AQA GCSE Physics (Separate Science) Unit 5: Forces

Scalar and Vector Quantities

A **scalar** quantity has **magnitude** only. Examples include temperature or mass.

A **vector** quantity has both **magnitude** and **direction**. Examples include velocity.

Speed is the scalar magnitude of **velocity**.

A vector quantity can be shown using an **arrow**. The size of the arrow is relative to the magnitude of the quantity and the direction shows the associated direction.

Contact and Non-Contact Forces

Forces either **push** or **pull** on an object. This is as a result of its interaction with another object.

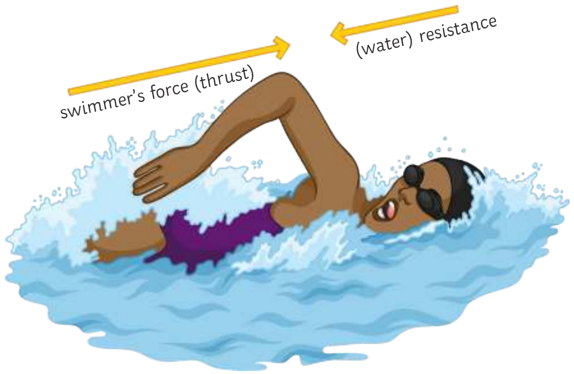
Forces are categorised into two groups:

Contact forces – the objects are touching e.g. friction, air resistance, tension and contact force.

Non-contact forces – the objects are not touching e.g. gravitational, electrostatic and magnetic forces.

Forces are calculated by the equation: **force (N) = mass (kg) × acceleration (m/s^2)**

Forces are another example of a **vector quantity** and so they can also be represented by an **arrow**.



Gravity

Gravity is the natural phenomenon by which any object with mass or energy is drawn together.

- The **mass** of an object is a scalar measure of how much matter the object is made up of. Mass is measured in **kilograms (kg)**.
- The **weight** of an object is a vector measure of how gravity is acting on the mass. Weight is measured in **newtons (N)**.

weight (N) = mass (kg) × gravitational field strength (N/kg)

(The gravitational field strength will be given for any calculations. On earth, it is approximately 9.8N/kg).

An object's **centre of mass** is the point at which the weight of the object is considered to be acting. It does not necessarily occur at the centre of the object.

The **mass** of an object and its **weight** are **directly proportional.** As the mass is increased, so is the weight. Weight is measured using a **spring-balance** (or **newton metre**) and is measured in **newtons** (N).

Resultant Forces

A **resultant force** is a single force which replaces several other forces. It has the same effect acting on the object as the combination of the other forces it has replaced.

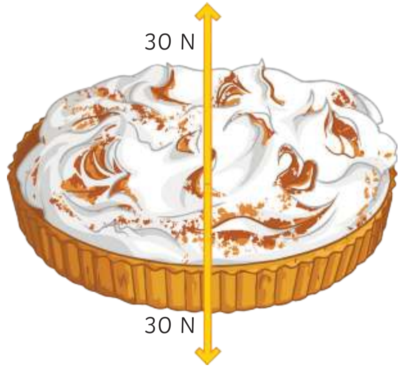
The forces acting on this object are represented in a **free body** diagram. The arrows are relative to the magnitude and direction of the force.

The car is being pushed to the left by a force of 30N. It is also being pushed to the right by a force of 50N.

The **resultant force is 50N – 30N = 20N**

The 20N resultant force is pushing to the right, **so the car will move right.**

When a resultant force is not zero, an object will **change speed (accelerate or decelerate)** or **change direction (or both)**.



When an object is stationary, there are still forces acting upon it.

In this case, **the resultant force is 30N – 30N = 0N**.

The forces are in **equilibrium** and are **balanced**.

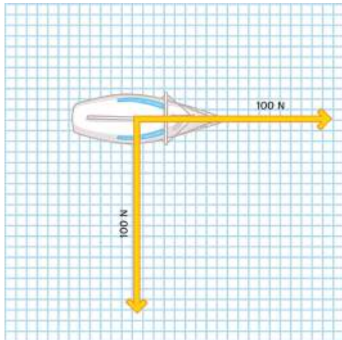
When forces are balanced, an object will either **remain stationary** or if it is moving, it will continue to move at a **constant speed**.

