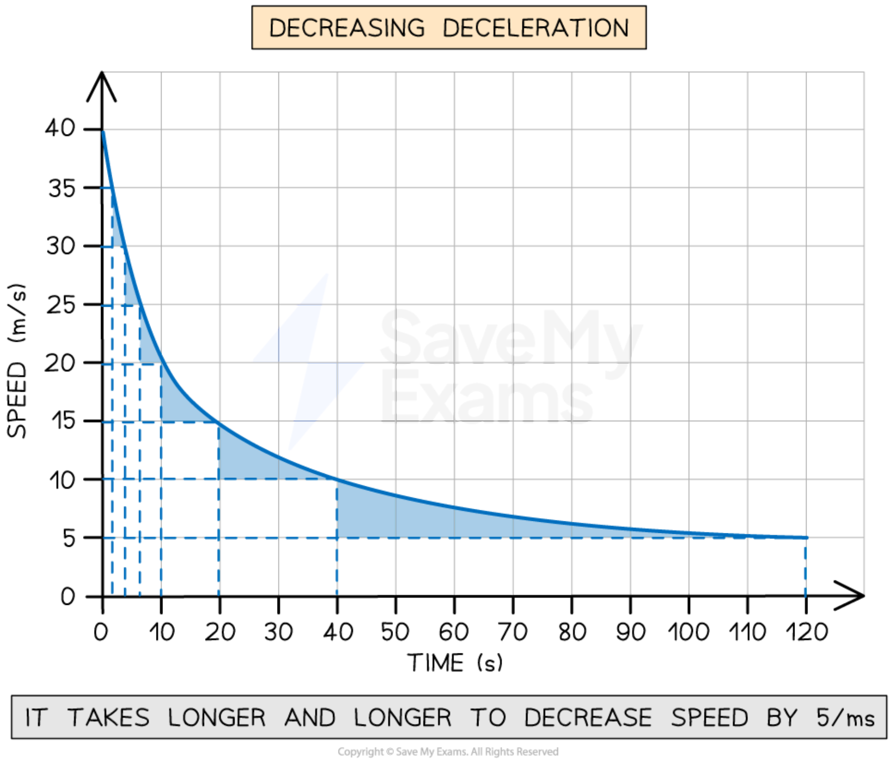


A speed-time graph for an object with changing positive acceleration. The time taken for the speed to increase by 5 m/s increases over time, showing that acceleration is decreasing.

Interpreting decreasing negative acceleration on a speed-time graph

- When the deceleration is **decreasing:**
  - the graph is a **curve**
  - the velocity is **decreasing** at a **decreasing** rate, i.e. the speed changes by the same amount in increasingly longer intervals of time

Decreasing negative acceleration on a speed-time graph



A speed-time graph for an object with changing negative acceleration. The time taken for the speed to decrease by 5 m/s increases over time, showing that deceleration is decreasing.

Examiner Tips and Tricks

Interpreting graphs can be difficult, and students often struggle with this key skill

In CIE IGCSE Physics, interpreting graphs is a **required** skill

- For your exam, you are also expected to calculate the **gradient** of a graph and the area under a graph
- Finding the **area under a graph** is covered in the revision note Speed-time graphs

Calculating acceleration

Extended tier only

- The **acceleration** of an object can be calculated from the **gradient** of a speed-time graph

Finding the gradient when acceleration is constant

- When acceleration is **constant**, the speed-time graph will be a **straight line**
- The gradient of a straight line can be found using:

