Speed, distance, time

Average Speed

Average speed is a measure of the distance travelled in a unit of time.
Average speed is calculated by using this formula:

Distance (m)

$$\text{Average speed (m/s)} \longrightarrow \bar{v} = \frac{d}{t}$$

time (s)

Units of speed

Speed can be measured in many different units.
Usually the unit is metres per second, **m/s** or **m** $\mathbf{s}^{-1}$. This means the distance must be measured in metres and the time taken in seconds.
Note: these notes will use the solidus for multiple units, e.g. m/s. However, you can use the negative index, e.g. m s^{-1}, if you prefer.

Measurement of average speed

To measure an average speed, you must:

- measure the **distance** travelled with a measuring tape or metre stick
- measure the **time** taken with a stop clock
- **calculate** the speed by dividing the distance by the time

Calculations involving distance, time and average speed

Note: care must be taken to use the correct units for time and distance.

Example

Calculate the average speed in metres per second of a runner who runs 1500 m in 5 minutes.

$d = 1500$ m

$t = 5$ minutes $= 5 \times 60$ seconds $= 300$ s ***(Important)***

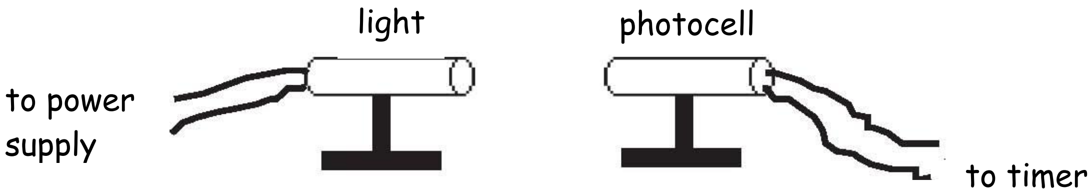
$$v = \frac{d}{t}$$

$$= \frac{1500}{300}$$

$$= 5\,\text{m/s}$$

Instantaneous speed

The instantaneous speed of a vehicle at a given point can be measured by finding the average speed during a **very short time** as the vehicle passes that point.
Average speed and instantaneous speed are often very different e.g. the average speed of a runner during a race will be less than the instantaneous speed as the winning line is crossed.



Measuring instantaneous speeds

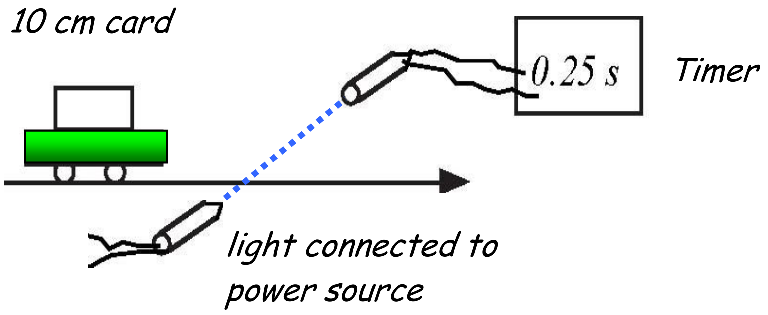
To measure instantaneous speeds, it is necessary to be able to measure **very** short times.
With an ordinary stopclock, human reaction time introduces large errors. These can be avoided by using electronic timers. The most usual is a light gate.

A light gate consists of a light source aimed at a photocell. The photocell is connected to an electronic timer or computer.
The timer measures how long an object takes to pass through the light beam.
The distance travelled is the length of the object which passes through the beam.
Often a card is attached so that the card passes through the beam. The length of the card is easy to measure.
The instantaneous speed as the vehicle passes through the light gate is then calculated using:

$$\text{Speed of vehicle} = \frac{\text{length of card or vehicle}}{\text{time to cut beam}}$$

Example

A vehicle moves through a light gate as shown in the diagram. Using the data from the diagram, calculate the instantaneous speed of the vehicle as it passes the light gate.



$$\text{speed} = \frac{\text{length of card}}{\text{Time to cut beam}}$$

$$\begin{aligned} \bar{v} &= \frac{d}{t} \\ &= \frac{10}{0.25} \\ &= 40 \text{ cm/s} \\ &= 0.4 \text{ m/s} \end{aligned}$$

Vectors and Scalars

Vector and Scalar quantities

Physical quantities can be divided into two groups:

- a **scalar** quantity is completely described by stating its **magnitude** (size).
- a **vector** quantity is completely described by stating its **magnitude** and **direction**.

Distance and Displacement

Distance is the total distance travelled, no matter in which direction.
Displacement is the length measured from the starting point to the finishing point in a straight line. Its direction must be stated.

Speed and Velocity

Speed and velocity are described by the equations below.

$$\text{Speed} = \frac{\text{distance}}{\text{time}}$$

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

Speed is a scalar quantity

$$\text{Velocity} = \frac{\text{displacement}}{\text{time}}$$

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

Velocity is a vector quantity

The direction of the velocity will be the same as the direction of the displacement.

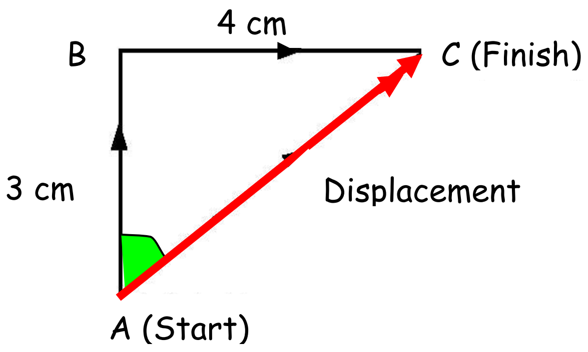
Example

A woman walks 3 km due North and then 4 km due East. She takes two hours.

a) Find the distance she has walked and her displacement.

b) Calculate her average speed and velocity.