Resultant Forces

A **scale vector diagram** can be used to calculate **resultant forces** that are not acting directly opposite of one another, on a straight line.

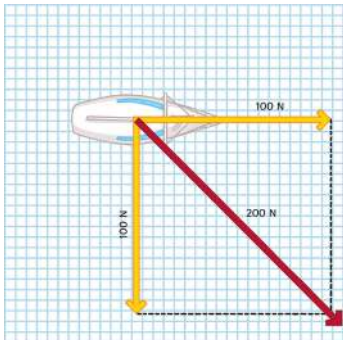
Worked example 1:

A boat is being pulled toward the harbour by two winch motors. Each motor is pulling with a force of 100N and they are working at right angles to one another.



To find the resultant force, you would first draw construction lines from the end of each arrow parallel to the other force arrow.

Remember that the size of the arrow is representative of the size of the force being exerted.



Where the construction lines intercept indicates the direction of the resultant force: from the centre of mass through the intercept.

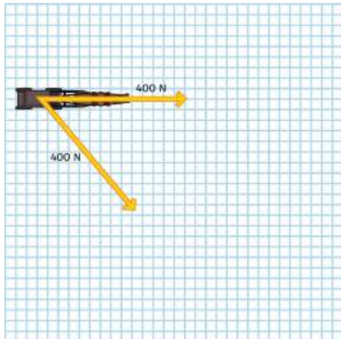
The resultant force is the sum of the forces acting so in this example, that is 200N.

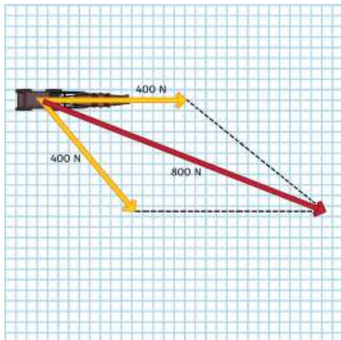
Measure the size of the arrows and make sure you draw your resultant force arrow to the correct scale so it represents the resultant force size.

Worked example 2:

A horse-drawn carriage is pulled by two horses at 400N each. One of the horses is pulling in a different direction to the other horse. Show the resultant force and direction of the horse-drawn carriage.

As before, you will need to draw construction lines from the end of each force arrow and parallel to the other one. The intercept represents the direction of the resultant force. The resultant force is the sum of the individual forces so in this example, it is 800N.





Work Done and Energy Transfer

When a force acts on an object and makes it move, there is **work done** on the object. This movement requires energy. The **input energy** could be from fuel, food or electricity for example.

The energy is **transferred to a different type of energy** when the work is done. Not all the energy transfers are useful, sometimes energy is **wasted**. For example, when car brakes are applied, some energy is wastefully transferred as heat to the surroundings. Work done against the force of **friction** always causes a **temperature rise** in the object.

Work done is calculated by this equation:

work done [*energy transferred*] **(J) = force (N) × distance moved (in the direction of the force) (m)**

Worked example

A man's car has broken down and he is pushing it to the side of the road. He pushes the car with a force of 160N and the car is moved a total of 8m. Calculate the energy transferred.

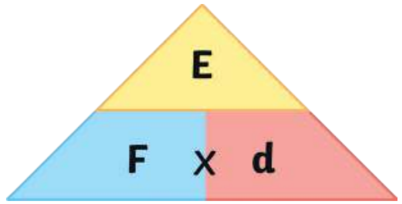
$E = F \times d$

$E = 160 \times 8$

$E = 1280J$

1 joule of energy is transferred for every 1 newton of force moving an object by a distance of 1 metre.

1J = 1Nm



Required Practical Investigation Activity 6: Investigate the Relationship Between Force and Extension for a Spring

F = k × e

force applied (N) = spring constant (N/m) × extension (m)

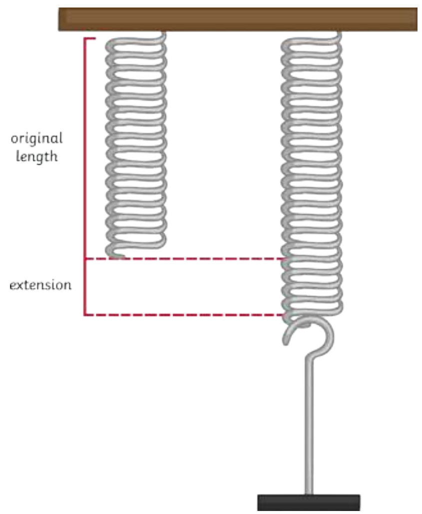
You should be familiar with the equation above and the required practical shown to the right.