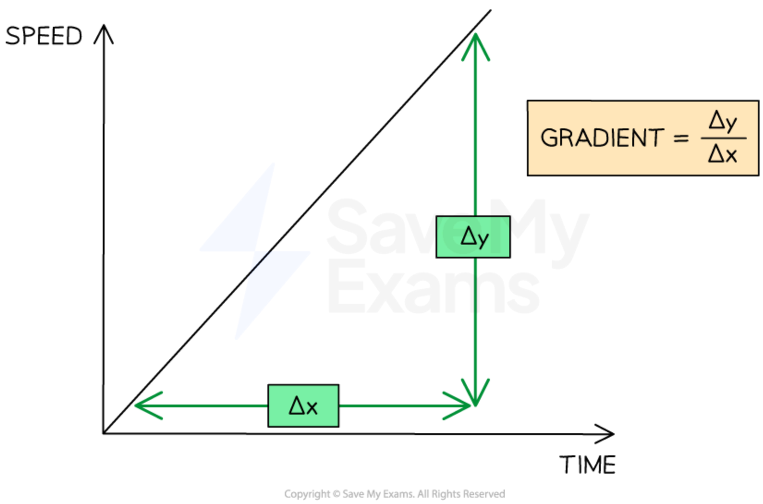
Your notes

$$\text{gradient} = \frac{\Delta y}{\Delta x}$$

- Where:
  - Δy = change in y (speed) values
  - Δx = change in x (time) values
- Therefore, the gradient is equal to:

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

- Where:
  - a = acceleration, measured in metres per second squared (m/s^2)
  - Δv = change in speed, measured in metres per second (m/s)
  - Δt = change in time, measured in seconds (s)

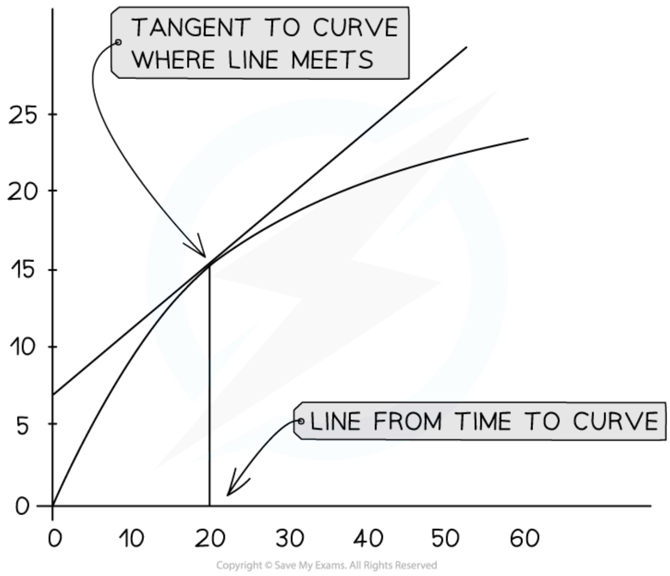


The gradient of a speed-time graph for constant acceleration can be found using Δy divided by Δx

Finding the gradient when acceleration is changing

- When acceleration is **changing**, the speed-time graph will be a **curve**
- The **gradient** of a point on a **curve** can be found by drawing a **tangent** to the curve
  - A tangent to the curve is a **straight line** drawn to match the **gradient** of the curve at a **specific point**

A tangent to the curve



The value of the gradient at a single point on a curve can be determined by finding the gradient of the tangent to that point

- The tangent provides a gradient that is representative of the gradient at a **specific point** on the curve
- The gradient of the tangent can be found using:

$$\text{gradient} = \frac{\Delta y}{\Delta x}$$

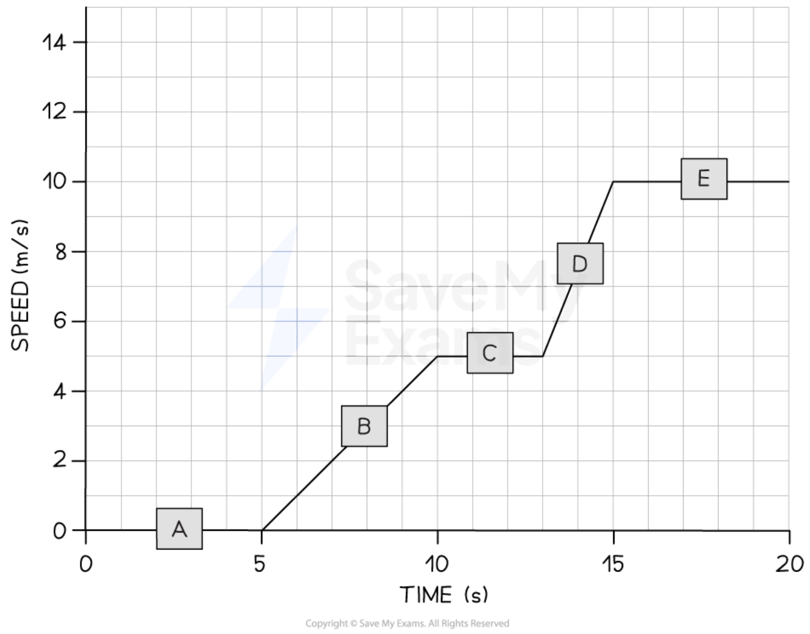
- The value of the gradient at specific point on the curve represents the acceleration of the object **at that moment**
  - This is called **instantaneous acceleration**

