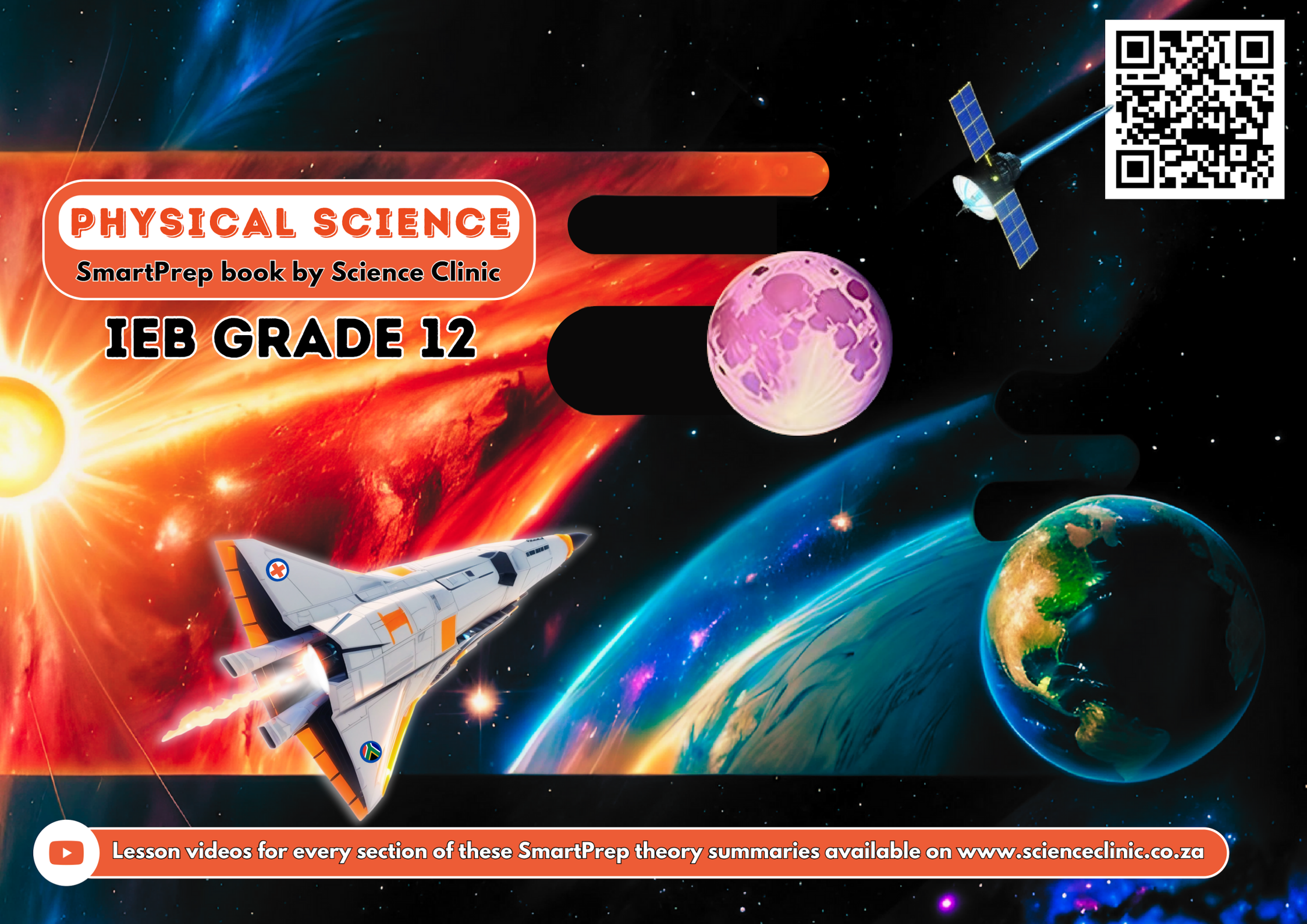

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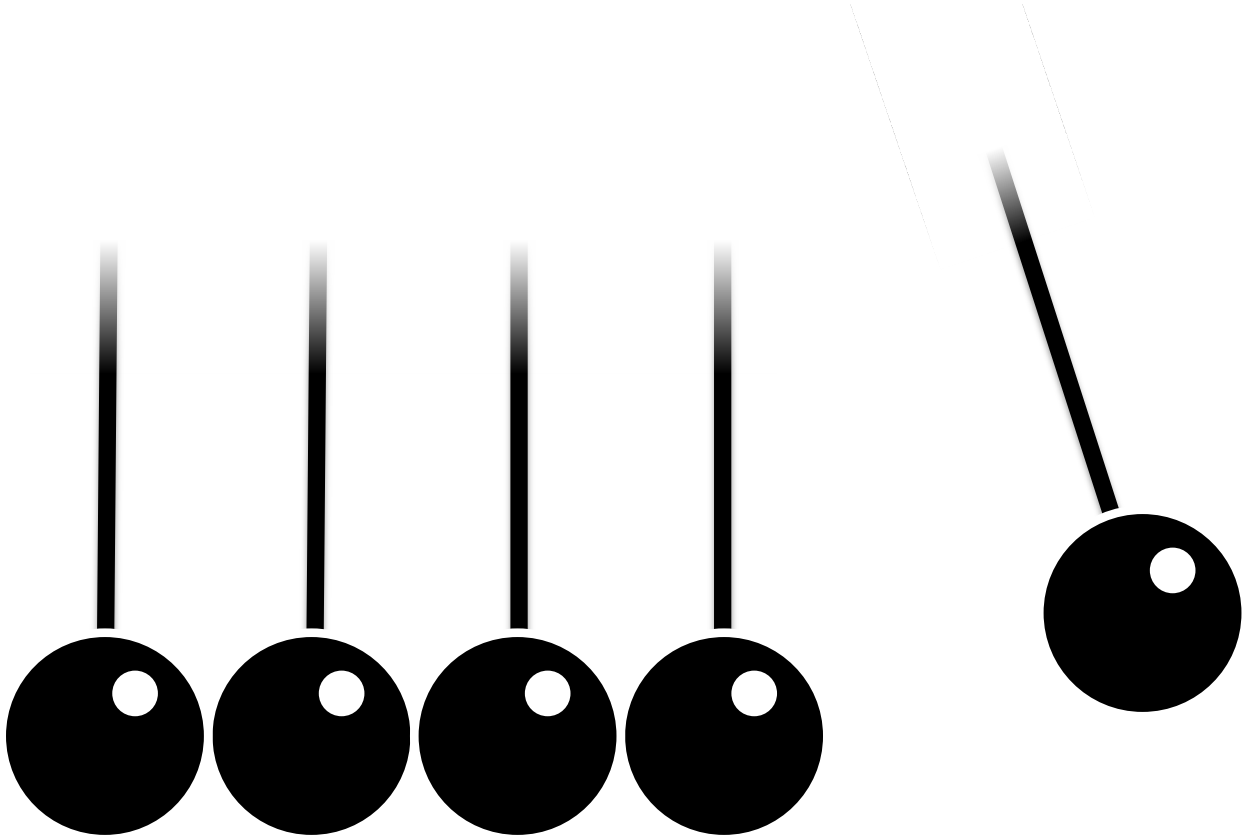
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# Physics



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# EXAMINATION DATA SHEET FOR THE PHYSICAL SCIENCES (PHYSICS)

## TABLE 1 PHYSICAL CONSTANTS

| NAME | SYMBOL | VALUE |
|---|---|---|
| Acceleration due to gravity | g | $9{,}8\ \text{m·s}^{-2}$ |
| Speed of light in a vacuum | c | $3{,}0 \times 10^{8}\ \text{m·s}^{-1}$ |
| Universal gravitational constant | G | $6{,}7 \times 10^{-11}\ \text{N·m}^2\text{·kg}^{-2}$ |
| Coulomb's constant | k | $9{,}0 \times 10^{9}\ \text{N·m}^2\text{·C}^{-2}$ |
| Magnitude of charge on electron | e | $1{,}6 \times 10^{-19}\ \text{C}$ |
| Mass of an electron | $m_e$ | $9{,}1 \times 10^{-31}\ \text{kg}$ |
| Planck's constant | h | $6{,}6 \times 10^{-34}\ \text{J·s}$ |
| 1 electron volt | eV | $1{,}6 \times 10^{-19}\ \text{J}$ |

## TABLE 2 PHYSICS FORMULAE

### MOTION

| | |
|---|---|
| $v = u + at$ **or** $v_f = v_i + a\Delta t$ | $s = \left(\frac{v+u}{2}\right)t$ **or** $\Delta x = \left(\frac{v_f + v_i}{2}\right)\Delta t$ |
| $v^2 = u^2 + 2as$ **or** $v_f^{\,2} = v_i^{\,2} + 2a\Delta x$ | $s = ut + \frac{1}{2}at^2$ **or** $\Delta x = v_i\Delta t + \frac{1}{2}a(\Delta t)^2$ |

### FORCE AND MOMENTUM

| | | |
|---|---|---|
| $F_{net} = ma$ | $F_{net} = \frac{\Delta p}{\Delta t}$ **or** $F_{net}\Delta t = m\Delta v$ | $J = \Delta p = mv - mu$ **or** $J = \Delta p = mv_f - mv_i$ |
| $p = mv$ | $F_g = mg$ | $F_{fs}^{\max} = \mu_s F_N$<br>$F_{fk} = \mu_k F_N$ |

### WORK, ENERGY AND POWER

| | | | |
|---|---|---|---|
| $W = Fs$ **or** $W = F\Delta x$ **or** $W = F\Delta x\cos\theta$ | | $P = \frac{W}{t}$ | $P = Fv$ |
| $E_p = mgh$ | $E_k = \frac{1}{2}mv^2$ | $W_{net} = \Delta E_K$ | $\text{efficiency} = \frac{\text{power}_{\text{out}}}{\text{power}_{\text{in}}} \times 100$ |

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## GRAVITATIONAL AND ELECTRIC FIELDS

| | | |
|---|---|---|
| $F = G\frac{m_1 m_2}{r^2}$ | $g = \frac{F}{m}$ | $g = G\frac{M}{r^2}$ |
| $F = k\frac{q_1 q_2}{r^2}$ | $E = \frac{F}{q}$ | $E = \frac{kQ}{r^2}$ |

## ELECTRIC CIRCUITS

| | |
|---|---|
| $I = \frac{q}{t}$ | $V = \frac{W}{q}$ |
| $R = \frac{V}{I}$ | $emf = I(R_{ext} + r)$ **or** $emf = V_{load} + V_{internal\ resistance}$ |
| $R_S = R_1 + R_2 + .....$ | $\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2} + .....$ |
| $P = \frac{W}{t}$ **or** $W = Pt$ | |
| $W = VIt$ **or** $W = I^2Rt$ **or** $W = \frac{V^2}{R}t$ | |
| $P = VI$ **or** $P = I^2R$ **or** $P = \frac{V^2}{R}$ | |

## ELECTRODYNAMICS

| | | |
|---|---|---|
| $\Phi = BA\cos\theta$ | $\text{emf} = -\frac{N\Delta\Phi}{\Delta t}$ | $F = IB\ell\sin\theta$ |
| $V_p I_p = V_s I_s$ | $\frac{N_s}{N_p} = \frac{V_s}{V_p}$ | |