We will represent her walk by drawing a diagram to scale. Scale 1cm = 1 km



a)

The **distance** she has travelled is 3 km + 4 km = 7 km.

Her **displacement** is from A to C. This can be measured on the diagram as 5 cm, then converted using the scale to 5 km. Alternatively this can be calculated using Pythagoras.

$AC^2 = 4^2 + 3^2 = 25$ therefore AC = 5km

The angle BAC is measured to find the direction of her final displacement. It is 53°.

Displacement = 5 km at a bearing of (053°).

b)

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

$$v = \frac{7}{2}$$

$$= 3.5\text{km/h}$$

$$\text{Average velocity} = \frac{\text{displacement}}{\text{time}}$$

$$v = \frac{5}{2}$$

$$= 2.5\text{km/h}(053^0)$$

Acceleration

Most vehicles do not travel at the same speed all the time. If they speed up, they are said to accelerate. If they slow down, they decelerate. Acceleration describes **how quickly** velocity changes.

Acceleration is a **vector** quantity. However, only the acceleration of vehicles travelling in straight lines will be considered.

Acceleration is the change in velocity in unit time.

$$\text{Acceleration} = \frac{\text{Change in Velocity}}{\text{time taken}}$$

Units of Acceleration

The units of acceleration are the units of velocity divided by the units of time (seconds).

If the velocity is in m/s, acceleration is in m/s^2 (metres per second squared).

An acceleration of 2 m/s^2 means that every second, the velocity increases by 2 m/s.

Formula for Acceleration

Note: If a vehicle is slowing down, the final velocity will be smaller than the initial velocity, and so the acceleration will be negative.

Final velocity (m/s)

Initial velocity (m/s)

Acceleration (m/s^2)

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

Time (s)

A negative acceleration is a deceleration.

The equation for acceleration can be rearranged to give an alternative version.

$v = u + at$

Example

A car is moving at 15 m/s, when it starts to accelerate at 2 m/s^2. What will be its speed after accelerating at this rate for 4 seconds?

u = 15 m/s

a = 2 m/s^2

t = 4 s

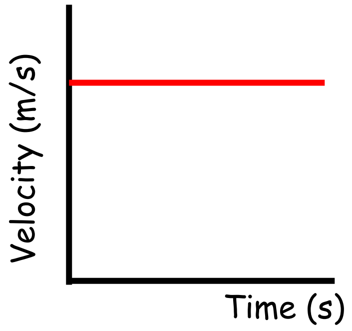
$$\begin{aligned} v &= u + at \\ &= 15 + (2 \times 4) \\ &= 23 \text{ m/s} \end{aligned}$$

The car will reach a speed of 23 m/s

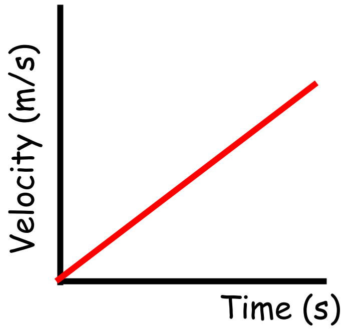
Velocity-time graphs

A velocity-time graph is a useful way to describe the motion of a vehicle.
Time is always plotted along the x-axis, and velocity is plotted along the y-axis.

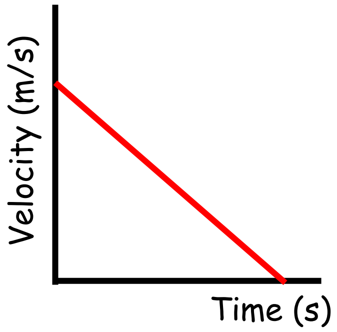
The **shape** of the graph indicates whether the vehicle is accelerating, decelerating or moving at a constant velocity.



constant velocity



increasing velocity
= acceleration



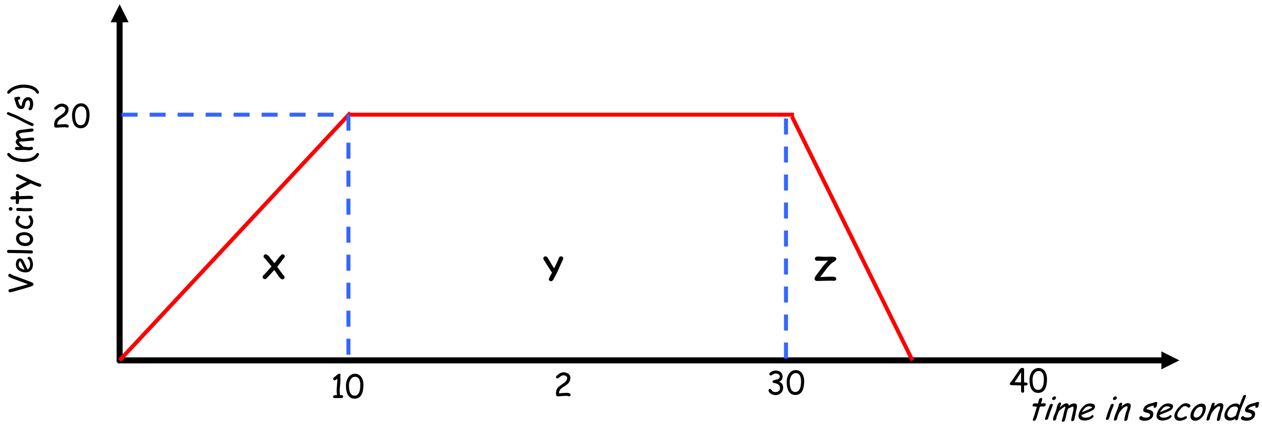
decreasing speed
= deceleration

The **slope** (or gradient) of the line on a velocity-time graph indicates the **acceleration**. While the slope is steady, the acceleration is constant. If the line gets steeper, the acceleration (or deceleration) gets greater.

Acceleration can be calculated using data from the graph and the formula.
The **area** vertically below a section of the graph is equal to the displacement during that time.