The spring constant is a value which describes the elasticity of a material. It is specific to each material. You can carry out a practical investigation and use your results to find the spring constant of a material.

1. Set up the equipment as shown.
2. Measure the original length of the elastic object, e.g. a spring, and record this.
3. Attach a mass hanger (remember the hanger itself has a weight). Record the new length of the spring.
4. Continue to add masses to the hanger in regular intervals and record the length each time.

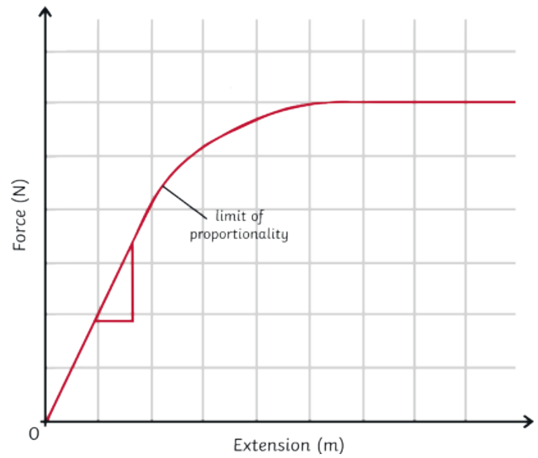
Once you have your results, you can find the extension for each mass using this formula: **spring length – original length**

The data collected is continuous so you would plot a **line graph** using the x-axis for extension (m) and the y-axis for force (N). As a result of Hooke's Law, you should have a **linear graph**. The **gradient of the graph is equal to the spring constant**. You can calculate it by rearranging the formula above or by calculating the gradient from your graph.



Spring Constant and Hooke's Law

Hooke's Law describes that the extension of an elastic object is **proportional** to the force applied to the object. However, there is a maximum applied force for which the extension will still increase proportionally. If the **limit of proportionality** is exceeded, then the object becomes **permanently deformed** and can no longer return to its original shape. This can be identified on a graph of extension against force when the gradient stops being linear (a straight line) and begins to **plateau**. The limit is shown on the graph above and this is the specific object's **elastic limit**.



Forces and Elasticity

When work is done on an elastic object, such as a spring, the energy is stored as elastic potential energy.

When the force is applied, the object changes shape and stretches. The energy is stored as elastic potential and when the force is no longer applied, the object returns to its original shape. The stored elastic potential energy is transferred as kinetic energy and the object recoils and goes back to its original shape.

Work Done: Elastic Objects

Work is done on elastic objects to **stretch** or compress them.

To calculate the work done (**elastic potential energy** transferred), use this equation:

$E\ (J) = 0.5 \times k \times e^2$

(elastic potential energy = 0.5 × spring constant × extension^2)

You might need to use this equation also: $F = k \times e$

Worked example:

A bungee jumper jumps from a bridge with a weight of 800N. The elastic cord is stretched by 25m. Calculate the work done.

Step 1: find the spring constant using $F = k \times e$

Rearrange to $k = F \div e$

$800 \div 25 = 32$N/m

Step 2: use the value for k to find the elastic potential energy (work done) using $E\ (J) = 0.5 \times k \times e^2$

$0.5 \times 32 \times 25^2$

E = 10 000J

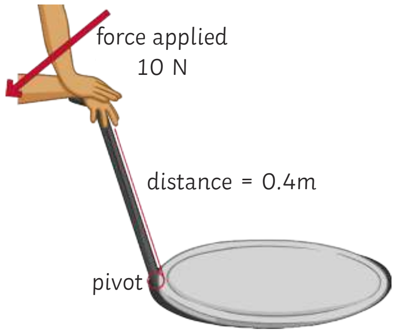
Moments, Levers and Gears

A moment is the turning effect produced by a force. To find the size of a moment, use the equation:

moment (Nm) = force (N) × distance (m)

Remember that the distance is the perpendicular distance from the pivot to the line of action of the force.