Worked Example

A cyclist is training for a cycling tournament.

The speed-time graph below shows the cyclist's motion as they cycle along a flat, straight road.

Your notes



(a) In which section (A, B, C, D, or E) of the speed-time graph is the cyclist's acceleration the largest?

(b) Calculate the cyclist's acceleration between 5 and 10 seconds.

Answer:

Part (a)

Step 1: Recall that the slope of a speed-time graph represents the magnitude of acceleration

- The slope of a speed-time graph indicates the magnitude of acceleration

  Therefore, the only sections of the graph where the cyclist is accelerating are sections B and D
- Sections A, C, and E are flat; in other words, the cyclist is moving at a constant velocity (therefore, not accelerating)

Step 2: Identify the section with the steepest slope

- Section D of the graph has the steepest slope
- Hence, the largest acceleration is shown in section D

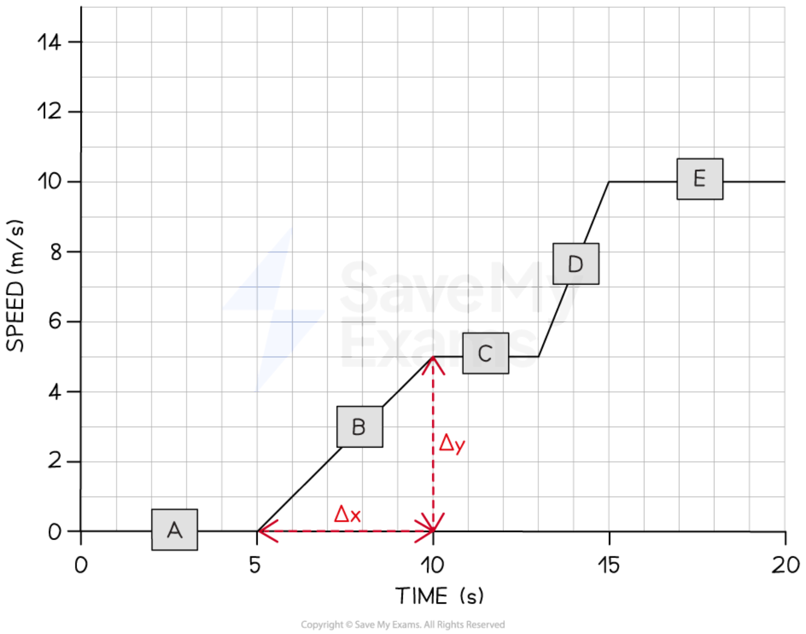
Part (b)

Step 1: Recall that the gradient of a speed-time graph gives the acceleration

- Calculating the gradient of a slope on a speed-time graph gives the acceleration for that time period

Step 2: Draw a large gradient triangle at the appropriate section of the graph

- A gradient triangle is drawn for the time period between 5 and 10 seconds



Step 3: Calculate the size of the gradient and state this as the acceleration

- The acceleration is given by the gradient, which can be calculated using:

$$a = \frac{\Delta y}{\Delta x}$$

$$a = \frac{5}{5}$$

$$a = 1 \text{ m/s}^2$$

- Therefore, the cyclist accelerated at 1 m/s^2 between 5 and 10 seconds

Examiner Tips and Tricks

Use the **entire slope**, where possible, to calculate the gradient. Examiners tend to award credit if they see a **large gradient triangle** used.