Example

The graph describes the motion of a car during 35 seconds.
a) What was the initial acceleration of the car?
b) What was the deceleration?
c) How far did the car travel in the 35 seconds?



a) initial acceleration lasts from 0 - 10 s: u = 0, v = 20 m/s, t = 10 s

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

$$= \frac{20 - 0}{10} \quad =$$

$$= 10 \text{ m} / \text{s}^2$$

b) deceleration was from 30 -35 s: u = 20 m/s, v = 0, t = 5 s

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

$$= \frac{0 - 20}{5}$$

$$= -4 \; m / s^2$$

c) distance travelled = area under graph:

divide into sections of rectangles and triangles: X + Y + Z: use scale for sizes
area X = 1/2 base x height = 1/2 × 10 × 20 = 100 m
area Y = length × breadth = 20 × 20 = 400 m
area Z = 1/2 base × height = 1/2 × 5 × 20 = 50 m

Total area = 550 m so: distance travelled = 550 m

Forces

Effects of forces

Forces can only be detected by their effects.

They can change: • the shape of an object (stretch it, squeeze it etc)

- the speed of an object
- the direction of movement of an object

Measurement of Forces

Forces are measured in units called **newtons** (N). (see later for definition)

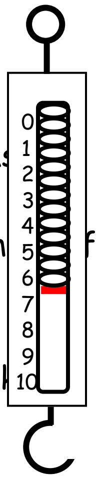
Forces can be measured with a newton balance. This instrument depends on the effect of a force on the shape (length) of a spring.

Mass and Weight

Weight is a force caused by gravity acting on an object's mass. On Earth, it meas the pull of the Earth on the object. It is measured in **newtons**.

Weight always acts vertically downwards. Its size does not just depend on the m f the object, but on the strength of gravity at that place.

Mass measures the amount of matter in an object. It is measured in **kilograms** (k



The value of mass does not change from place to place.

The strength of gravity in a particular place is called **the gravitational field strength**.

This tells you the weight of 1 kilogram. Its symbol is **g** and its unit is **N/kg**.

On Earth, g = 10 N/kg.

Mass and weight are connected by the following formula:-

$$\boxed{W = mg}$$

Weight (N)

Acceleration due to gravity (m/s^2)
OR
Gravitational field strength (N/Kg)

mass (Kg)

Example

a) What is the weight of a 50 kg girl on Earth?

b) What would she weigh on the moon where the gravitational field strength is 1.6 N/kg?

a) W = mg = 50 x 10 = 500 N

b) W = mg = 50 x 1.6 = 80 N

The Force of Friction

Friction is a **resistive** force, which opposes the motion of an object. This means that it acts in the **opposite** direction to motion. Friction acts between any two surfaces in contact. When one surface moves over another, the force of friction acts between the surfaces and the size of the force depends on the surfaces, e.g. a rough surface will give a lot of friction.

Air friction is usually called **air resistance**. It depends mainly on two factors:

- the shape and size of the object
- the speed of the moving object.

Air resistance **increases** as the speed of movement increases.

Increasing and Decreasing Friction

Where friction is making movement difficult, friction should be reduced.
This can be achieved by:

- lubricating the surfaces with oil or grease
- separating the surfaces with air, e.g. a hovercraft
- making the surfaces roll instead of slide, e.g. use ball bearings
- streamlining to reduce air friction.

Where friction is used to slow an object down, it should be increased.
This can be achieved by:

- choosing surfaces which cause high friction e.g. sections of road before traffic lights have higher friction than normal roads
- increasing surface area and choosing shape to increase air friction, e.g. parachute.

Forces are Vectors

A force is a vector quantity because to describe it properly requires a direction as well as size.

Two forces which are equal in size but which act in opposite directions are called **balanced** forces. Balanced forces have the same effect as **no force** at all.

Newton's First Law

When the forces on an object are balanced (or when there are no forces at all), then neither the speed nor direction of movement will change.

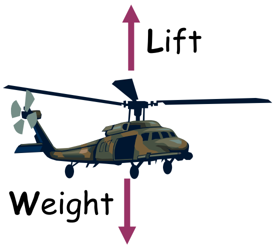
Balanced forces mean **constant velocity** or the object is **stationary**.

Examples of balanced forces

Parachutist drifting down at **steady speed** (terminal velocity)

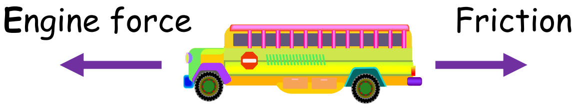
Weight down = **A**ir **R**esistance up

Stationary hovering helicopter



Weight down = **L**ift up

Bus at **steady speed**



Engine force forward = **F**riction forces backwards

Newton's Second Law of Motion

This law deals with the situation when there is an **unbalanced** force acting on an object. The velocity cannot remain constant, and the acceleration produced will depend on the mass of the object and the value of the unbalanced force.

As the unbalanced force acting on an object increases, the acceleration increases also.

As the accelerated mass increases, the acceleration decreases for a given force.

The **newton** is defined as the force which makes a mass of 1 kg accelerate at 1 m/s^2.

These facts can be summarised in an equation:

force (N)
(Unbalanced or resultant)

$$\boxed{F = ma}$$

acceleration (m/s^2)

mass (Kg)

Example
A car of mass 1000 kg has an unbalanced force of 1600 N acting on it.
What will be its acceleration?

m = 1000 kg *a = ?* *F = 1600 N*

$$a = \frac{F}{m}$$
$$= \frac{1600}{1000}$$
$$= 1.6\ m / s^2$$

Resultant Forces

When several forces act on one object, they can be replaced by one force which has the same effect. This single force is called the **resultant** or **unbalanced** force.

Combining forces in a straight line

Draw a diagram of the object and mark in all the forces acting, using an arrow to represent each force. (Do not forget weight, which is often not specifically mentioned in the question).