Worked example:



A crowbar is being used to lift a manhole cover. Calculate the moment produced.

$M = F \times d$

$M = 10 \times 0.4$

m = 40Nm

To increase the turning affect achieved without increasing the amount of force applied, you would need to increase the distance between the force and the pivot.

For example, if the crowbar in the example above was 0.5m, then the moment would be:

$M = F \times d$

$M = 10 \times 0.5$

M = 50Nm

Levers can be used to increase the effect of a force applied, acting as a force multiplier. Some everyday examples include:

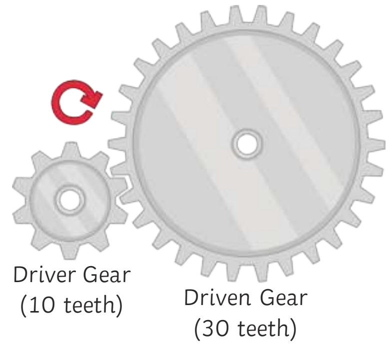

spanner


wheelbarrow


pair of scissors

A force multiplier makes it easier to do work because the same force applied at a greater distance from the pivot increases the moment produced.

A **gear** is a wheel which has 'teeth' around the circumference.



The teeth of different gears lock together and the gear can turn on an **axle**, turning the other gears it is connected to. Where the teeth meet, they must move in the same direction. This means that the gears rotate in **opposite directions**. If one gear is turning clockwise, it will turn the connected gear anticlockwise.

When gears are connected, the **same force** is applied to each; however, if they are different sizes, they will produce **different moments**. This is because the moment is calculated using the distance from the pivot (the radius of the gear) and if the gear is smaller, it will move a shorter distance. If the gear is larger, it will move a greater distance.

Worked example:

A gear has a radius of 0.25m. It turns a second gear with a radius of 1.5m. The moment of the smallest gear is 30Nm. Calculate the moment of the largest gear.

Step 1: calculate the force using $M = F \times d$

Rearrange to $F = M \div d$

$F = 30 \div 0.25$

F = 120N

Step 2: use the force to calculate the moment of the larger gear.

$M = F \times d$

$M = 120 \times 1.5$

M = 180Nm

Balanced Moments

When the anticlockwise moment on an object is equal to the clockwise moment, the **resultant moment** is zero and the object does not move or turn.

To balance moments: **total anticlockwise moments = total clockwise moments**

Worked example:

An elephant sits on a seesaw. It has a weight of 750N and is sat 2.5m from the pivot. A mouse with a weight of 60N is sitting on the other side of the seesaw. The seesaw is balanced.

What distance is the mouse from the pivot?

Step 1:	**Step 2:**	**Step 3:**
Calculate the anticlockwise moment. M = F × d = 750N × 2.5m = 1875Nm	total anticlockwise moments = total clockwise moments 1875Nm = 1875Nm	Use the value calculated for the moment to find the distance on the clockwise side. rearrange: d = M ÷ F d = 1875 ÷ 60 d = 31.25m

Pressure and Pressure Difference in Fluids

A **fluid** is any material in a state of matter which flows; it is a **liquid** or a **gas.**

The pressure in a fluid causes a force at a **right angle** (normal) to the surface.

The pressure is calculated using the equation:

$$\textbf{pressure (Pa)} = \frac{\textbf{force (N)}}{\textbf{surface area (m}^2\textbf{)}}$$

Worked example:

Find the pressure exerted by an elephant on a frozen pond. The force exerted by the elephant is 4500N and the area of the pond is 30m^2.

p = 4500 ÷ 30

p = 150Pa

Pressure in Fluids

You can find the pressure produced by a column of liquid using the equation:

pressure (Pa) = height of column (m) × density of liquid (kg/m^3) × gravitational field strength (N/kg)

The more water above an object, then the greater the force applied and the greater the pressure exerted. Scuba divers have to monitor the pressure as they dive to ensure they are not endangering their lives by going too deep.

This can be demonstrated by placing holes in a bucket or other container of water at two different heights.

Water leaking from the hole higher up the bucket will be at a lower pressure than water leaking from the hole lower in the bucket.