## PHOTONS AND ELECTRONS

| | | |
|---|---|---|
| $c = f\lambda$ | $E = hf$ **or** $E = \frac{hc}{\lambda}$ | |
| $E = W_0 + E_{K(\max)}$ | $W_0 = hf_0$ | $E_{K(max)} = \frac{1}{2}mv_{max}^2$ |

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# Grade 12 Physics Definitions



| | |
|---|---|
| **Vectors and Scalars** | **Vector:** A physical quantity that has both magnitude and direction<br>**Scalar:** A physical quantity that has magnitude only<br>**Resultant vector:** A single vector which has the same effect as the original vectors acting together<br>**Distance:** Length of path travelled<br>**Displacement:** A change in position<br>**Speed:** Rate of change of distance<br>**Velocity:** Rate of change of position (or displacement)<br>**Acceleration:** Rate of change of velocity |
| **Newton's Laws** | **Weight ($F_g$):** The gravitational force the Earth exerts on any object on or near its surface<br>**Normal force ($F_N$):** The perpendicular force exerted by a surface on an object in contact with it<br>**Frictional force due to a surface ($F_f$):** The force that opposes the motion of an object and acts parallel to the surface with which the object is in contact<br>**Newton's First Law of Motion:** An object continues in a state of rest or uniform (moving with constant) velocity unless acted upon by a net or resultant force<br>**Inertia:** The property of an object that causes it to resist a change in its state of rest or uniform motion<br>**Newton's Second Law of Motion**: When a net force, $F_{net}$, is applied to an object of mass, m, it accelerates in the direction of the net force. The acceleration, a, is directly proportional to the net force and inversely proportional to the mass<br>**Newton's Third Law of Motion:** When object A exerts a force on object B, object B simultaneously exerts an oppositely directed force of equal magnitude on object A<br>**Newton's Law of Universal Gravitation:** Every particle with mass in the universe attracts every other particle with a force which is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centres<br>**Gravitational field:** The force acting per unit mass |
| **Momentum and Impulse** | **Momentum**: The product of the mass and velocity of the object<br>**Newton's Second Law in terms of Momentum:** The net force acting on an object is equal to the rate of change of momentum<br>**Impulse (J):** The product of the net force and the contact time<br>**Law of conservation of linear momentum:** The total linear momentum of an isolated system remains constant (is conserved)<br>**Elastic collision**: A collision in which both momentum and kinetic energy are conserved<br>**Inelastic collision:** A collision in which only momentum is conserved |
| **Work, Energy and Power** | **Work done on an object**: The product of the displacement and the component of the force parallel to the displacement<br>**Gravitational potential energy:** The energy an object possesses due to its position relative to a reference point<br>**Kinetic energy:** The energy an object has as a result of the object's motion<br>**Mechanical energy:** The sum of gravitational potential and kinetic energy at a point<br>**Law of conservation of energy:** The total energy in a system cannot be created nor destroyed; only transformed from one form to another<br>**Principle of conservation of mechanical energy**: In the absence of air resistance or any external forces, the mechanical energy of an object is constant<br>**Work-energy theorem:** Work done by a net force on an object is equal to the change in the kinetic energy of the object<br>**Power**: The rate at which work is done OR rate at which energy is transferred<br>**Watt:** The power when one joule of work is done in one second<br>**Efficiency:** The ratio of output power to input power |
| **Electrostatics** | **Coulomb's law:** Two point charges in free space or air exert a force on each other. The force is directly proportional to the product of the charges and inversely proportional to the square of the the distance between the charges.<br>**Electric field at a point:** The force per unit positive charge |
| **Electric Circuits** | **Potential difference:** The work done per unit positive charge<br>**Current:** The rate of flow of charge<br>**Ohm's law**: Current through a conductor is directly proportional to the potential difference across the conductor at constant temperature<br>**Resistance:** A material's opposition to the flow of electric current<br>**Emf:** The total energy supplied per coulomb of charge by the cell |
| **Electrodynamics** | **Magnetic flux density:** Is a representation of the magnitude and direction of the magnetic field.<br>**Magnetic flux linkage:** Product of the number of turns on the coil and the flux through the coil.<br>**Faraday's law of electromagnetic induction**: The emf induced is directly proportional to the rate of change of magnetic flux (flux linkage)<br>**Lenz's law**: The induced current flows in a direction so as to set up a magnetic field to oppose the change in magnetic flux<br>**Diode:** A component that only allows current to flow in one direction |
| **Optical Phenomena and Properties of Materials** | **Threshold (cut-off) frequency ($f_o$):** the minimum frequency of incident radiation at which electrons will be emitted from a particular metal<br>**Work function ($W_o$):** the minimum amount of energy needed to emit an electron from the surface of a metal |

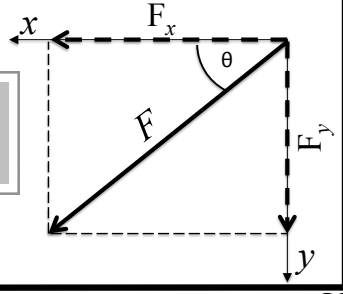
# VECTORS IN 2D



## RESOLVING INTO COMPONENTS

Diagonal vectors can be broken into components. When vectors are broken into the x- and y-components, we are determining the horizontal (x-axis) and vertical (y-axis) effect of the vector.

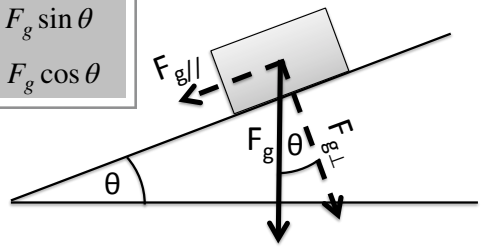
$$F_x = F\cos\theta$$
$$F_y = F\sin\theta$$

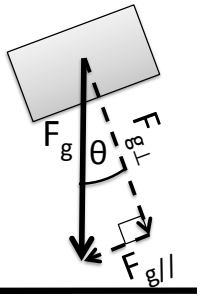



## COMPONENTS ON A SLOPE

When forces act on objects on a slope, it is useful to resolve vectors into components that are parallel (//) or perpendicular (⊥) components. The most common force resolved into components on a slope is weight ($F_g$). Remember, the weight ($F_g$) is the **hypotenuse.**

$$F_{g//} = F_g\sin\theta$$
$$F_{g\perp} = F_g\cos\theta$$



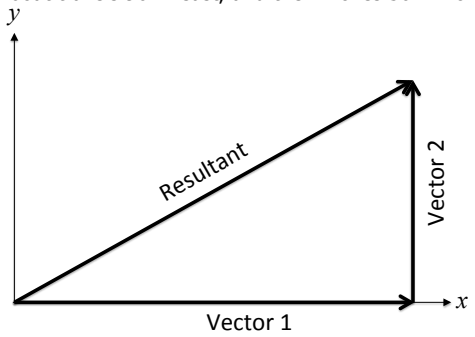

## CONSTRUCTING FORCE TRIANGLE

When forces are not co-linear, force triangles can be used to determine resultant forces or the equilibrant. When force triangles are formed, basic geometric rules can be used to determine vectors or resultants.

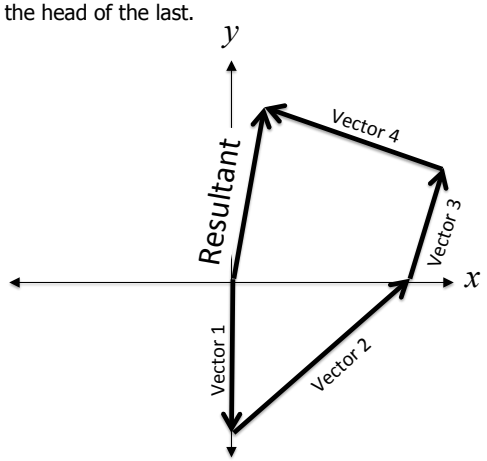
### Tail-to-head

Used for consecutive vectors (vectors that occur in sequence).

Eg. A boat travels 90 m east, and then moves 50 m north.

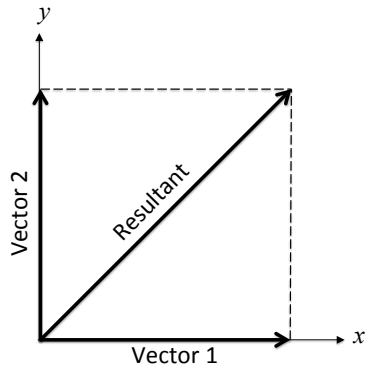



This principle can also be applied to more than 2 vectors taken in order. The resultant is from the tail of the first vector to the head of the last.

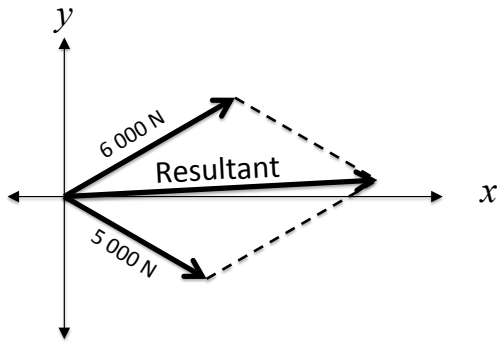



### Parallelogram

Used for vectors that act concurrently on the same object. The resultant is the diagonal of a parallelogram that originates from the tail of the vectors.




Eg. Two tugboats apply a force of 6 000N and 5 000N at bearings of 60° and 120° respectively on a cargo ship.




### Manipulation

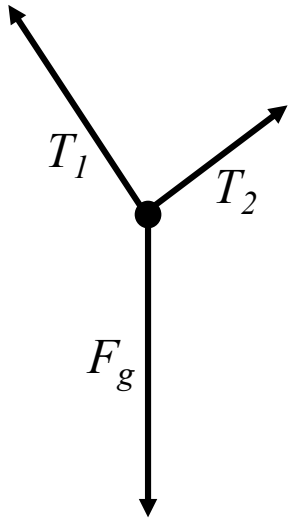
The vector arrows can be manipulated to form a force triangle to determine the resultant forces or an equilibrant. The vectors/arrows may only be moved if the magnitude and direction are both kept constant.

When manipulating the vector arrows, the following has to remain the same:

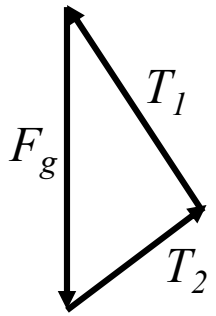
- Length of arrow (magnitude)
- Angle of the arrow (direction)
- The direction of the arrow head

Eg. An object is suspended from a ceiling by 2 cables. Below is a free body diagram as well as a force triangle that can be used to calculate the values of $T_1$ and $T_2$.

**Free body diagram**




**Force triangle**



# 2D Vectors- Resultant and Equilibrant

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**RESULTANT: The single vector which has the same effect as the original vectors acting simultaneously on an object.**

**EQUILIBRANT: The force that keeps a system in equilibrium.**

The equilibrant is equal in magnitude but opposite in direction to the resultant force.

## PYTHAGORAS (90° ONLY)

Pythagoras can only be applied to vector triangles that are right angle triangles.