Use arithmetic to find the resultant:

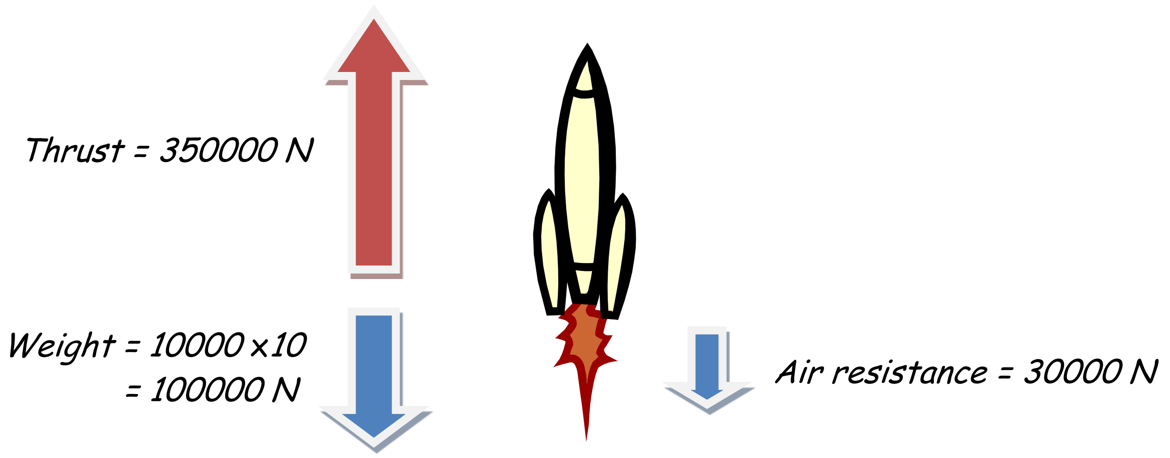
- **add** together forces which act in the **same** direction
- **subtract** forces which act in the **opposite** direction.

A diagram like this is called a **free body diagram**.

Example

A short time after take off, a rocket of mass 10000 kg has a thrust of 350000 N and experiences air resistance of 30000 N.

Draw a free body diagram and find the resultant force acting on the rocket.



Total upward force = 350000 N

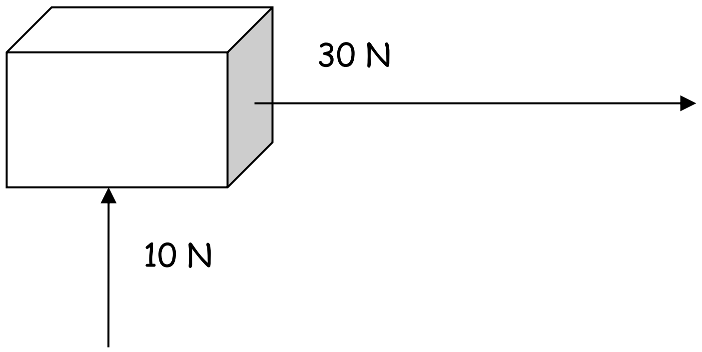
Total downward force = 100000 N + 30000 N = 130000 N

Resultant force upwards = 350000 – 130000 = 220000 N

Combining forces at right angles

There are two possible methods for finding the size and direction of the resultant of two forces acting at right angles to each other.

- Draw a scale diagram:
- Use Pythagoras and trig functions.

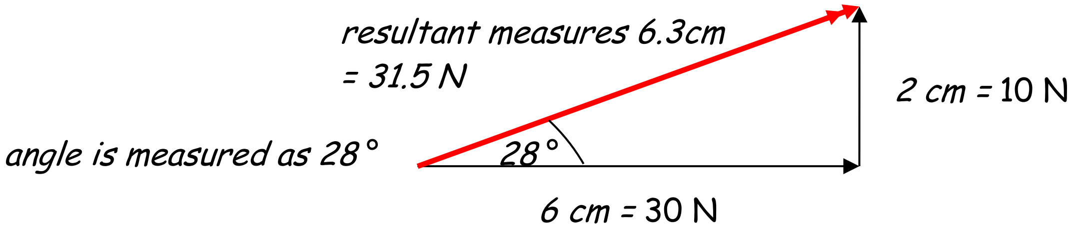


Example

What is the resultant force produced by two forces of 10 N and 30 N which act on an object as shown in the diagram?

Method 1: scale diagram *Choose Scale: 1 cm = 5 N*

Draw vectors head to tail, complete triangle, then measure resultant size and direction.



Resultant = 6.3 cm *F = 31.5 N at an angle of 28° to the 30 N force.*

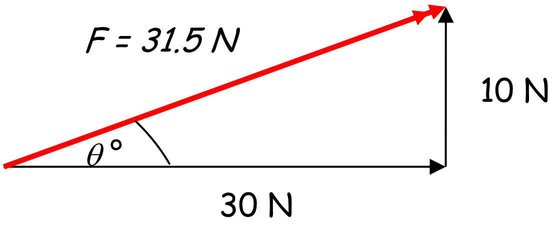
Method 2: Pythagoras and trig functions

Draw sketch of vector diagram, but not to scale.