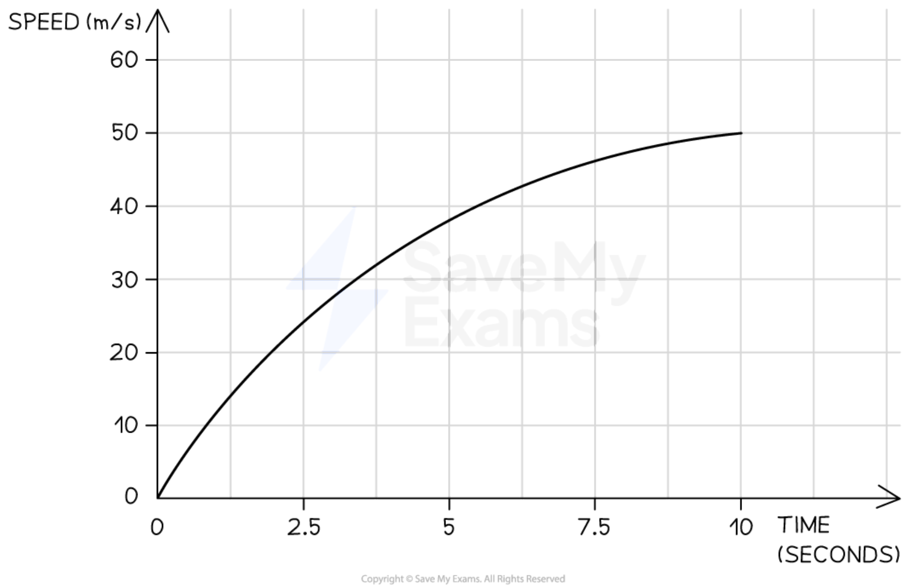
Remember to actually draw the lines directly on the graph itself, particularly when the question asks you to **use the graph** to calculate the acceleration.

Worked Example

Your notes

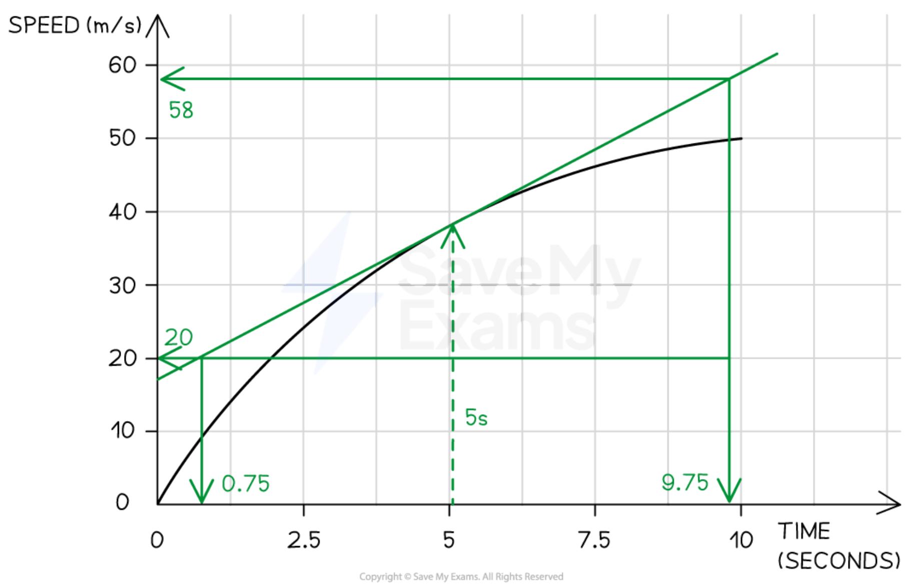
A skydiver jumps from a plane and reaches terminal velocity after 15 seconds. A speed-time graph of their motion is shown below.