**FOR FINDING SIDES:**

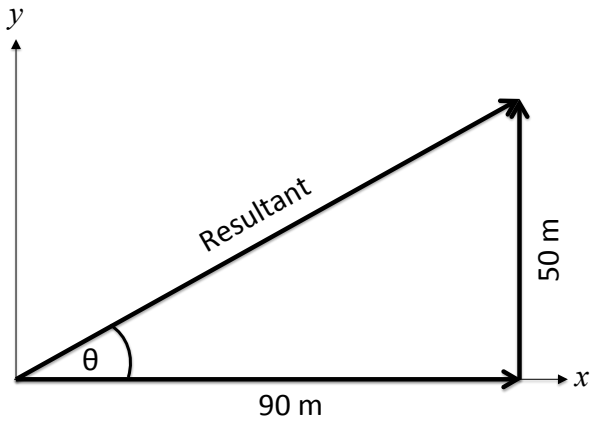
$$R^2 = x^2 + y^2$$

**FOR FINDING ANGLES:**

$$\sin\theta = \frac{o}{h} \quad \cos\theta = \frac{a}{h} \quad \tan\theta = \frac{o}{a}$$

**EXAMPLE:**

A boat travels 90 m due east, and then moves 50 m due north. Determine the displacement of the boat.




$$\begin{aligned} R^2 &= x^2 + y^2 \\ R &= \sqrt{90^2 + 50^2} \\ R &= 102{,}96 \text{ m} \end{aligned}$$

$$\begin{aligned} \tan\theta &= \tfrac{o}{a} \\ \theta &= \tan^{-1}\left(\tfrac{50}{90}\right) \\ \theta &= 29{,}05^\circ \end{aligned}$$

Remember that θ calculated is relative to the $x$-axis,

$\therefore$ bearing $= 90^\circ - 29{,}05^\circ = \mathbf{60,95^\circ}$

$\therefore$ Displacement = 102,96 m at a bearing of 60,95°

## COMPONENT ADDITION

The resultant of diagonal forces can be determined using Pythagoras by determining the $x$-resultant and $y$-resultant first. This is especially useful for determining resultants when more than 2 forces act on an object and a force triangle can not be used.

**EXAMPLE:**

Three forces act on an object as shown in the diagram below. Determine the resultant force on the object.

**1.Determine the x- and y-components of each force.**

**11N force:**

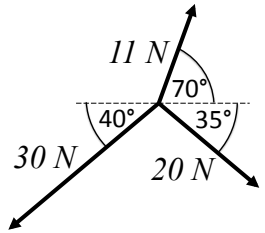
$$\begin{aligned} F_x &= F\cos\theta & F_y &= F\sin\theta \\ &= 11\cos 70 & &= 11\sin 70 \\ &= 3{,}76 \text{ N right } (90^o) & &= 10{,}34 \text{ N up } (0^o) \end{aligned}$$

**30N force:**

$$\begin{aligned} F_x &= F\cos\theta & F_y &= F\sin\theta \\ &= 30\cos 40 & &= 30\sin 40 \\ &= 22{,}98 \text{ N left } (270^o) & &= 19{,}28 \text{ N down } (180^o) \end{aligned}$$

**20N force:**

$$\begin{aligned} F_x &= F\cos\theta & F_y &= F\sin\theta \\ &= 20\cos 35 & &= 20\sin 35 \\ &= 16{,}38 \text{ N right } (90^o) & &= 11{,}47 \text{ N down } (180^o) \end{aligned}$$



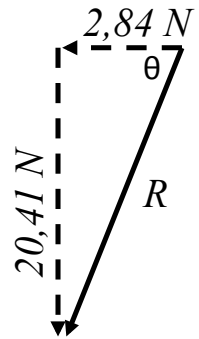

**2. Determine the x- and y-resultants of components.**

**Take left (270°) as positive**

$$\begin{aligned} F_x &= -3{,}76 + 22{,}98 - 16{,}38 \\ &= 2{,}84 \text{ N left } (270^o) \end{aligned}$$

**Take down (180°) as positive**

$$\begin{aligned} F_y &= -10{,}34 + 19{,}28 + 11{,}47 \\ &= 20{,}41 \text{ N down } (180^o) \end{aligned}$$




**3. Find resultant-Pythagoras.**

$$\begin{aligned} R^2 &= x^2 + y^2 \\ R &= \sqrt{2{,}84^2 + 20{,}41^2} \\ R &= 20{,}61 \text{ N} \end{aligned}$$

**4. Find angle- trigonometry**

$$\begin{aligned} \tan\theta &= \tfrac{o}{a} \\ \theta &= \tan^{-1}\tfrac{20{,}41}{2{,}84} \\ \theta &= 82{,}08^\circ \end{aligned}$$

$\therefore$Resultant = 20,61 N at a bearing of 187,92°

# NEWTON'S LAWS OF MOTION



## FORCES

| **Non-contact force:** A force exerted between objects over a distance without physical contact. | **Contact force:** A force exerted between objects that are in contact with each other. |
|---|---|
| Electrostatic force ($F_E$) | Applied force ($F_A$) |
| Gravitational force (w/$F_g$) | Tension (T or $F_T$) |
| Magnetic force | Friction ($F_f$ or $f_s$/$f_k$) |
| | Normal force ($F_N$) |

A force is a push or a pull action exerted on an object by another object. This action can be exerted while objects are in contact (contact force) or over a distance (non-contact force).

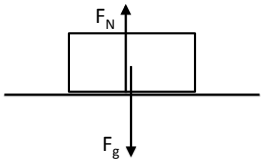
Because forces have magnitude and direction, they are vectors. Force is measured in newton (N). 1 N is the force required to accelerate a 1 kg object at 1 $m{\cdot}s^{-2}$ in the direction of the force. We can therefore say that 1 N = 1 $kg{\cdot}m{\cdot}s^{-2}$.

**NOTE:**
**Free-Body Diagram:** forces drawn away from a dot which represents the object

### Normal force ($F_N$)

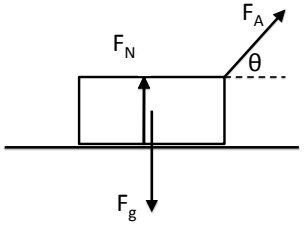
**The perpendicular force exerted by a <u>surface</u> on an object in contact with it**.

$F_N$ is NOT a fixed value. The reaction force of the surface on an object helps to keep vertical equilibrium. The normal force is equal to the **perpendicular component** of gravity **if there are no other forces acting on the object**.

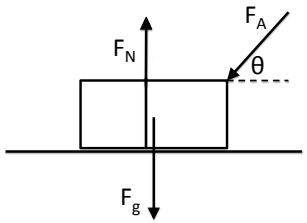



$$F_N = F_g$$

If alternative forces act on the object, the normal force will change depending on the direction and magnitude of the applied force. All vertical forces must be balanced if there is no acceleration in the vertical plane.

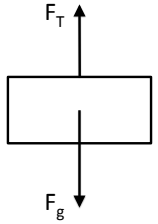



$$F_N + F_{Ay} - F_g = 0$$
$$F_N + F_A \sin\theta = F_g$$




$$F_N - F_g - F_{Ay} = 0$$
$$F_N = F_g + F_A \sin\theta$$

Objects suspended from a rope/string/cable have no normal force, as there is no surface on which the object rests. The <u>tension</u> is equal to the **perpendicular component** of gravity **if there are no other forces acting on the object OR the full magnitude of $F_g$ for vertically suspended objects that are stationary/moving at constant velocity.**




$$F_T + (-F_g) = 0$$

### Friction ($F_f$ or $f_s$/$f_k$)

**Frictional force due to a surface is the force that opposes the motion of an object and acts parallel to the surface with which the object is in contact.**

Friction is the parallel component of the contact force on an object by the surface on which it rests. The friction between the contact surfaces is determined by the properties of both the contact surfaces of the object and surface. The coefficient of friction ($\mu_s$/$\mu_k$) is a description of the roughness of the surface. The rougher the surface, the greater the coefficient of friction.

#### Static friction ($f_s$)

Static friction is the **frictional force on a stationary object that opposes the tendency of motion of the object**. The magnitude of the static friction will increase from 0N as the parallel component of the applied force is increased, until maximum static friction is reached. $f_{s(max)}$ is the magnitude of friction when the object **just starts to move.**

$$f_{s(max)} = \mu_s F_N$$

$f_{s(max)}$ = maximum static friction (N)

$\mu_s$ = coefficient of friction (no unit)

$F_N$ = normal force (N)

#### Kinetic friction ($f_k$)

Kinetic friction is the **frictional force on a moving object that opposes the motion of the object**. The magnitude of the kinetic friction is constant for the specific system at all velocities greater than zero, and irrespective of the applied force.

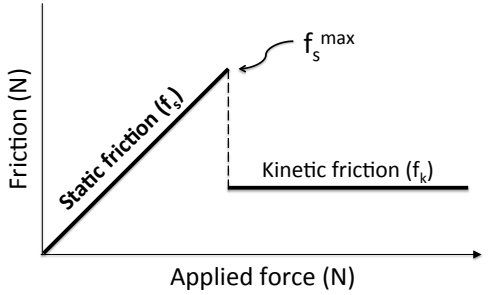
$$f_k = \mu_k F_N$$

$f_k$ = kinetic friction (N)

$\mu_k$ = coefficient of friction (no unit)

$F_N$ = normal force (N)

If the applied force is greater than the maximum static friction, the object will start to move.



# NEWTON'S LAWS OF MOTION



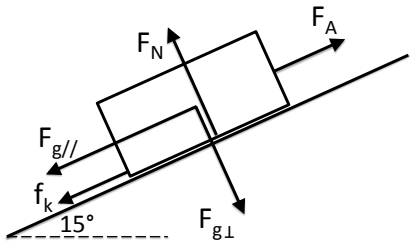
## Newton's First Law of Motion

**An object continues in a state of rest or uniform (moving with constant) velocity unless it is acted upon by a net or resultant force.**

Inertia is defined as the property of an object that causes it to resist a change in its state of rest or uniform motion.

$$F_{net} = 0 \text{ N} \qquad a = 0\ m \cdot s^{-2}$$

A 3kg object moves up an incline surface at an angle of 15° with a constant velocity. The coefficient of friction is 0,35. Determine the magnitude of the applied force.




Take upwards as positive:

$$\begin{aligned} F_{net\perp} &= 0 \\ F_N + (-F_{g\perp}) &= 0 \\ F_N &= F_{g\perp} \\ F_N &= mg\cos\theta \\ F_N &= (3)(9{,}8)\cos 15° \\ F_N &= 28{,}40 \text{ N} \\ \therefore F_N &= 28{,}40 \text{ N} \perp \text{ up from slope} \end{aligned}$$

$$\begin{aligned} F_{net//} &= 0 \\ F_A + (-F_{g//}) + (-f_k) &= 0 \\ F_A &= F_{g//} + f_k \\ F_A &= mg\sin\theta + \mu_k F_N \\ F_A &= (3)(9{,}8)\sin 15° + (0{,}35)(28{,}40) \\ \therefore F_A &= 17{,}55 \text{ N} \end{aligned}$$

**Importance of wearing safety belts:**

According to Newton's First Law, an object will remain in motion at a constant velocity unless a non-zero resultant force acts upon it. When a car is in an accident and comes to a sudden stop, the person inside the car will **continue** with a **constant forward velocity**. Without a safety belt, the person will make contact with the windscreen of the car, causing severe head trauma. The safety belt acts as an **applied force** (new Fnet), preventing the forward motion of the person.