Calculations using F = ma for more than one force

Draw a free body diagram and mark in all the known forces. Use this to calculate the resultant force (F in the equation) before using the equation.

$$\begin{aligned} F &= \sqrt{30^2 + 10^2} \\ &= \sqrt{900 + 100} \\ &= \sqrt{1000} \\ &= 31.5\text{N} \end{aligned}$$



$$\tan\theta = \frac{\text{opposite}}{\text{adjacent}}$$

$$\tan\theta = \frac{10}{30}$$

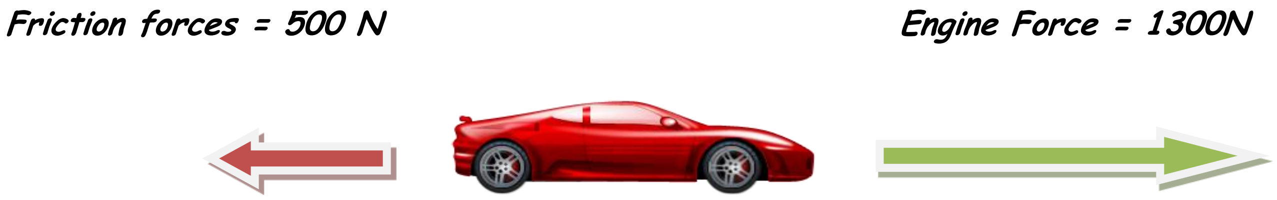
$$\theta = (\tan^{-1} 0.33)$$

$$\theta = 28^\circ$$

Resultant Force = 31.5 N at an angle of 28 ° to the 30 N force.

Example

A car of mass 1000 kg experiences friction equal to 500 N. If the engine force is 1300 N, what will be the car's acceleration?



Resultant force = 1300 – 500 = 800 N mass = 1000Kg

$$\begin{aligned} a &= \frac{F}{m} \\ &= \frac{800}{1000} \\ &= 0.8\ \text{m/s}^2 \end{aligned}$$

Acceleration due to gravity and gravitational field strength

Weight is the force which causes an object to accelerate downwards and has the value mg,
where g is the gravitational field strength.
The value of the acceleration caused by weight can be calculated from Newton's second law,
using the equation F = ma where F is now the weight W, and W = mg.

$$a = \frac{F}{m} = \frac{mg}{m} = g$$ where g is in m/s^2

The numerical values of the acceleration due to gravity and gravitatonal field strength are equal.
Their units, N/kg and m/s^2 are also equivalent.

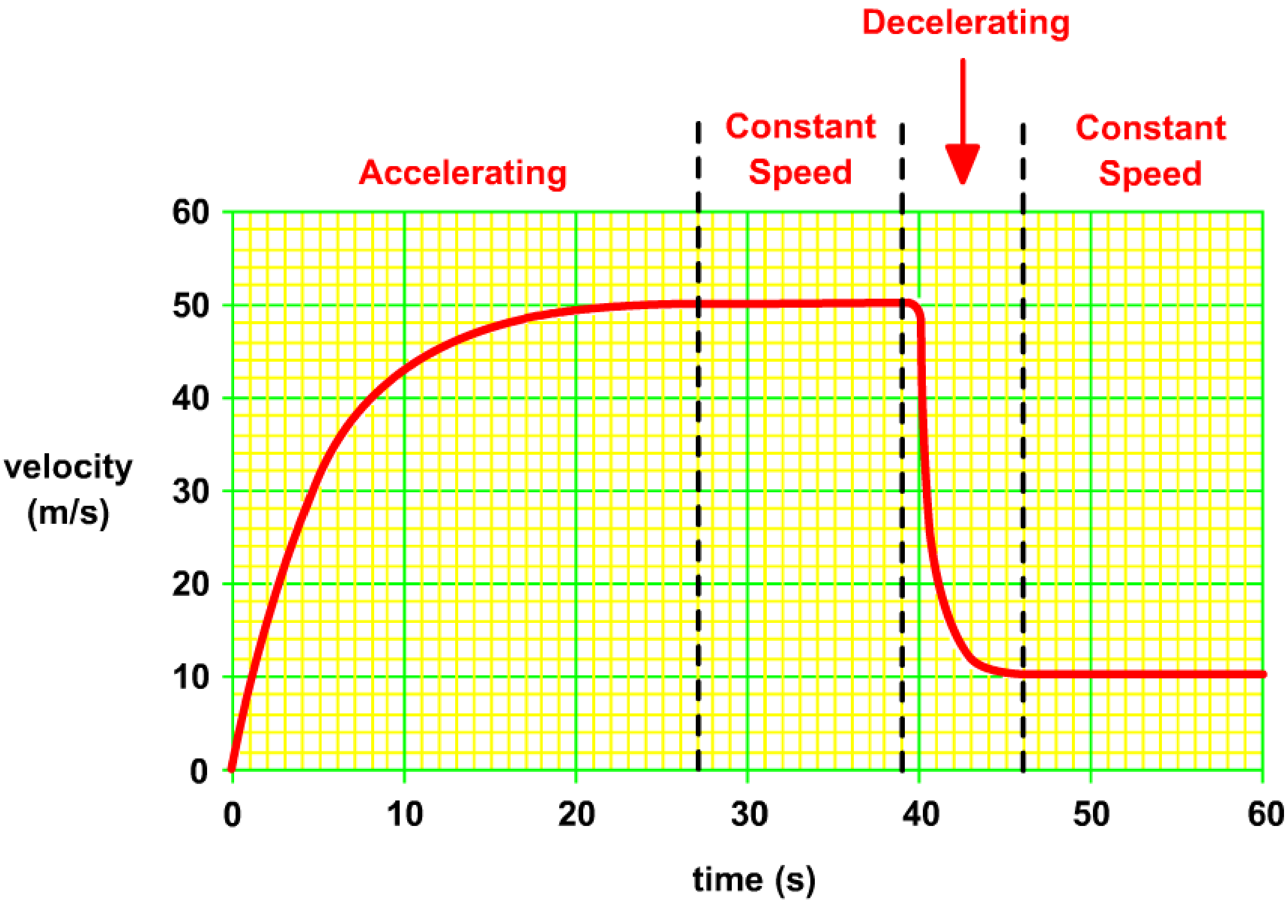
Free-fall and Terminal Velocity

An object falling from a height on Earth will **accelerate** due to its weight. This is called **free-fall**.

As the velocity increases, the air resistance acting on the object will increase. This means that the unbalanced force on the object will decrease, producing a smaller acceleration. Eventually, the air resistance will balance the object's weight, meaning that the object will fall with a **constant velocity**.