Use the graph to find the acceleration at 5 seconds.



Answer:

Step 1: Draw a tangent to the curve at the point where t = 5 s



Step 2: Calculate the gradient of the tangent

- Change in y (speed): Δy
- Change in x (time): Δx

Your notes

$$a = \frac{\Delta y}{\Delta x}$$

$$a = \frac{58 - 20}{9.75 - 0.75}$$

$$a = \frac{38}{9.0}$$

$$a = 4.2\ \mathrm{m/s^2}\ (2\ \mathrm{s.f.})$$

Examiner Tips and Tricks

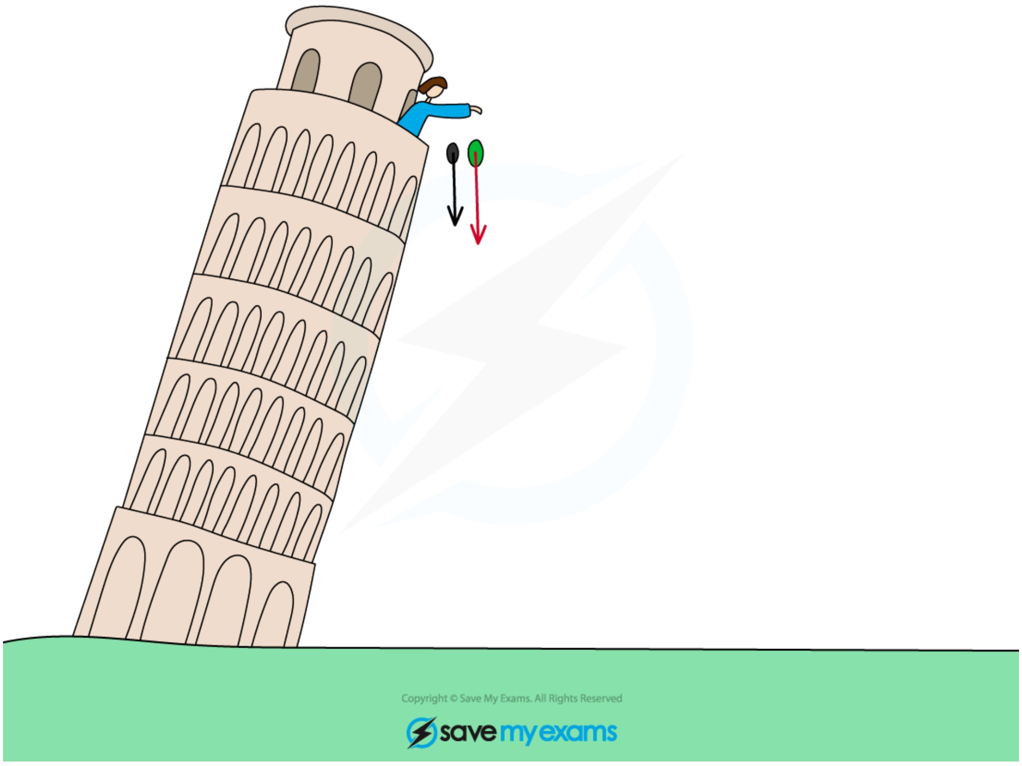
The CIE IGCSE Physics specification includes knowing how to calculate the gradient of a tangent to the curve in the maths skills section. This means that you could be asked to demonstrate this skill in any topic. The skills in this revision note are applicable to any type of graph. For more information on interpreting graphs in Physics, see the article Graph skills in GCSE Physics

Your notes

Acceleration of free fall

- In the absence of **air resistance**, all objects fall with the **same acceleration** regardless of their mass
- This is called the **acceleration of freefall**
  - This is also sometimes called acceleration due to gravity

$$\text{acceleration of freefall} = g = 9.8 \text{ m/s}^2$$



In the absence of air resistance, Galileo discovered that all objects (near Earth's surface) fall with an acceleration of about 9.8 m/s^2