When an object is **submerged partially**, it will have a greater pressure on the bottom surface than on the top surface (there is more water behind the force acting upwards). This creates an upwards resultant force called **upthrust** and this is what causes an object to float.

Atmospheric Pressure

Surrounding the earth is a layer of **air** called the **atmosphere**. Compared to the size of the planet, this layer is relatively thin. The air becomes less dense the farther from the planet's surface you are (with increasing **altitude**).

When the air molecules collide with the surface of the earth, pressure is exerted and this is called **atmospheric pressure.** The amount of air molecules above a surface **decreases** with **altitude** and so the **pressure exerted** also **decreases** with increasing height.

Velocity

Velocity is a **vector** quantity. It is the **speed** of an object in a given **direction**.

Circular Motion (Higher tier only)

Objects moving in a **circular path** don't go off in a straight line because of a **centripetal** force caused by another force acting on the object.

For example, a car driving around a corner has a centripetal force caused by **friction** acting between the surface of the road and the tyres. When the Earth orbits around the Sun, it is held in orbit by **gravity** which causes the centripetal force.

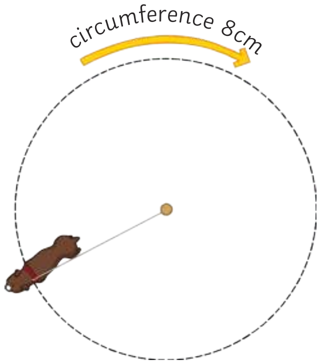
When an object is moving in a circular motion, its **speed** is **constant.** Its **direction changes** constantly and because direction is related to **velocity**, this means that the velocity of the object is constantly changing too. The changes in velocity mean that the object is **accelerating**, even though it travels at a constant speed.

The acceleration occurs because there is a **resultant force** acting on the object. In this case, the resultant force is the velocity, which is greater than the centripetal force acting.

Forces and Motion: Distance vs Displacement

Distance is a **scalar** quantity. It measures how far something has moved and does not have any associated direction.

Displacement is a **vector** quantity. It measures how far something has moved and is measured in relation to the direction of a straight line between the starting and end points.



E.g. A dog is tethered to a post. It runs 360˚ around the post three times. Each 360˚ lap is 8m

distance = 8 × 3 = 24m

displacement = 0m (The dog is in the same position as when it started.)

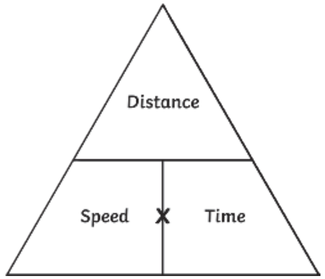
Speed

You should be able to recall the typical speed of different transportation methods.

Activity	Typical Value
walking	**1.5m/s**
running	**3m/s**
cycling	**6m/s**
driving a car	25mph (40km/h)
train travel	60mph (95km/h)
aeroplane travel	550mph (885km/h)
speed of sound	*330m/s*

These values are average only. The speed of a moving object is rarely constant and always fluctuating.

speed = distance ÷ time



You should be able to use this equation and rearrange it to find the distance or time.

Worked example:

John runs 5km. It takes him 25 minutes. Find his average speed in metres per second.

Step 1: convert the units

km ⟶ m (×1000) = 5000m

min ⟶ s (×60) = 1500s

Step 2: calculate s = d ÷ t

s = 5000 ÷ 1500

s = 3.33m/s

Worked example 2:

Zi Xin has driven along the motorway. Her average speed is 65mph. She has travelled 15 miles. How long has her journey taken? Give your answer in minutes.

Step 1: calculate t = d ÷ s

t = 15 ÷ 65

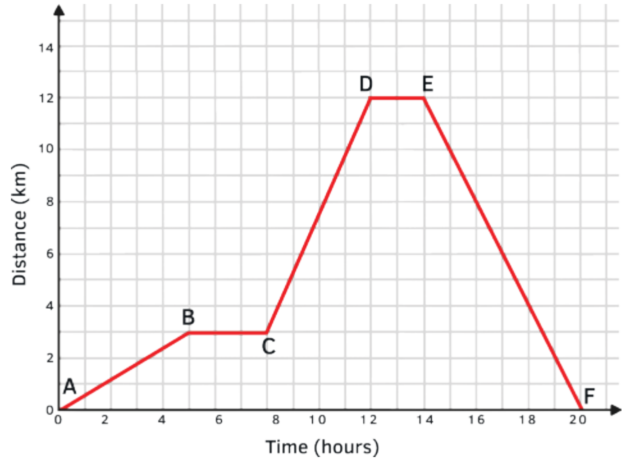
t = 0.23 (hours)