This final velocity is called **terminal velocity**.

The velocity-time graph shown below is for a parachutist undergoing free-fall before opening her parachute.



Point A – parachutist jumps from plane and undergoes acceleration due to gravity **(free-fall)**

Point B – air resistance has increased to balance weight – constant velocity: **terminal velocity 1**

Point C – parachutist opens parachute – increased air resistance causes deceleration

Point D – weight and air resistance balanced again so new slower constant velocity reached: **terminal velocity 2**

Projectile Motion

A projectile is an object which has been given a forward motion through the air, but which is also pulled downward by the force of gravity. This results in the path of the projectile being curved.

A projectile has two **separate** motions at right angles to each other.
Each motion is **independent** of the other.

The **horizontal** motion is at a **constant velocity** since there are no forces acting horizontally(air resistance can be ignored).

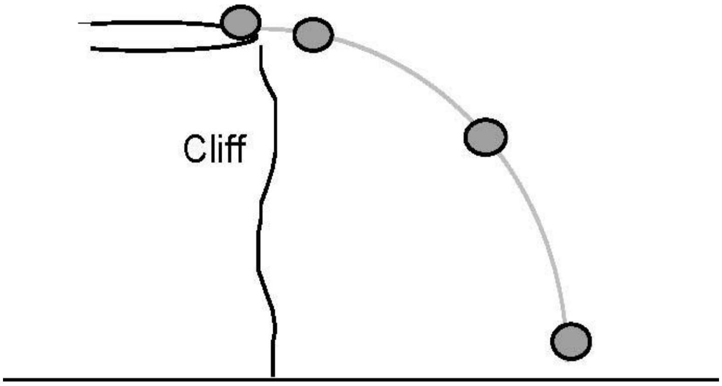
Horizontal distance travelled = horizontal velocity x time in the air. ($S_h = v \times t$)

The **vertical** motion is one of **constant acceleration**, equal to g.

For projectiles which are projected horizontally, the initial vertical velocity is zero.
For vertical calculations, use $v = u + at$, where $u = 0$ and $a = g$

Example

A ball is kicked horizontally at 5 m/s from a cliff top as shown below.
It takes 2 seconds to reach the ground.



a) What horizontal distance did it travel in the 2 seconds?
b) What was its vertical speed just before it hit the ground? (Take g = 10 m/s2)

Horizontal

a) $v = 5$ m/s
$t = 2$ s

$s_H = v \times t$
$= 5 \times 2$
$= 10$ m

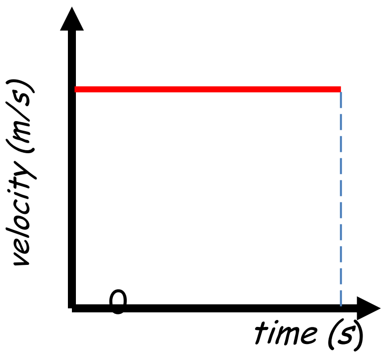
Vertical

b) $u = 0$
$a = 10$ m/s^2
$t = 2$ s

$v = u + at$
$= 0 + 10 \times 2$
= 20 m/s

Velocity time graphs for horizontal and vertical motion

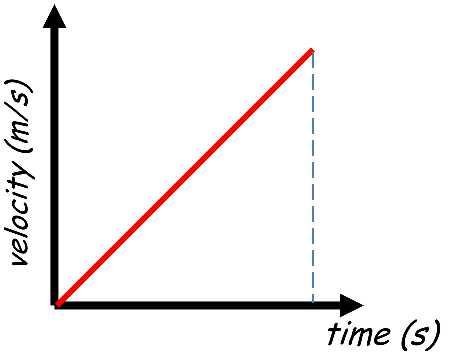
Horizontal motion



constant horizontal velocity

horizontal distance can be found using area area under graph (equivalent to $d_h=v_ht$)

Vertical motion



constant acceleration from rest

constant acceleration from rest vertical height can be found from under graph (equivalent to $h=\frac{1}{2} v_{max}t$)

Example

An aircraft flying horizontally at 200 m/s drops a food parcel which lands on the ground 12 seconds later. Calculate:

a) the horizontal distance travelled by the food parcel after being dropped
b) the vertical velocity of the food parcel just before it strikes the ground
c) the height that the food parcel was dropped from.

Solution

(a useful layout is to present the horizontal and vertical data in a table)
(then select the data you need for the question, and clearly indicate whether you are using horizontal or vertical data).

Horizontal	**Vertical**
$V_h = \frac{d_h}{t}$	$V_v = u_v + at$
d_h = ?	u_v = 0
v_h = 200 m/s	v_v = ?
	$a = 10\ m/s^2$
t = 12 s	t = 12 s

initial vertical velocity = 0 for a projectile launched horizontally

Time of flight the same for both

(a) Horizontal:

d_h = ? V_h = 200 m/s t = 12 s

$d_h = V_h t$

$d_h = 200 \times 12$

$d_h = \underline{\underline{2400 \text{ m}}}$

(b) Vertical

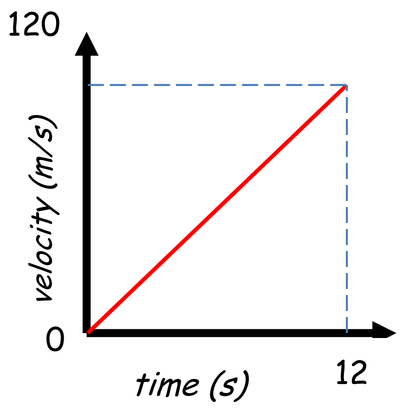
$U_v = 0$ $V_v = ?$ $a=10 \text{ m/s}^2$ t= 12s

$V_v = U_v + at$

$V_v = 0 + 10 \times 12$

$V_v = 120$ m/s

(c) (Draw a velocity time graph of **vertical** motion)



height = area under v-t graph

$= \frac{1}{2} \times 12 \times 120$

$= \underline{\underline{720 \text{ m}}}$

Newton's Third Law

Newton noticed that forces occur in pairs.
He called one force the **action** and the other the **reaction**.
These two forces are always **equal in size, but opposite in direction**. They do not both act on the same object.