- This means that for every second an object falls, its velocity will increase by 9.8 m/s
- The symbol g also stands for the **gravitational field strength**, and can be used to calculate the force of weight acting an object using its mass:

$$W = mg$$

- Where:
  - W = the force of weight acting on an object, measured in newtons (N)
  - m = mass of object, measured in kilograms (kg)

- g = gravitational field strength, measured in newtons per kilogram (N/kg)

Motion of falling objects

Extended tier only

Falling objects without air resistance

- A **vacuum** is a space that contains no matter, so there are **no particles** to exert frictional forces on a falling object
- When objects fall in a vacuum, there is no air resistance or liquid resistance so the only force acting on them is the force of **weight**

$$W = mg$$

- Newton's second law of motion describes acceleration as:

$$a = \frac{F}{m}$$

- Where:
  - a = acceleration, measured in metres per second squared (m/s^2)
  - F = force exerted on object, measured in newtons (N)
  - m = mass of object, measured in kilograms (kg)
- Since the only force acting on a falling object in a vacuum is weight, the equation can be expressed as

$$a = \frac{W}{m}$$

- Weight is the product of mass and gravitational field strength, so the equation can be expressed as

$$a = \frac{mg}{m}$$

- Here, the masses cancel each other out

$$a = \frac{\cancel{m}g}{\cancel{m}}$$

- So, for objects falling in a vacuum

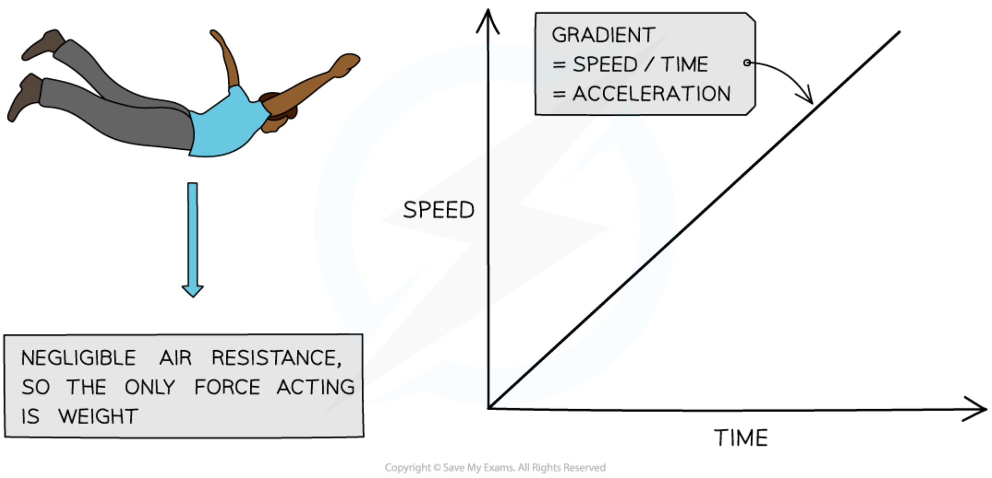
$$a = g$$

- Where g = acceleration of free fall
- This theory was tested by astronauts on the Moon

Your notes

- A hammer and a feather were dropped from **equal heights** on the Moon, where there is **no air resistance**
  - The hammer and the feather fell with the **same acceleration** and landed at the same time
  - This proved that objects falling in a vacuum have the same acceleration **regardless of their mass**
- This also applies when air resistance is so small that it can be disregarded
  - When air resistance is described as **negligible**, it can be **approximated** to an object is falling in a vacuum