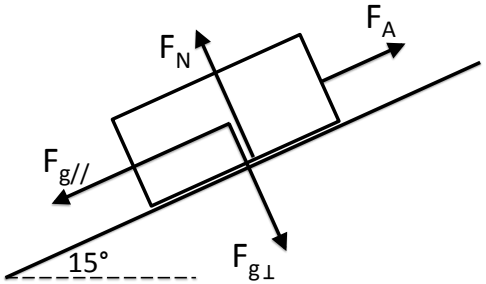
## Newton's Second Law of Motion

**When a net force, $F_{net}$, is applied to an object of mass, it accelerates in the direction of the net force. The acceleration, a, is directly proportional to the net force and inversely proportional to the mass.**

Newton's Second Law is dependent on the resultant force– The vector sum of all forces acting on the same object.

$$F_{net} = ma \qquad a \neq 0\ m \cdot s^{-2}$$

A 20 N force is applied to a 5 kg object. The object accelerates up a frictionless incline surface at an angle of 15°. Determine the acceleration of the object.




Take upwards as positive:

$$\begin{aligned} F_{net//} &= ma \\ F_A + (-F_{g//}) &= ma \\ 20 - (5)(9{,}8)\sin 15° &= 5a \\ 20 - 12{,}68 &= 5a \\ a &= \frac{7{,}32}{5} \\ \therefore a &= 1{,}46 \text{ m} \cdot \text{s}^{-2} \text{ // up the slope} \end{aligned}$$

**Effect of Newton's Second Law on overloading:**

According to Newton's Second Law, the acceleration of an object is directly proportional to the net force and inversely proportional to the mass of the object. If a vehicle is overloaded, the stopping distance will increase which can lead to serious accidents. When brakes are applied, the net force and brake force remain the same, but the increase in mass causes a decrease in negative acceleration, increasing the time (and distance) it takes for the vehicle to stop.

## Newton's Third Law of Motion

**When object A exerts a force on object B, object B simultaneously exerts an oppositely directed force of equal magnitude on object A.**

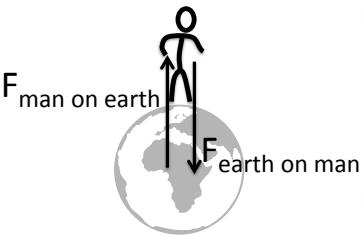
**NB!**

Newton's Third Law describes action-reaction force pairs. These are forces on **different objects** and **can not be added or subtracted.**

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

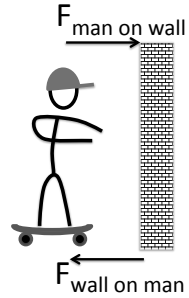
Force pairs properties:

- Equal in magnitude
- Opposite in direction
- Acts on different objects (and therefore **DO NOT CANCEL** each other out)




**NOTE:**
The force pairs shown here are gravitational forces.

Gravity and Normal force are **NOT** force pairs.




**Newton's Third Law during an accident**

According to Newton's Third Law, the force that two objects exert on each other is equal in magnitude but opposite in direction. If two cars are in an accident, they will both exert the same amount of force on each other irrespective of their masses.

# NEWTON'S LAWS OF MOTION

**ALL EXAMPLES: DIRECTION OF MOTION POSITIVE**

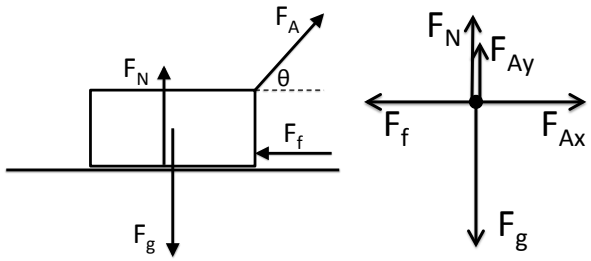
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## Horizontal

The vertical resultant = 0 N.

The horizontal resultant determines acceleration.

**Pulled at an angle**



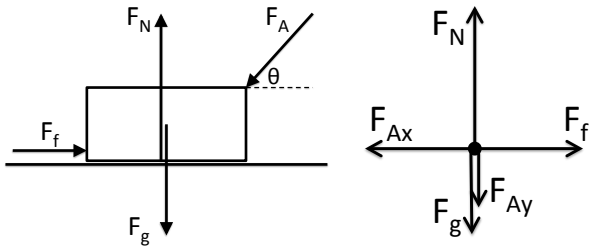

Horizontal:

$$F_{net} = ma$$
$$F_{A_x} + (-F_f) = ma$$

Vertical:

$$F_{net} = 0$$
$$(-F_g) + F_N + F_{A_y} = 0$$

**Pushed at an angle**




Horizontal:

$$F_{net} = ma$$
$$F_{A_x} + (-F_f) = ma$$

Vertical:

$$F_{net} = 0$$
$$F_g + (-F_N) + F_{A_y} = 0$$

## Slopes

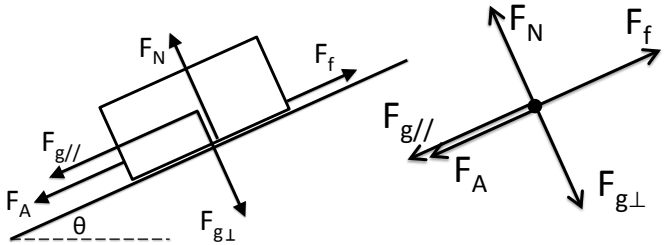
The perpendicular (⊥) resultant = 0 N.

The parallel (//) resultant determines acceleration.

**REMEMBER: Use components of weight.**

$$F_{g//} = F_g \sin\theta$$
$$F_{g\perp} = F_g \cos\theta$$

**Force applied down the slope**



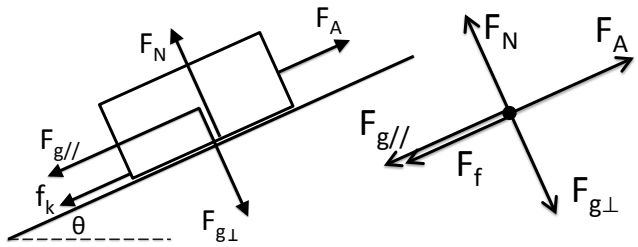

Parallel:

$$F_{net} = ma$$
$$F_{g\parallel} + F_A + (-F_f) = ma$$

Perpendicular:

$$F_{net} = 0$$
$$F_{g\perp} + (-F_N) = 0$$

**Force applied up the slope**



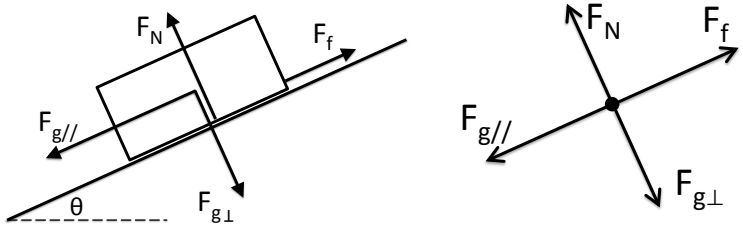

Parallel:

$$F_{net} = ma$$
$$(-F_{g\parallel}) + (-F_f) + F_A = ma$$

Perpendicular:

$$F_{net} = 0$$
$$F_{g\perp} + (-F_N) = 0$$

**No force applied**




Parallel:

$$F_{net} = ma$$
$$F_{g\parallel} + (-F_f) = ma$$

Perpendicular:

$$F_{net} = 0$$
$$F_{g\perp} + (-F_N) = 0$$

## Suspended

Horizontal resultant = 0 N.

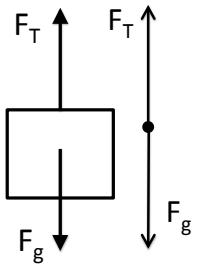
Vertical resultant determines acceleration.

**REMEMBER:** No normal or friction forces.

**Lift stationary/constant velocity**

Vertical:

$$F_{net} = 0$$
$$F_g + (-F_T) = 0$$

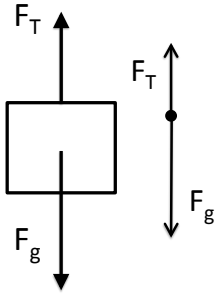



**Lift accelerating**

Vertical:

$$F_{net} = ma$$
$$F_g + (-F_T) = ma$$

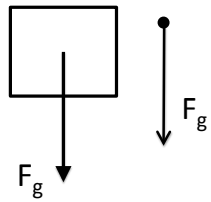
Acceleration will be in the direction of the greatest force.




**Lift in freefall (cable snap)**

Vertical:

$$F_{net} = ma$$
$$F_g = ma$$



# NEWTON'S LAWS OF MOTION

**ALL EXAMPLES: DIRECTION OF MOTION POSITIVE**



## Connected objects (e.g Pulley Systems)

**Do separate free body diagrams for each object.**

The velocity and acceleration of all objects are equal in magnitude and direction.

Applied forces are applied to only one object at a time.

Simultaneous equations for acceleration and tension are sometimes needed.

**REMEMBER:**

**Ropes/cables-** The tension forces on the objects are the same in magnitude but opposite in direction.

**Touching objects-** Newton's Third Law

### Same axis

Can be horizontal (multiple objects on a surface) or vertical (multiple suspended objects).

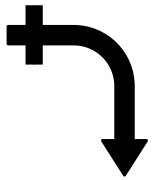
The velocity and acceleration of all objects are equal in magnitude and direction.

### Multiple axes

Horizontal (objects on a surface) **AND** vertical (suspended objects).

The velocity and acceleration of all objects are equal in magnitude NOT DIRECTION.

### Vector direction on multiple axes

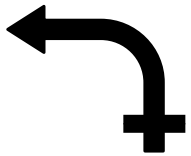


Clockwise:

Right and Down positive

Left and Up negative

**OR**



Anti-clockwise:

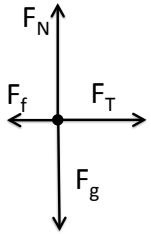
Left and Up positive

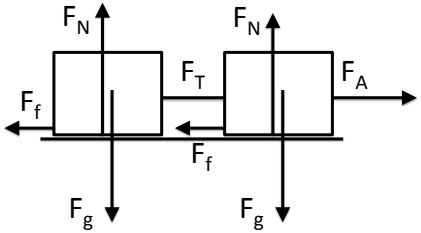
Right and Down negative

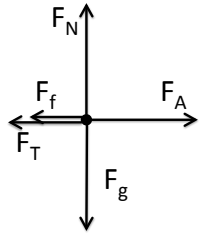
### Objects attached by rope/cable

Horizontal:

$$F_{net} = ma$$
$$(-F_f) + F_T = ma$$



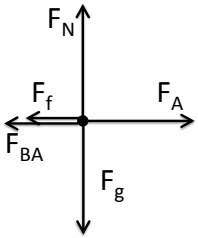

Horizontal:

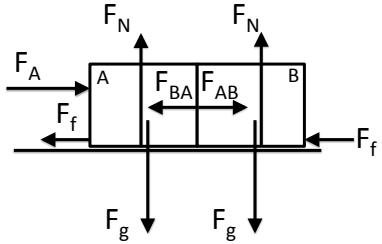
$$F_{net} = ma$$
$$F_A + (-F_T) + (-F_f) = ma$$