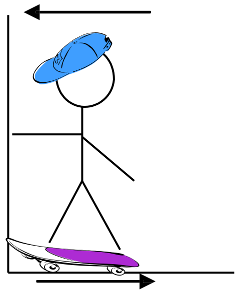
Newton's Third Law can be stated as:

> **If an object A exerts a force (the action) on object B, then object B will exert an equal, but opposite force (the reaction) on object A.**

Newton Pairs

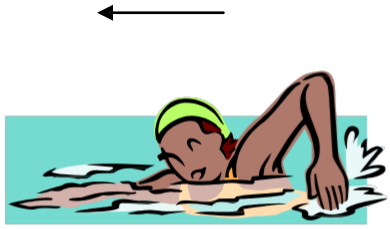
Examples These action and reaction forces are also known as **Newton Pairs.**

Skateboarder pushes wall to the left (action force)



Wall pushes skateboarder to right (reaction force)

Swimmer pushes water to right (action force

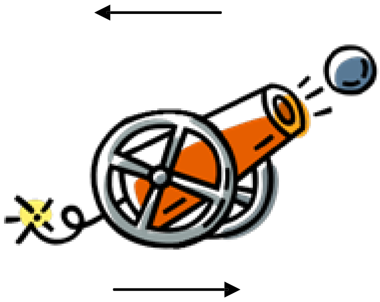


Water pushes swimmer to left (reaction force)

Fuel forces rocket upwards (reaction force)

Rocket forces fuel downwards (action force)

Cannon fires cannonball to the right (action force)



Cannonball forces back to the left (reaction force)

Momentum

Momentum is the product of mass and velocity. Its unit is the kilogram metre/second (kg m/s)
Momentum is a **vector** quantity, but this course will only consider situations where all the objects move in the same direction.

Conservation of momentum

When two objects collide, the momentum of each changes as a result of the forces acting between the objects.

However, **providing there are no external forces,**

the total momentum before the collision = the total momentum after the collision.

This statement is known as the Law of Conservation of Momentum. This law can be used to calculate velocities in collisions.

Example

A car of mass 1000 kg travelling at 20 m/s collides with a stationary van of mass 1200 kg. If the van moves off at 5 m/s, what will be the velocity of the car after the collision?

Before After

Total momentum before = Total momentum after

(1000 x20) + 0 = (1000 x v) + (1200 x 5)

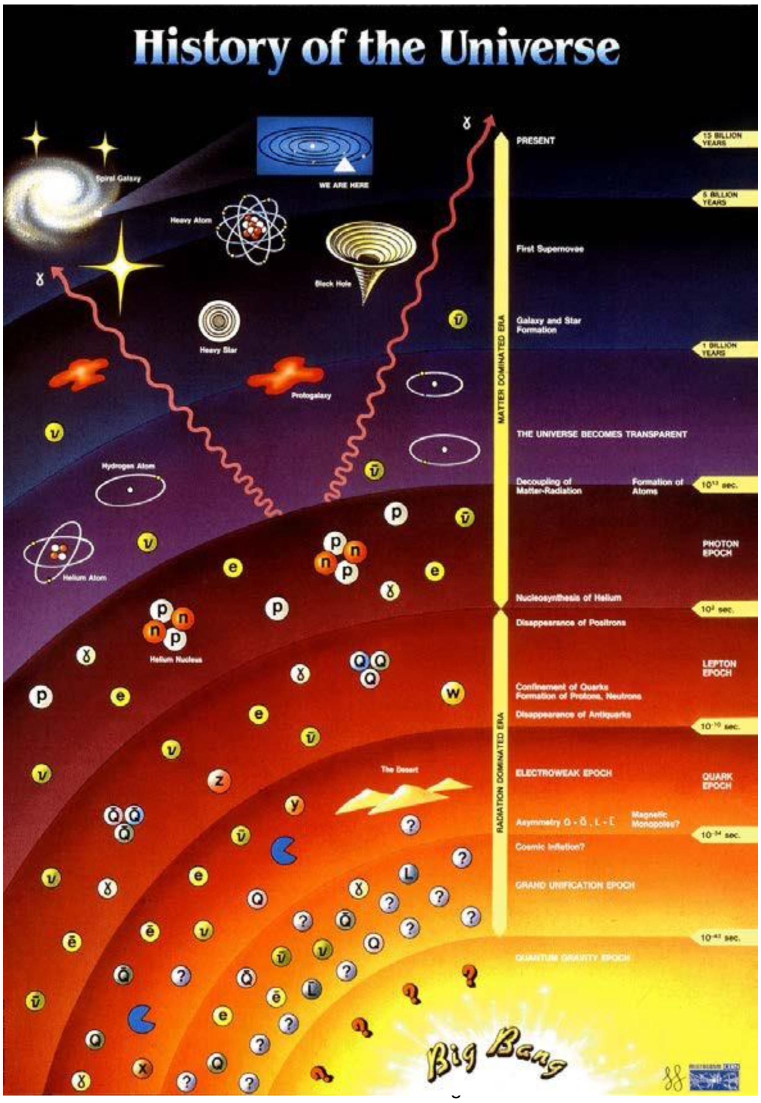
20000 = 1000 v + 6000

1000 v = 14000

velocity of car after collision = 14 m/s forwards.