Object falling with no air resistance



In the absence of air resistance, objects fall with constant acceleration

- Objects falling through a vacuum will **never** reach a **terminal velocity**

Falling objects with air resistance

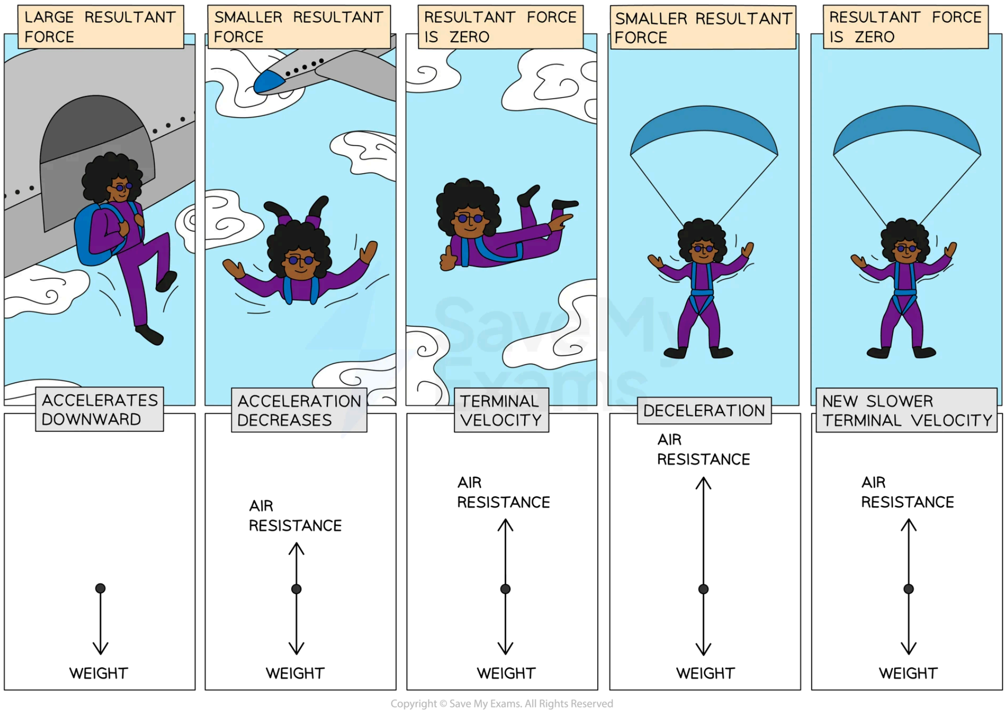
- When objects fall through a **fluid**, the fluid exerts a **frictional force** on the object as it falls
  - Fluids are **liquids** or **gases**
- Frictional forces **oppose the motion** of an object
  - They act to slow it down
- When an object falls through **air**, it experiences **air resistance**
  - Air resistance is a **frictional** force produced by collisions with air particles as the object moves through the air
- Air resistance **increases** as the **speed** of the object **increases**
- When objects fall through **air**, **two forces** are exerted on the object:
  - The force of **weight**

Your notes

- The force of **air resistance**
- When the force of **air resistance** becomes **equal** to the force of weight, then the object **stops accelerating** and falls at a **constant speed**
  - This is called **terminal velocity**

Your notes

How does a skydiver reach terminal velocity?