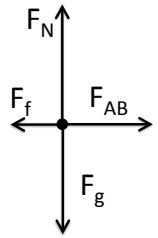
### Objects in contact

Horizontal:

$$F_{net} = ma$$
$$F_A + (-F_{BA}) + (-F_f) = ma$$



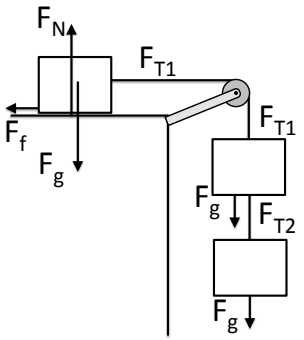




Horizontal:

$$F_{net} = ma$$
$$(-F_f) + F_{AB} = ma$$

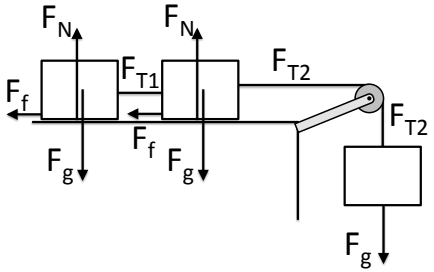
### Multiple axes

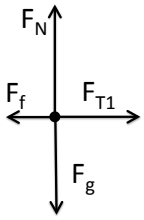



In these examples, clockwise is positive:

Right positive

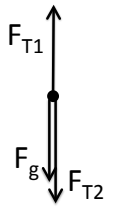
Down positive



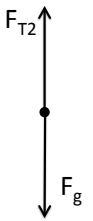

Horizontal:

$$F_{net} = ma$$
$$F_{T1} + (-F_f) = ma$$



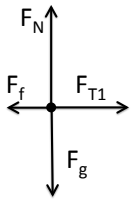

Vertical:

$$F_{net} = ma$$
$$F_g + (-F_{T1}) + F_{T2} = ma$$



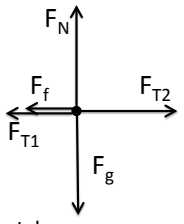

Vertical:

$$F_{net} = ma$$
$$F_g + (-F_{T2}) = ma$$




Horizontal:

$$F_{net} = ma$$
$$F_{T1} + (-F_f) = ma$$




Horizontal:

$$F_{net} = ma$$
$$F_{T2} + (-F_{T1}) + (-F_f) = ma$$




Vertical:

$$F_{net} = ma$$
$$F_g + (-F_{T2}) = ma$$

# NEWTON'S LAW OF UNIVERSAL GRAVITATION



**Every particle, with mass, in the universe attracts every other particle with a force which is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centres.**

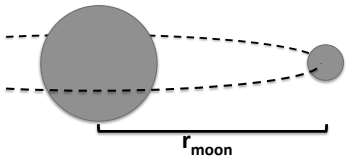
$$F = \frac{Gm_1m_2}{r^2}$$

F = force of attraction between objects (N)
G = universal gravitational constant ($6,7 \times 10^{-11}\ N{\cdot}m^2{\cdot}kg^{-2}$)
m = object mass (kg)
r = distance between object centers (m)

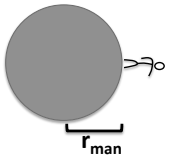
A uniform sphere of matter attracts a body that is outside the shell as if all the sphere's mass was concentrated at its center.



Thus, the distance is determined between the centers of the two bodies.




**NOTE:**
The radius of the earth is added to the distance between the earth and the moon.




**NOTE:**
The radius of object (man) on the earth is negligibly small.

## KNOW THE DIFFERENCE!

### g vs G

g: Gravitational acceleration (9,8 $m{\cdot}s^{-2}$ on earth)
g is the acceleration due to gravity on a specific planet.

G: Universal gravitational constant ($6,7\times10^{-11}\ N{\cdot}m^2{\cdot}kg^{-2}$)
Proportionality constant which applies everywhere in the universe.

### Mass vs Weight

Mass (kg)
A scalar quantity of matter which remains constant everywhere in the universe.

Weight (N) [gravitation force]
Weight is the gravitational force the Earth exerts on any object. Weight differs from planet to planet. $F_g = mg$. Weight is a vector quantity.

## RATIOS

1. Write out the original formula.
2. Manipulate unknown as subject.
3. Substitute changes into formula (Keep symbols!).
4. Simplify ratio number.
5. Replace original formula with unknown symbol.

**EXAMPLE:**
Two objects, $m_1$ and $m_2$, are a distance r apart and experience a force F. How would this force be affected if:

a) One mass is doubled and the distance between the masses is halved?

$F = \frac{Gm_1m_2}{r^2}$ Write out the formula

$F_{new} = \frac{G(\mathbf{2}m_1)m_2}{(\frac{\mathbf{1}}{\mathbf{2}}r)^2}$ Substitute changes into formula

$= \frac{\mathbf{2}}{\frac{\mathbf{1}}{\mathbf{4}}}\frac{Gm_1m_2}{r^2}$ Simplify ratio number

$= \mathbf{8}\left(\frac{Gm_1m_2}{r^2}\right)$

$\therefore F_{new} = \mathbf{8}\ F$ Replace original formula

b) Both the two masses as well as the distance are doubled?

$F = \frac{Gm_1m_2}{r^2}$ Write out the formula

$F_{new} = \frac{G(\mathbf{2}m_1)(\mathbf{2}m_2)}{(\mathbf{2}r)^2}$ Substitute changes into formula

$= \frac{\mathbf{4}}{\mathbf{4}}\frac{Gm_1m_2}{r^2}$ Simplify ratio number

$= \mathbf{1}\left(\frac{Gm_1m_2}{r^2}\right)$

$\therefore F_{new} = \mathbf{1}\ F$ Replace original formula

## DETERMINING GRAVITATIONAL ACCELERATION (g)

$F = m_{object}g$ and $F = \frac{Gm_{object}m_{Planet}}{r^2_{Planet}}$

$$m_o g = \frac{Gm_o m_P}{r_P^2}$$

$$g = \frac{G\cancel{m_o}m_P}{\cancel{m_o}r_P^2}$$

$$\therefore g = \frac{Gm_P}{r_P^2}$$

Therefore the gravitational acceleration of an object only depends on the mass and radius of the planet. **Object mass is irrelevant!**

## CALCULATIONS

The gravitational force can be calculated using $F = \frac{Gm_1m_2}{r^2}$

**REMEMBER:**
Mass in **kg**
Radius in **m**
Radius: centre of mass to centre of mass.
Direction is **ALWAYS** attractive.
Both objects experience the same force. (Newton's Third Law of Motion)

**EXAMPLE:**

The earth with a radius of 6,38 x $10^3$ km is 149,6 x $10^6$ km away from the sun with a radius of 696 342 km. If the earth has a mass of 5,97 x $10^{24}$ kg and the sun has a mass of 1,99 x $10^{30}$ kg, determine the force between the two bodies.

$r = 6,38\times10^3\ \underline{km} + 149,6\times10^6\ \underline{km} + 696\ 342\ \underline{km}$
$= 6,38\times10^6\ \underline{m} + 149,6\times10^9\ \underline{m} + 696\ 342\times10^3\ \underline{m}$
$= 1,5\times10^{11}\ m$

$F = \frac{Gm_1m_2}{r^2}$
$F = \frac{6,7\times10^{-11}(5,97\times10^{24})(1,99\times10^{30})}{(1,50\times10^{11})^2}$
$F = 3,54\times10^{22}\ N$ attraction

The force of gravitational attraction is a vector, therefore all vector rules can be applied:

- Direction specific
- Can be added or subtracted



Take right as positive:

$F_{net\ on\ satallite} = F_{m\ on\ s} + F_{e\ on\ s}$
$= -\left(\frac{Gm_m m_s}{r_{ms}^{\ 2}}\right) + \left(\frac{Gm_e m_s}{r_{es}^{\ 2}}\right)$
$\therefore \left(\frac{G\cancel{m_m}\cancel{m_s}}{r_{ms}^{\ 2}}\right) = \left(\frac{G\cancel{m_e}\cancel{m_s}}{r_{es}^{\ 2}}\right)$

# MOMENTUM AND IMPULSE



## MOMENTUM

**Momentum: the product of the mass and velocity of the object.**

Momentum can be thought of as quantifying the motion of an object. The following equation is used to calculate momentum:

$$p = mv$$

$p$ = momentum $(\text{kg} \cdot \text{m} \cdot \text{s}^{-1})$

$m$ = mass (kg)

$v$ = velocity $(\text{m} \cdot \text{s}^{-1})$

## VECTOR NATURE OF MOMENTUM

Momentum is a vector quantity and has both magnitude and direction. It is therefore important to **always include direction** in all momentum calculations. Momentum has the same direction as the velocity vector.

**EXAMPLE:**

A golf ball of mass 0,05 kg leaves a golf club at a velocity of 90 m·s$^{-1}$ in an easterly direction. Calculate the momentum of the golf ball.

$p = mv$

$= (0{,}05)(90)$

$= 4{,}5 \text{ kg} \cdot \text{m} \cdot \text{s}^{-1}$ east

## CHANGE IN MOMENTUM

When a moving object comes into contact with another object (moving or stationary) it results in a change in velocity for both objects and therefore a change in momentum (p) for each one. The change in momentum can be calculated by using:

$$\Delta p = p_f - p_i$$

$\Delta p$ = change in momentum $(\text{kg} \cdot \text{m} \cdot \text{s}^{-1})$

$p_f$ = final momentum $(\text{kg} \cdot \text{m} \cdot \text{s}^{-1})$

$p_i$ = initial momentum $(\text{kg} \cdot \text{m} \cdot \text{s}^{-1})$

Due to the vector nature of momentum, it is very important to choose a positive direction.

**EXAMPLE:**

A 1000 kg car initially moving at a constant velocity of 16 m·s$^{-1}$ in an easterly direction approaches a stop street, starts breaking and comes to a complete standstill. Calculate the change in the car's momentum.

Choosing east as positive:

$$\begin{aligned} \Delta p &= p_f - p_i \\ \Delta p &= mv_f - mv_i \\ \Delta p &= (1000)(0) - (1000)(16) \\ \Delta p &= -16\,000 \end{aligned}$$

$\therefore \Delta p = 16\,000 \text{ kg} \cdot \text{m} \cdot \text{s}^{-1}$ west

**EXAMPLE:**

A cricket ball with a mass of 0,2 kg approaches a cricket bat at a velocity of 40 m·s$^{-1}$ east and leaves the cricket bat at a velocity of 50 m·s$^{-1}$ west. Calculate the change in the ball's momentum during its contact with the cricket bat.

Choosing east as positive:

$$\begin{aligned} \Delta p &= p_f - p_i \\ \Delta p &= mv_f - mv_i \\ \Delta p &= (0{,}2)(-50) - (0{,}2)(40) \\ \Delta p &= -18 \end{aligned}$$

$\therefore \Delta p = 18 \text{ kg} \cdot \text{m} \cdot \text{s}^{-1}$ west

## NEWTON'S SECOND LAW OF MOTION

**Newton's second law in terms of momentum: The net force acting on an object is equal to the rate of change of momentum.**

According to Newton's Second Law, a net force applied to an object will cause the object to accelerate. When the net force on an object changes, so does its velocity and hence the momentum.

$$F_{net} = \frac{\Delta p}{\Delta t}$$

$F_{net}$ = resultant force (N)

$\Delta p$ = change in momentum $(\text{kg} \cdot \text{m} \cdot \text{s}^{-1})$

$\Delta t$ = time (s)

Derivation from Newton's Second Law

$$F_{net} = ma$$

$$F_{net} = m\frac{\Delta v}{\Delta t}$$

$$F_{net} = \frac{mv_f - mv_i}{\Delta t}$$

$$F_{net} = \frac{\Delta p}{\Delta t}$$

## IMPULSE (J)

**Impulse (J): the product of the net force and the contact time.**

By rearranging Newton's second law in terms of momentum, we find that impulse is equal to the change in momentum of an object according to the impulse-momentum theorem:

$$\text{Impulse} = F\Delta t$$
$$\text{Impulse} = \Delta p$$
$$m\Delta v = \Delta p$$

Impulse (J), FΔt , is measured in N·s.