Step 2: convert units

hr ⟶ min (×60) = 13.8 minutes

Distance-Time and Velocity-Time Graphs

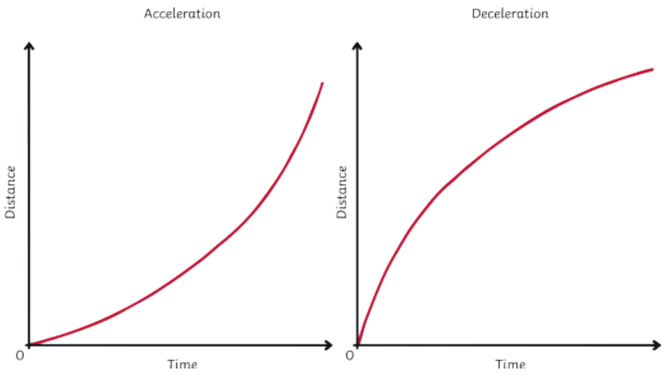
When an object travels in a **straight line**, we can show the distance which has been covered in a **distance-time graph**.



You should be able to understand what the features of the two types of graph can tell you about the motion of an object.

Graph Feature	Distance-Time Graph	Velocity-Time Graph
x-axis	time	time
y-axis	distance	velocity
gradient	speed	acceleration (or deceleration)
plateau	stationary (stopped)	constant speed
uphill straight line	steady speed moving away from start point	acceleration
downhill straight line	steady speed returning to the start point	deceleration
uphill curve	acceleration	increasing acceleration
downhill curve	deceleration	increasing deceleration
area below graph		distance travelled

Changing Speed on a D-T graph



When the graph is a **straight line**, it is representing a **constant speed**. A **curve** represents a changing speed, either **acceleration** or **deceleration**. The speed at any given point can be calculated by drawing a **tangent** from the curve and finding the **gradient** of the tangent.

Terminal Velocity

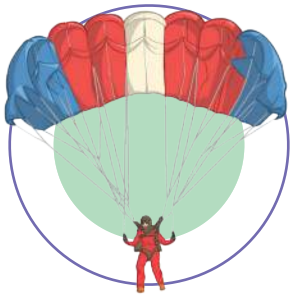
When an object begins moving, the force **accelerating** the object is much greater than the force resisting the movement. A resistant force might be **air resistance** or **friction**, for example.

As the **velocity** of the object increases, the force **resisting** the movement also increases. This causes the acceleration of the object to be reduced gradually until the forces become **equal** and are **balanced**. This doesn't cause the object to stop moving. As the object is already in motion, balanced forces mean it will continue to move at a **steady speed**. This steady speed is the maximum that the object can achieve and is called the **terminal velocity**.

The terminal velocity of an object depends on its shape and weight. The shape of the object determines the amount of resistant force which can act on it. For example, an object with a large surface area will have a greater amount of resistance acting on it.

Consider a skydiver and his parachute. When the skydiver first jumps from the aeroplane, he has a small area where the air resistance can act. He will fall until he reaches a terminal velocity of approximately 120mph.

After the skydiver releases his parachute, the shape and area has been changed and so the amount of air resistance acting is increased. This causes him to decelerate and his terminal velocity is reduced to about 15mph. This makes it a much safer speed to land on the ground.



Acceleration

Acceleration can be calculated using the equation:

$$\textbf{acceleration (m/s}^2\textbf{)} = \frac{\textbf{change in velocity (m/s)}}{\textbf{time taken (s)}}$$

Worked example:

A dog is sitting, waiting for a stick to be thrown. After the stick is thrown, the dog is running at a speed of 4m/s. It has taken the dog 16s to reach this velocity. Calculate the acceleration of the dog.