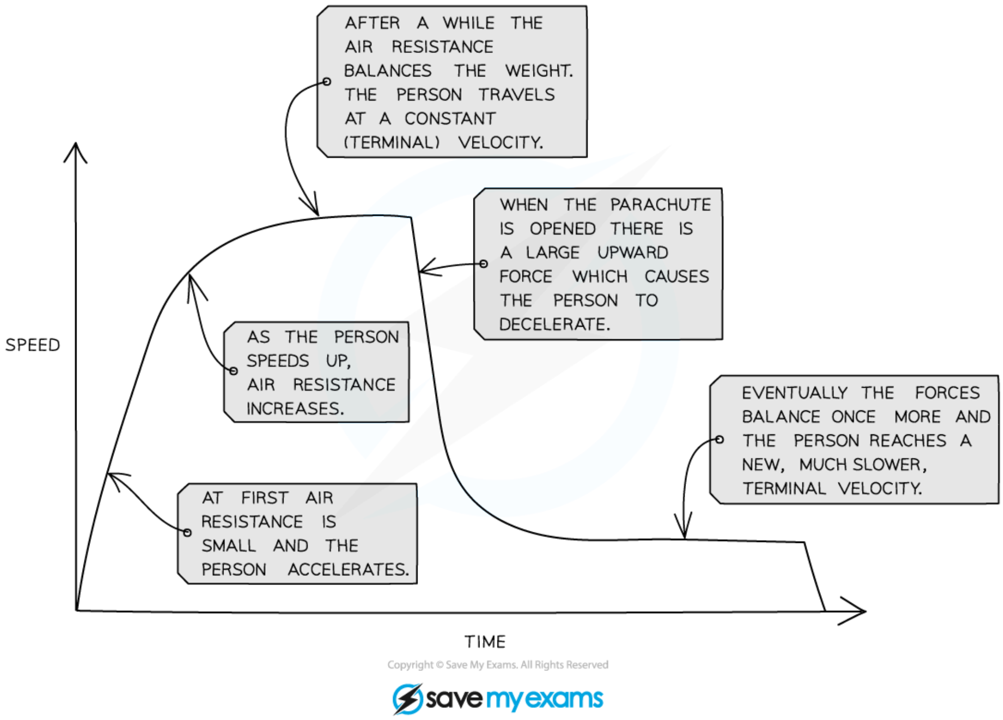


The stages of a skydivers fall until they reach terminal velocity

- When a skydiver jumps out of a plane, initially the only force acting on them is **weight**
  - The resultant force acts in the downward direction
  - The skydiver **accelerates**
- As the skydiver accelerates, their **speed increases,** so the force of **air resistance increases**
  - The resultant force acts in the downward direction with a smaller magnitude
  - The skydiver continues to **accelerate** but at a **slower** rate
- **Air resistance** increases until it is **equal** to the **weight**
  - The forces are balanced
  - There is no resultant force
  - **Terminal velocity** is reached
- The parachute is deployed, increasing the surface area of the skydiver

- The parachute collides with many more air particles
- **Air resistance increases** greatly
- The force of **air resistance** is now **greater than** the force of **weight**
  - The resultant force acts in the upward direction
  - The skydiver continues falling in a downward direction
  - The skydiver is **decelerating**
- As the skydiver decelerates, their **speed decreases**
  - Therefore, **air resistance decreases**
  - Therefore, the resultant force decreases
- **Air resistance** decreases until it is **equal** to the **weight**
  - The forces are balanced
  - There is no resultant force
  - A new, **slower terminal velocity** is reached

Graph showing the motion of the skydiver as they reach terminal velocity



The graph shows how the speed of the skydiver changes during the descent. The horizontal parts of the graph show the periods of terminal velocity

Your notes

Your notes

Worked Example

A small object falls out of an aircraft. Choose words from the list to complete the sentences below:

air resistance **gravitational field strength** **air pressure**

accelerates **falls at a steady speed** **slows down**

(a) The weight of an object is the product of the object's mass and the __________.

(b) When an object falls, initially it ____________.

(c) As the object falls faster, the force of ______________ acting upon the object increases.

(d) Eventually the object ______________ when the force of friction equals the force of weight acting on it.

Answer:

Part (a)

The weight of an object is the product of the object's mass and the **gravitational field strength**.

- The weight force is due to the Earth's gravitational pull on the object's mass as it falls through a uniform gravitational field
-

Part (b)

When an object falls, initially it **accelerates.**

- The **resultant force** on the object is **very large** initially, so it accelerates
- This is because there is a **large unbalanced force** downwards (its weight) - the upward force of air resistance is very small to begin with

Part (c)

As the object falls faster, the force of **air resistance** acting on the object increases.

- The force of **air resistance** is due to **friction** between the object's motion and **collisions with air particles**
- Collisions with air particles slow the object down, so air itself produces a **frictional force**, called **air resistance** (sometimes called **drag**)

Part (d)

Eventually, the object **falls at a steady speed** when the force of friction equals the force of weight acting on it.

- When the upward acting **air resistance** increases enough to **balance** the downward **weight** force, the resultant force on the object is **zero**

- This means the object is no longer accelerating; it is moving at a **steady speed** called **terminal velocity**

Your notes

Examiner Tips and Tricks

Don't confuse 'air resistance' with 'air pressure' - these are two different concepts!

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