Δp is measured in kg·m·s$^{-1}$

The change in momentum is directly dependent on the magnitude of the resultant force and the duration for which the force is applied. Impulse is a vector, and has the same direction as the net force vector.

**EXAMPLE:**

A golf ball with a mass of 0,1 kg is driven from the tee. The golf ball experiences a force of 1000 N while in contact with the golf club and moves away from the golf club at 30 m·s$^{-1}$. For how long was the golf club in contact with the ball?

$$\begin{aligned} F_{net}\Delta t &= m\Delta v \\ 1000t &= (0{,}1)(30 - 0) \\ t &= 3 \times 10^{-3} \text{ s} \end{aligned}$$

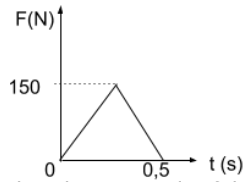
**EXAMPLE:**

Why can airbags be useful during a collision? State your answer by using the relevant scientific principle.

The change in momentum remains constant, but the use of an airbag prolongs the time **(t)** of impact during the accident. The net force experienced is inversely proportional to the contact time **($F \propto 1/t$)**, therefore resulting in a smaller net force **($F_{net}$)** (Δp is constant).

**EXAMPLE:**

The following graph shows the force exerted on a hockey ball over time. The hockey ball is initially stationary and has a mass of 150 g.




Calculate the magnitude of the impulse (change in momentum) of the hockey ball.

$$\begin{aligned} F_{net}\Delta t &= \text{area under graph} \\ \text{impulse} &= \tfrac{1}{2} b \perp h \\ \text{impulse} &= \tfrac{1}{2}(0{,}5)(150) \\ \text{impulse} &= 37{,}5 \text{ N} \cdot \text{s} \end{aligned}$$

# CONSERVATION OF MOMENTUM



## CONSERVATION OF MOMENTUM

**Conservation of linear momentum: The total linear momentum of an isolated system remains constant (is conserved).**

$$(p_{\text{total}})_{\text{before}} = (p_{\text{total}})_{\text{after}}$$
$$p_{\text{A(before)}} + p_{\text{B(before)}} = p_{\text{A(after)}} + p_{\text{B(after)}}$$
$$m_{\text{A}}u_{\text{A}} + m_{\text{B}}u_{\text{B}} + \ldots = m_{\text{A}}v_{\text{A}} + m_{\text{B}}v_{\text{B}} + \ldots$$

**System:** A set number of objects and their interactions with each other.
**Internal forces**: Forces applied on each other by objects within the system - such as the contact forces between colliding cars.
**External forces**: Forces outside of the system, e.g. friction, air resistance
**Isolated system:** Is on that has no net external force acting on it.

## NEWTON'S THIRD LAW AND MOMENTUM

During a collision, the objects involved will exert forces on each other. Therefore, according to Newton's third law, if object A exerts a force on object B, object B will exert a force on object A where the two forces are equal in magnitude, but opposite in direction.

**The magnitude of the force, the contact time and therefore the impulse on both objects are equal in magnitude.**

**Forces are applied between objects during:**

**Collisions:** Move off together, collide and deflect, object dropped vertically on moving object.

**Explosions:** Explosions, springs, firearms

## Collisions

### Move off together

When objects collide and move off together, their masses can be added as one object

Objects that are stationary (B) have an initial velocity of zero.




$$(p_{\text{total}})_{\text{before}} = (p_{\text{total}})_{\text{after}}$$
$$m_{\text{A}}u_{\text{A}} + m_{\text{B}}u_{\text{B}} = (m_{\text{A}} + m_{\text{B}})v$$

### Collide and rebounds

Objects can collide and move off separately

**REMEMBER:** The velocity and momentum are vectors (i.e. direction specific). Velocity substitution must take direction into account.




$$(p_{\text{total}})_{\text{before}} = (p_{\text{total}})_{\text{after}}$$
$$m_{\text{A}}u_{\text{A}} + m_{\text{B}}u_{\text{B}} = m_{\text{A}}v_{\text{A}} + m_{\text{B}}v_{\text{B}}$$

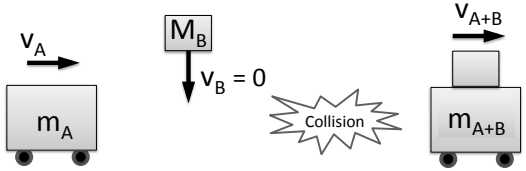
### Object dropped vertically on a moving object

Example: A stuntman jumps off a bridge and lands on a truck.

Linear momentum= momentum along one axis.

A dropped object has a horizontal velocity of zero,

$\therefore v_{iB} = 0 \text{m·s}^{-1}$




$$(p_{\text{total}})_{\text{before}} = (p_{\text{total}})_{\text{after}}$$
$$m_{\text{A}}u_{\text{A}} + m_{\text{B}}u_{\text{B}} = (m_{\text{A}} + m_{\text{B}})v$$

## Explosions

### Explosions

Objects that experience the same explosion will experience the same force.

The acceleration, velocity and momentum of the object is dependent on the mass.

Objects that are stationary (A+B) have an initial velocity of zero.



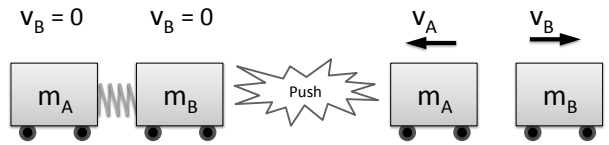

$$(p_{\text{total}})_{\text{before}} = (p_{\text{total}})_{\text{after}}$$
$$(m_{\text{A}} + m_{\text{B}})u = m_{\text{A}}v_{\text{A}} + m_{\text{B}}v_{\text{B}}$$

### Springs

The spring will exert the same force on both objects (Newton's Third Law).

The acceleration, velocity and momentum of the object is dependent on the mass.

Objects that are stationary (A+B) have a velocity of zero.



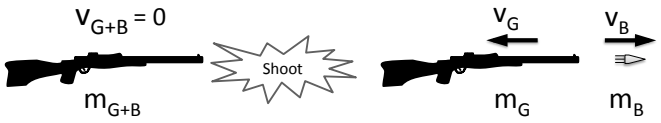

$$(p_{\text{total}})_{\text{before}} = (p_{\text{total}})_{\text{after}}$$
$$(m_{\text{A}} + m_{\text{B}})u = m_{\text{A}}v_{\text{A}} + m_{\text{B}}v_{\text{B}}$$

### Firearms/ cannons

The gun and bullet will experience the same force.

The acceleration of the weapon is significantly less than the bullet due to mass difference

Recoil can be reduced by increasing the mass of the weapon.




$$(p_{\text{total}})_{\text{before}} = (p_{\text{total}})_{\text{after}}$$
$$(m_{\text{G}} + m_{\text{B}})u = m_{\text{G}}v_{\text{G}} + m_{\text{B}}v_{\text{B}}$$

# MOMENTUM AND ENERGY



## ELASTIC VS INELASTIC COLLISIONS

**Elastic collision:** a collision in which <u>both</u> momentum and kinetic energy are conserved.

**Inelastic collision:** a collision in which <u>only</u> momentum is conserved.

In an isolated system, momentum will always be conserved. To prove that a collision is elastic, we only have to prove that kinetic energy is conserved.

Kinetic energy can be calculated using the mass and velocity of an object:

$$E_K = \frac{1}{2}mv^2$$

$E_K$ = kinetic energy (J)

$m$ = mass (kg)

$v$ = velocity ($\text{m} \cdot \text{s}^{-1}$)

**Elastic collision:** $E_{k(before)} = E_{k(after)}$

**Inelastic collision:** $E_{k(before)} \neq E_{k(after)}$

(some energy is lost as sound or heat)

**EXAMPLE:**

The velocity of a moving trolley of mass 1 kg is 3 $\text{m}\cdot\text{s}^{-1}$. A block of mass 0,5 kg is dropped vertically on to the trolley. Immediately after the collision the speed of the trolley and block is 2 $\text{m}\cdot\text{s}^{-1}$ in the original direction. Is the collision elastic or inelastic? Prove your answer with a suitable calculation.

$$\begin{aligned} E_{K(before)} &= \frac{1}{2}m_t v_t^2 + \frac{1}{2}m_b v_b^2 \\ &= \frac{1}{2}(1)(3)^2 + \frac{1}{2}(0{,}5)(0)^2 \\ &= 4{,}5 \text{ J} \end{aligned}$$

$$\begin{aligned} E_{K(after)} &= \frac{1}{2}m_{t+b} v_{t+b}^2 \\ &= \frac{1}{2}(1 + 0{,}5)(2)^2 \\ &= 3 \text{ J} \end{aligned}$$

$E_{K(before)} \neq E_{K(after)}$

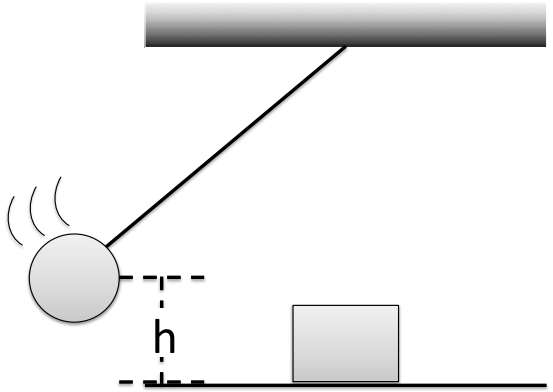
$\therefore$ Kinetic energy is not conserved and the collision is inelastic

## PENDULUMS

**DOWNWARD SWING:**

**Conservation of mechanical energy ($E_M$)** to determine velocity at the bottom of the swing:

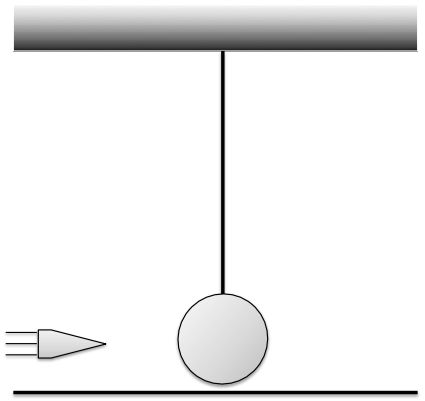
$$E_{M(top)} = E_{M(bottom)}$$
$$mgh + \frac{1}{2}mv^2 = mgh + \frac{1}{2}mv^2$$




**COLLISION:**

**Conservation of linear momentum** to determine the velocity of the block after impact.

$$(p_{\text{total}})_{\text{before}} = (p_{\text{total}})_{\text{after}}$$
$$p_{\text{A(before)}} + p_{\text{A(before)}} = p_{\text{A(after)}} + p_{\text{A(after)}}$$
$$m_{\text{A}}u_{\text{A}} + m_{\text{B}}u_{\text{B}} + \ldots = m_{\text{A}}v_{\text{A}} + m_{\text{B}}v_{\text{B}} + \ldots$$