$a = \Delta v \div t$

$a = (4-0) \div 16$

$A = 0.25 m/s^2$

Changes in velocity due to acceleration can be calculated using the equation below. This equation of motion can be applied to any moving object which is travelling in a **straight line** with a **uniform acceleration**.

Final velocity^2 (m/s) – initial velocity^2 (m/s) = 2 × acceleration (m/s^2) × displacement (m)

or

$\mathbf{v^2 - u^2 = 2as}$

Worked example:

A bus has an initial velocity of 2m/s and accelerates at 1.5m/s^2 over a distance of 50m. Calculate the final velocity of the bus.

Step 1: rearrange the equation: $v^2 - u^2 = 2as$

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

Step 2: insert known values and solve

$v^2 = (2 \times 1.5 \times 50) + 2^2$

$v^2 = (150) + 4$

$v^2 = 154$

$v = \sqrt{154}$

$v = 12.41 m/s$

Stopping Distance

The **stopping distance** of a vehicle is calculated by:

stopping distance = thinking distance + braking distance

Reaction time is the time taken for the driver to respond to a hazard. It varies from 0.2s to 0.9s between most people.

Reaction time is affected by:

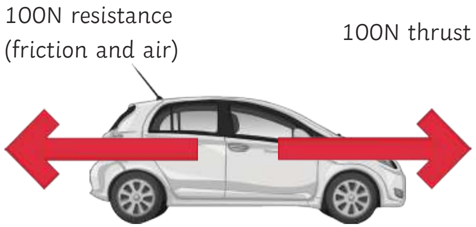
- **tiredness**
- **drugs**
- **alcohol**
- **distractions**

You can measure human reaction time in the lab using simple equipment: a metre ruler and stopwatch can be used to see how quickly a person reacts and catches the metre ruler. The data collected is quantitative and you should collect repeat readings and calculate an average result.

Newton's Laws of Motion: Newton's First Law

If the resultant force acting on an object is zero...

- **a stationary object will remain stationary.**
- **a moving object will continue at a steady speed and in the same direction.**



Inertia – the tendency of an object to continue in a state of rest or uniform motion (same speed and direction).

Newton's Laws of Motion: Newton's Second Law

The acceleration of an object is proportional to the resultant force acting on it and inversely proportional to the mass of the object

resultant force (N) = mass (kg) × acceleration (m/s^2)

Inertial mass – how difficult it is to change an objects velocity. It is defined as the ratio of force over acceleration.

Newton's Laws of Motion: Newton's Third Law

When two objects interact, the forces acting on one another are always equal and opposite.

For example, a book laid on a table is being acted upon by at least two forces: the downward pull of gravity and the upward reaction force from the table surface. The forces are equal and opposite so the book does not move. We describe the forces as being **balanced**.

Braking Distance

The **braking distance** is the distance travelled by a vehicle once the **brakes are applied** and until it reaches a full stop.

Braking distance is affected by:

- **adverse weather conditions** (wet or icy)
- **poor vehicle condition** (brakes or tyres)

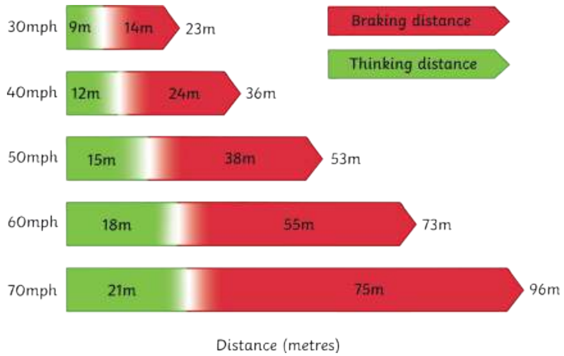
When **force** is applied to the brakes, **work is done** by the **friction** between the car wheels and the brakes.

The work done reduces the **kinetic energy** and it is transferred as **heat** energy, increasing the **temperature** of the brakes.

increased speed = increased force required to stop the vehicle

increased braking force = increased deceleration

Large decelerations can cause a huge increase in **temperature** and may lead to the **brakes overheating** and the driver **losing control** over the vehicle



Momentum

momentum (N) = mass (kg) × velocity (m/s)

The law of conservation of mass (in a closed system) states that the total momentum **before** an event is equal to the total momentum **after** an event.