The Universe

Scientific evidence indicates that we live in a finite but ever expanding universe. The universe started at a certain point in time and at that time all the matter, energy and space in the universe was squeezed into an infinitesimally small volume. Something caused a sudden and dramatic expansion, the story of this expansion has become known as the Big Bang Theory. It is just a model to describe what happened at the beginning but it was not an actual explosion. (The phrase "Big Bang" was introduced by accident when English astronomer Fred Hoyle used it as an insulting description of the theory he disagreed with). The Big Bang Theory is currently considered by many scientists as the most likely scenario for the birth of universe. The finer details of the early universe will continue to be revised as our understanding increases in years to come. Current best estimates are that the universe began 13.8 billion years ago.



What is the universe?

The universe contains planets, which orbit stars (Solar systems). These stars exist in massive collections called galaxies. Galaxies exist in clusters (groups of galaxies) and these clusters exist in super clusters which are evenly dispersed across the whole of the universe.

http://images.sciencedaily.com/2010/04/100413202858-large.jpg

http://www.le.ac.uk/ph/faulkes/web/images/galaxies.jpg

How big is the Universe?

The Universe is massive, so big it is pretty much impossible to really imagine how big it is! It is estimated that the universe is at least 9.2 x 10^{26} metres wide. This number is too large to really comprehend; indeed all distances in the universe are huge. The Earth is approximately 150 million kilometres away from the Sun and approximately 39.9 x 10^{12} km away from Proximal Centauri (the nearest star to our Solar system). These numbers are just too big so astronomers use a longer standard unit of distance – The Light Year.

The light year is a measure of distance
and is the distance that light travels in one year

How many metres are in a light year?

d = ?

v = 3 x 10^8 m/s

t = 1 year = 365 x 24 x 60 x 60

= 31 536 000 s

d = s x t

d = 3 x 10^8 x 31 536 000

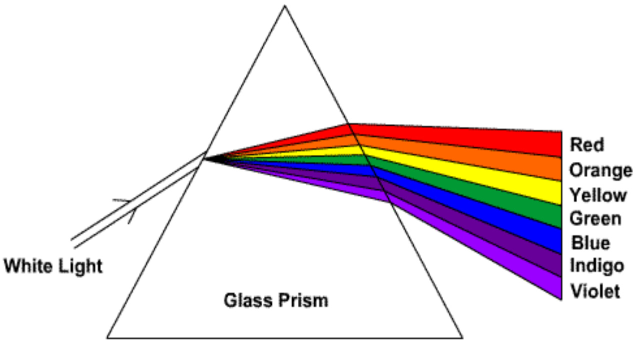
= 9.46 x 10^{15} m

There are **9.46 x 10^{15} m** in a light year.
You must be able to convert distances in light years into metres.

How Do Scientists Know the Composition of the Universe?

The simple answer is by looking! Looking with our eyes we can see (on a very clear night) approximately 2000 stars in the night sky at any one time. However, using telescopes we can capture more light and so we can see stars that are not visible to the naked eye. This is when the fun really begins.

Most stars look white to the naked eye (some look blue or red) however much like when watching TV or using an energy efficient bulb our brain is being tricked. Red, blue and green light shone together look white. When white light is shone through a prism, a continuous spectrum is visible.



Looking at this spectrum in details reveals all the visible colours as shown below. White light produces a continuous spectrum displaying all visible colours.

http://highered.mcgraw-hill.com/sites/dl/free/0072415932/9304/spectrumc.gif

All atoms give off light when heated, although sometimes this light is not visible to the human eye. (genera red and UV). A prism can be used to split the light from the atoms to form a spectrum. Each element produces a distinctive and unique line spectrum. The coloured lines (or Spectral Lines) are a kind of "fingerprint" or "barcode" for the atoms. This technique is known as spectroscopy. A Spectroscope is a device that allows detailed spectra to be captured. Example spectra are given below.

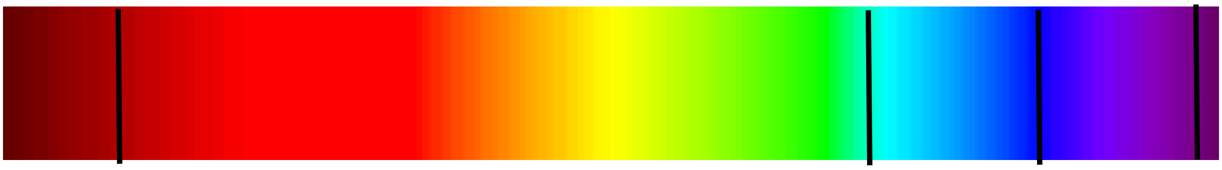
Hydrogen

Helium

Nitrogen

As can be seen above, each atom has its own colour spectrum.

A gas can also absorb energy, the emission and absorption lines appear in the same position but for an absorption spectra we see dark lines as shown below. It is the absorption lines that are used to identify gases within stars. Shown below is the absorption spectra for hydrogen.



Using the Rest of the Electromagnetic Spectrum to Investigate the Universe.

Observations of light from other parts of the e.m. spectrum have allowed a greater understanding of the origin, composition and history of the Universe.

Range of em spectrum	Information gained
Gamma rays & x rays	Extremely high energy particles, cosmic explosions, high speed collisions can be detected. Material moving at extremely high speeds emit these rays. Some emanate from supernovae remnants.
Ultra-violet	Very young massive stars, some very old stars, bright nebulae, white dwarfs stars, active galaxies and quasars shine brightly in the ultraviolet region.
Visible	Chemical composition of the stars, particles at the outer edges of nebula
Infra Red	Infrared observations are used to peer into star-forming regions and into the central areas of our galaxy. Cool stars and cold interstellar cloud are detected.
Radio Waves	The study of the radio universe brought us the first detection of the radiation left over from the Big Bang. Radio waves also bring us information about supernovae, quasars, pulsars, regions of gas between the stars, and interstellar molecules.

http://chemistry.bd.psu.edu/jircitano/periodic4.html
http://www.winsornewton.com/assets/hints_tips/Colour%20Mixing/add_colour.jpg
http://annandiluz.files.wordpress.com/2012/08/ligh t_dispersion1.gif