**UPWARD SWING:**

**Conservation of mechanical energy ($E_M$)** to determine height that the pendulum will reach:

$$E_{M(bottom)} = E_{M(top)}$$
$$mgh + \frac{1}{2}mv^2 = mgh + \frac{1}{2}mv^2$$

**COLLISION:**

**Conservation of linear momentum** to determine the velocity of the pendulum after impact.

$$(p_{\text{total}})_{\text{before}} = (p_{\text{total}})_{\text{after}}$$
$$p_{\text{A(before)}} + p_{\text{A(before)}} = p_{\text{A(after)}} + p_{\text{A(after)}}$$
$$m_{\text{A}}u_{\text{A}} + m_{\text{B}}u_{\text{B}} + \ldots = m_{\text{A}}v_{\text{A}} + m_{\text{B}}v_{\text{B}} + \ldots$$

# ENERGY



## ENERGY

**The ability to do work**

Unit: joules (J)

Scalar quantity

### Gravitational Potential Energy ($E_P$)

**The energy an object possesses due to its position relative to a reference point.**

Amount of energy transferred when an object changes position relative to the earth's surface.

$$E_P = mgh$$

**g = 9,8 m·s$^{-2}$, m is mass in kg, h is height in m above the ground**

Example:

Determine the gravitational potential energy of a 500 g ball when it is placed on a table with a height of 3 m.

$$\begin{aligned} E_P &= mgh \\ &= (0{,}5)(9{,}8)(3) \\ &= 14{,}7\ J \end{aligned}$$

### Kinetic Energy ($E_K$)

**The energy an object has as a result of the object's motion**

Amount of energy transferred to an object as it changes speed.

$$E_K = \frac{1}{2}mv^2$$

**m is mass in kg, v is velocity in m·s$^{-1}$**

Example:

Determine the kinetic energy of a 500 g ball when it travels with a velocity of 3 m.s$^{-1}$.

$$\begin{aligned} E_K &= \tfrac{1}{2}mv^2 \\ &= \tfrac{1}{2}(0{,}5)(3^2) \\ &= 2{,}25\ J \end{aligned}$$

### Mechanical Energy ($E_M$)

**The sum of gravitational potential and kinetic energy of an object at a point**

$$E_M = E_P + E_K$$

$$E_M = mgh + \frac{1}{2}mv^2$$

**EXAMPLE:**

A ball, mass 500 g, is thrown horizontally through the air. The ball travels at a velocity of 1,8m·s$^{-1}$ and is 2,5 m from the ground. Determine the mechanical energy of the ball.

$$\begin{aligned} E_M &= E_P + E_K \\ E_M &= mgh + \tfrac{1}{2}mv^2 \\ E_M &= (0{,}5)(9{,}8)(2{,}5) + \tfrac{1}{2}(0{,}5)(1{,}8^2) \\ E_M &= 13{,}06\ J \end{aligned}$$

## PRINCIPLE OF CONSERVATION OF MECHANICAL ENERGY

**Principle of conservation of mechanical energy: In the absence of air resistance or any external forces, the mechanical energy of an object is constant.** The law of conservation of mechanical energy applies when there is no friction or air resistance acting on the object. In the absence of air resistance, or other forces, the mechanical energy of an object moving in the earth's gravitational field in free fall, is conserved.

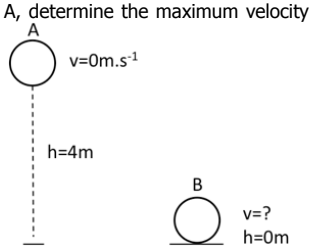
$$\begin{aligned} E_{MECH_A} &= E_{MECH_B} \\ (E_P + E_K)_A &= (E_P + E_K)_B \\ (mgh + \tfrac{1}{2}mv^2)_A &= (mgh + \tfrac{1}{2}mv^2)_B \end{aligned}$$

**Conservation of energy: the total energy in a system cannot be created or destroyed, only transformed from one form to another.**

In the following instances the gravitational potential energy of an object is converted to kinetic energy (and vice versa), while the mechanical energy remains constant.

### EXAMPLE 1: Object moving vertically

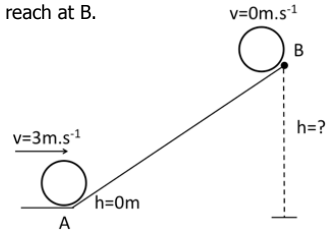
A 2 kg ball is dropped from rest at A, determine the maximum velocity of the ball at B just before impact.




$$\begin{aligned} (E_P + E_K)_A &= (E_P + E_K)_B \\ (mgh + \tfrac{1}{2}mv^2)_A &= (mgh + \tfrac{1}{2}mv^2)_B \\ (2)(9{,}8)(4) + \tfrac{1}{2}(2)(0^2) &= (2)(9{,}8)(0) + \tfrac{1}{2}(2)v_B^2 \\ 78{,}4 + 0 &= 0 + 1v_B^2 \\ v_B &= \sqrt{78{,}4} \\ v_B &= 8{,}85\ \text{m} \cdot \text{s}^{-1}\ \text{downwards} \end{aligned}$$

### EXAMPLE 2: Object moving on an inclined plane

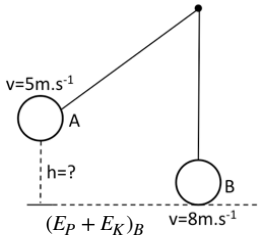
A 2 kg ball rolls at 3 m·s$^{-1}$ on the ground at A, determine the maximum height the ball will reach at B.




$$\begin{aligned} (E_P + E_K)_A &= (E_P + E_K)_B \\ (mgh + \tfrac{1}{2}mv^2)_A &= (mgh + \tfrac{1}{2}mv^2)_B \\ (2)(9{,}8)(0) + \tfrac{1}{2}(2)(3^2) &= (2)(9{,}8)(h_B) + \tfrac{1}{2}(2)(0^2) \\ 0 + 9 &= 19{,}6h_B + 0 \\ \tfrac{9}{19{,}6} &= h_B \\ h_B &= 0{,}46\ \text{m} \end{aligned}$$

### EXAMPLE 3: Pendulum

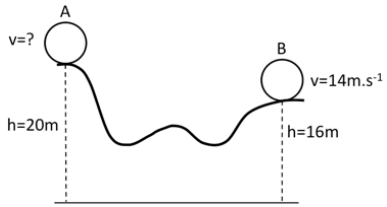
The 2 kg pendulum swings from A at 5 m·s$^{-1}$ to B, on the ground, where its velocity is 8 m·s$^{-1}$. Determine the height at A.




$$\begin{aligned} (E_P + E_K)_A &= (E_P + E_K)_B \\ (mgh + \tfrac{1}{2}mv^2)_A &= (mgh + \tfrac{1}{2}mv^2)_B \\ (2)(9{,}8)(h_A) + \tfrac{1}{2}(2)(5^2) &= (2)(9{,}8)(0) + \tfrac{1}{2}(2)(8^2) \\ 19{,}6h_A + 25 &= 0 + 64 \\ \tfrac{64 - 25}{19{,}6} &= h_A \\ h_A &= 1{,}99\ \text{m} \end{aligned}$$

### EXAMPLE 4: Rollercoaster

The 2 kg ball rolls on a toy rollercoaster from A, at 20 m above the ground, to B where its height is 8 m and velocity is 14 m·s$^{-1}$. Calculate its starting velocity at A.




$$\begin{aligned} (E_P + E_K)_A &= (E_P + E_K)_B \\ (mgh + \tfrac{1}{2}mv^2)_A &= (mgh + \tfrac{1}{2}mv^2)_B \\ (2)(9{,}8)(20) + \tfrac{1}{2}(2)(v_A^2) &= (2)(9{,}8)(16) + \tfrac{1}{2}(2)(14^2) \\ 392 + v_A^2 &= 313{,}6 + 196 \\ v_A &= \sqrt{313{,}6 + 196 - 392} \\ v_A &= 10{,}84\ \text{m} \cdot \text{s}^{-1}\ \text{to the right} \end{aligned}$$

# WORK, ENERGY AND POWER



## WORK

Work done is the transfer of energy. **Work done on an object by a force is the product of the displacement and the component of the force parallel to the displacement.**

$$W = F\Delta x \cos\theta$$

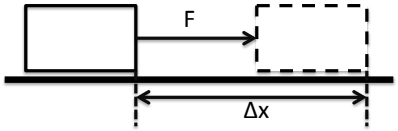
W = work (J)
F = force applied (N)
Δx = displacement (m)
θ = Angle between F and Δx

**NOTE:**
Work is a scalar quantity, i.e. NO DIRECTION for F or x!

The joule is the amount of work done when a force of one newton moves its point of application one meter in the direction of the force.

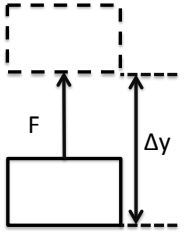
Work always involves two things:

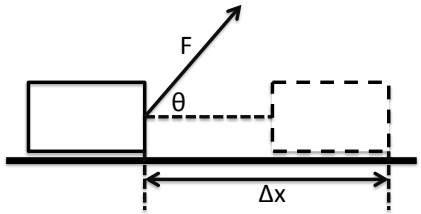
1. A **force** which acts on a certain object. (F)
2. The **displacement** of that object. (Δx / Δy)




When a resultant force is applied to an object, the resultant force **accelerates** the block across distance Δx. Work has been done to increase the **kinetic energy** of the block.

If a resultant force is applied to an object vertically, the resultant force **lifts** the block through distance Δy. Work has been done to increase the **potential energy** of the block. "Lifting" usually implies at a constant velocity.

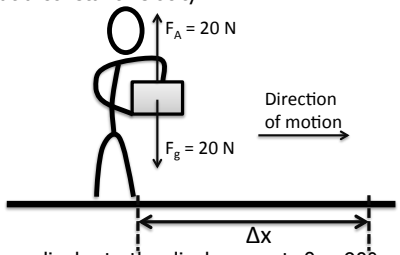



Work is only done in the direction of the displacement. Work is done by the component of the force that is parallel to the displacement. The angle between the force and the displacement is θ. If no displacement takes place due to the applied force, no work is done.

No Work done on an object (moving at a constant velocity) if the force and displacement are perpendicular to each other.

Consider a man carrying a suitcase with a weight of 20 N on a 'travelator' moving at a constant velocity.



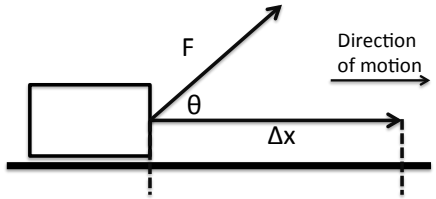

$$W = F_x \Delta x \cos\theta$$
$$F_x = F\cos\theta$$

$F_A$ is perpendicular to the displacement: θ = 90° ; cos 90° = 0.

No force in the plane of the displacement, hence, NO WORK IS DONE by $F_A$ and $F_g$ and no energy is transferred. We can also say that $F_A$ / $F_g$ does not change the potential energy (height) or kinetic energy (vertical velocity) of the object.