Worked example:

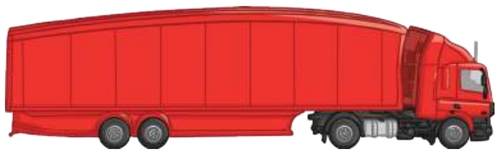
Calculate the momentum of a 85kg cyclist travelling at 7m/s.

p = m × v

p = 85kg × 7m/s

p = 595kg m/s

Worked example: 2



A lorry with a mass of 12 000kg, travelling at 20m/s, collides with a stationary car with a mass of 1500kg. After the collision, the vehicles move off together. Calculate their velocity.

Step 1: find the momentum of each vehicle before the collision.

Calculate the momentum of the lorry:

p = m × v

p = 12 000 × 20 = 240 000kg m/s

Calculate the momentum of the car:

p = m × v

p = 1500 × 0 = 0kg m/s

Step 2: find the total momentum before the collision.

total momentum before = 240 000 + 0 = 240 000kg m/s

Step 3: use the law of conservation of momentum and rearrange the equation.

total momentum before collision = total momentum after collision

$\frac{p}{m} = v$

240 000kg m/s ÷ (12 000 + 1500) = 17.78m/s.

Worked example: 3

A cannon fires a 5kg cannonball at a velocity of 90m/s. The cannon recoils at a velocity of 2m/s after the explosion. Calculate the mass of the cannon.

Step 1: find the total momentum before the explosion.

$p = m \times v$ (for the cannonball)

$p = 5 \times 90 = 450$kg m/s

Although you don't have all the information to calculate the momentum of the cannon, you know it is zero because it is stationary and therefore has a velocity of zero. Since momentum is mass × velocity, you know the momentum will be zero regardless of the mass.

total momentum before = 450kg m/s

Step 2: use the law of conservation of momentum and rearrange the equation.

total momentum before explosion = total momentum after explosion

$\frac{p}{v} = m$

450kg m/s ÷ 2m/s = 225kg

Changes in Momentum

When a force acts on a **moving** or **moveable** object there is a **change of momentum**.

The equations for calculating **force** and **acceleration** can be combined:

$$F = m \times a \text{ and } a = (v - u) \div t$$

To give:

force(N) = change in momentum (kg m/s) ÷ time taken (s)

or

$$F = \frac{m\Delta v}{\Delta t}$$

This equation tells you that the f**orce is equal to the rate of change of momentum** in the object.

Car Safety Features

When people are travelling in a moving car, they have momentum. If the car were to crash and become stationary all of a sudden, the passengers would lose all their momentum. This would result in a large force being exerted; therefore, it is important to change the momentum gradually.

This is done by the seatbelts and the air bags which are fitted into vehicles.

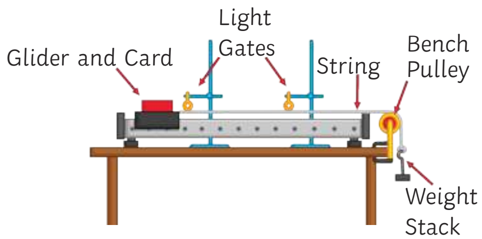
An airbag is also designed to reduce the momentum. The air bag is filled with air as is it deployed and has a small hole inside. As the person makes contact with the airbag, the air is slowly released from the hole and the person is slowed down more gradually.

The force exerted on the passenger is reduced because the time taken to slow them down is increased.

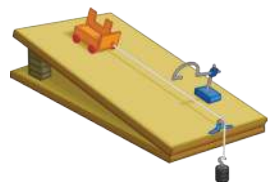
Required Practical Investigation 7

Aim: investigate the effect of varying the force on the acceleration of an object of constant mass, and the effect of varying the mass of an object on the acceleration produced by a constant force.

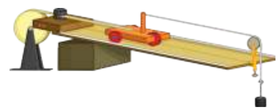
You may be given any of the following apparatus set-ups to conduct these investigations:



or



or



Something is a **fair test** when **only** the independent variable has been allowed to affect the dependent variable.

The independent variable was **force**.

The dependent variable was **acceleration**.

The control variables were:

- **same total mass**
- **same surface/glider/string/pulley (friction)**
- **same gradient if you used a ramp**