A force/force component in the direction of the displacement does positive work on the object. **The force increases the energy of the object.**

**Positive work means that energy is added to the system.**

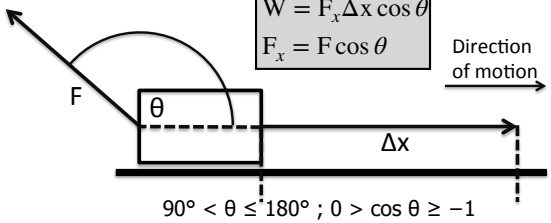



$$W = F_x \Delta x \cos\theta$$
$$F_x = F\cos\theta$$

0° ≤ θ < 90° ; +1 ≥cos θ > 0

A force/force component in the opposite direction of the displacement does negative work on the object. **The force decreases the energy of the object.**

**Negative work means that energy is being removed from the system.**




$$W = F_x \Delta x \cos\theta$$
$$F_x = F\cos\theta$$

90° < θ ≤ 180° ; 0 > cos θ ≥ −1

**NB: Never use a – for F in the opposite direction. The cos θ makes provision for that.**

## NET WORK ON AN OBJECT

A number of forces can act on an object at the same time. Each force can do work on the object to change the energy of the object. The net work done on the object is the sum of the work done by each force acting on the object.

If $W_{net}$ is **positive**, energy is **added** to the system.
If $W_{net}$ is **negative**, energy is **removed** from the system.

Work and Energy are SCALARS, and NOT direction specific.

**EXAMPLE:**

Calculate the net work done on a trolley where a force of 30 N is applied to the trolley. The trolley moves 3 m to the left. The force of friction is 5 N to the right.

**Work done by applied force:**

$$W_A = F\Delta x\cos\theta$$
$$= (30)(3)\cos 0$$
$$= 90 \text{ J gained}$$

**Work done by frictional force:**

$$W_f = F_f\Delta x\cos\theta$$
$$= (5)(3)\cos 180$$
$$= -15 \text{ J "lost"}$$

**Work done by gravity**

$$W_g = F_g\Delta x\cos\theta$$
$$= (F_g)(3)\cos 90$$
$$= 0 \text{ J}$$

**Work done by normal force:**

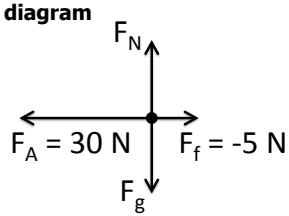
$$W_N = F_N\Delta x\cos\theta$$
$$= (F_N)(3)\cos 90$$
$$= 0 \text{ J}$$

$$W_{net} = W_A + W_f + W_N + W_g$$
$$= 90 - 15 + 0 + 0$$
$$= 75 \text{ J nett energy gained}$$

Alternative method for determining net work:

1. Draw a free body showing only the forces acting on the object.
2. Calculate the resultant (net) force acting on the object.
3. Calculate the net work using $W_{net} = F_{net}\Delta x \cos\theta$

**Step 1: Freebody diagram**




**Take left as positive:**

**Step 2: Calculate $F_{net}$**

$$F_{net} = F_A + F_f$$
$$= 30 - 5$$
$$= 25 \text{ N left}$$

**Step 3: Net work**

$$W_{net} = F_{net}\Delta x\cos\theta$$
$$= (25)(3)\cos 0$$
$$= 75 \text{ J gained}$$

# WORK, ENERGY AND POWER



## WORK ENERGY THEOREM

According to Newton's Second Law of Motion, when a resultant force acts on an object, the object accelerates. This means there is a change in velocity of the object, and therefore a change in kinetic energy of the object, since $E_k = ½ mv^2$

**WORK-ENERGY THEOREM: The work done by a net force on an object is equal to the change in the kinetic energy of the object**

$$W_{net} = \Delta E_K$$

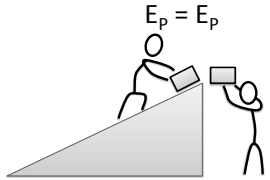
$$F_{net}\Delta x \cos\theta = \frac{1}{2}m(v_f^2 - v_i^2)$$

## CONSERVATIVE FORCES

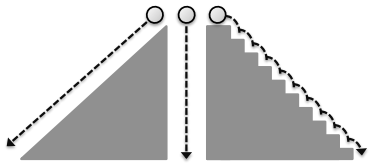
A force is a conservative force if:

1. The work done by the force in moving an object from point A to point B is independent of the path taken.

2. The net work done in moving an object in a closed path which starts and ends at the same point is zero.




**Conservative force conserve mechanical energy.** Example of conservative forces are gravitational force and spring force.



The work done by gravity on each ball is independent of the path taken. Only the $h_\perp$ is considered.

## NON-CONSERVATIVE FORCES

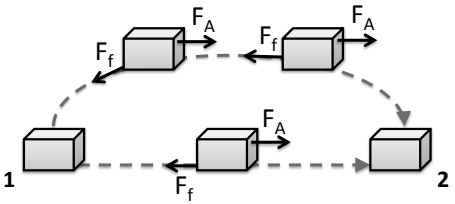
**($F_T$, $F_A$, $F_f$, $F_{air\ resistance}$)**

A force is a non-conservative force if:

1. The work done by the force in moving an object from point A to point B is dependent of the path taken.
2. The net work done in moving an object in a closed path which starts and ends at the same point is not zero.

**A non-conservative force does not conserve mechanical energy.** A certain amount of energy is converted into other forms such as internal energy of the particles which the objects is made of. An example of a non-conservative force is the frictional force.

Consider the crate on a rough surface being pushed with a constant force $F_A$ from position 1 to position 2 along two different paths.



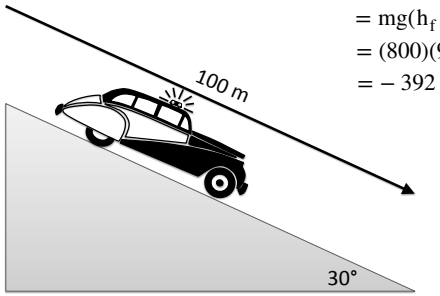

The work done by $F_A$ is more when the longer path is taken. The work done to overcome the friction will result in the surface of the crate becoming hotter. This energy is dissipated (as sound and/or heat) and is very difficult to retrieve, i.e. not conserved.

Note: the total energy of the system is conserved in all cases, whether the forces are conservative or non-conservative.

$$W_{nc} = \Delta E_K + \Delta E_P$$
$$= \frac{1}{2}m(v_f^2 - v_i^2) + mg\Delta h$$

**EXAMPLE:**

An 800 kg car traveling at 15 m·s$^{-1}$ down a 30° hill needs to stop within 100 m to avoid an accident. Using energy calculations only, determine the magnitude of the average force that must be applied to the brakes over the 100 m. Assume that the surface is frictionless.




$$\Delta E_P = mg\Delta h$$
$$= mg(h_f - h_i)$$
$$= (800)(9,8)(0 - 100\sin 30°)$$
$$= -392\ 000\ J$$

$$\Delta E_K = E_{Kf} - E_{Ki}$$
$$= \frac{1}{2}m(v_f^2 - v_i^2)$$
$$= \frac{1}{2}(800)(0^2 - 15^2)$$
$$= -90\ 000\ J$$

$$\mathbf{W_{nc} = \Delta E_K + \Delta E_P}$$
$$F_A\Delta x\cos\theta = \Delta E_K + \Delta E_P$$
$$F_A(100)\cos 180 = -90\ 000 - 392\ 000$$
$$F_A = \frac{-482\ 000}{-100}$$
$$F_A = 4\ 820\ N$$

## POWER

**Power is the rate at which work is done OR the rate at which energy is transferred.**

$$P = \frac{W}{\Delta t} = \frac{E}{\Delta t}$$

P = power (watt)
W = work (J)
Δt = time (s)

**EXAMPLE:**

Calculate the power expended by an engine when an object of mass 100 kg is lifted to a height of 2,2 m in a time of 3 s, at a constant velocity.

$$P = \frac{W}{\Delta t}$$
$$= \frac{F\Delta x\cos\theta}{\Delta t}$$
$$= \frac{(100)(9,8)(2,2)\cos 0}{3}$$
$$= 718,67\ W$$

**NOTE:**

**$F_{net}$ = 0 N**
**∴ $W_{net}$ = 0 J**
**∴ $P_{net}$ = 0 W**

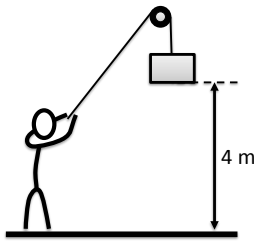
## AVERAGE POWER (CONSTANT VELOCITY)

We can calculate the average power needed to keep an object moving at constant speed using the equation:

$$P_{average} = Fv_{average}$$
$$P_{average} = F\frac{\Delta x}{\Delta t}$$

**EXAMPLE:**

A man lifts a 50 kg bag of cement from ground level up to a height of 4 m above ground level in such a way that the bag of cement moves at constant velocity (i.e. no work is done to change kinetic energy). Determine his average power if he does this in 10 s.




$$P_{average} = Fv_{average}$$
$$= F\frac{\Delta y}{\Delta t}$$
$$= (50)(9,8)\left(\frac{4}{10}\right)$$
$$= 196\ W$$

This cannot be used for object in freefall, unless the object has reached terminal velocity.

# WORK, ENERGY AND POWER

## WHEN TO USE WHICH FORMULAE



### CONSERVATION OF MECHANICAL ENERGY

$$\begin{aligned} \mathbf{E_{M_A}} &= \mathbf{E_{M_B}} \\ \mathbf{(E_P + E_K)_A} &= \mathbf{(E_P + E_K)_B} \end{aligned}$$

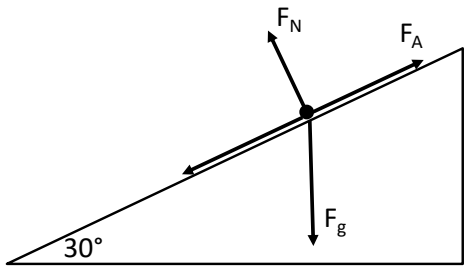
- When there are no external force ($F_A$/$F_f$) present.
- Any track/pendulum with a curve that is not a straight line.

### WORK-ENERGY PRINCIPLE

$$\begin{aligned} \mathbf{W_{net}} &= \mathbf{\Delta E_K} \\ &= \mathbf{\frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2} \end{aligned}$$

- If an object is accelerating on a horizontal/incline plane.

**Any of the following methods may be used:**




**A. $F_{net} \rightarrow W_{net}$**

1. Determine $F_{net}$ separately

$$\begin{aligned} F_{net} &= F_A - Ff - F_{g//} \\ F_{net} &= F_A - F_f - F_g \sin\theta \\ F_{net} &= F_A - F_f - (100 \sin 30°) \end{aligned}$$

2. Apply $F_{net}$ to $W_{net}$

$$W_{net} = F_{net}\Delta x \cos\theta = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2$$

**A. $W_{net} = \Sigma W$**

1. Determine W of each force seperately

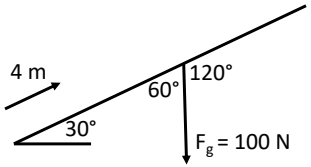
$$\begin{aligned} W_A &= F_A \Delta x \cos\theta \\ W_N &= F_N \Delta x \cos\theta \\ W_g &= F_g \Delta x \cos\theta \\ W_f &= F_f \Delta x \cos\theta \end{aligned}$$

2. Apply $\Sigma W$ to $W_{net}$

$$W_A + W_f + W_g + W_A = W_{net} = \frac{1}{2}mv_f^2 - \frac{1}{2}mv_i^2$$

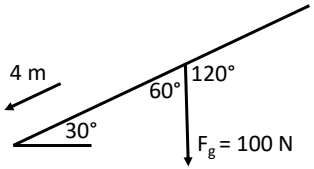
### ALTERNATIVE METHODS TO DETERMINE WORK DONE BY $F_g$ ON A SLOPE WITHOUT RESOLVING $F_g$ INTO $F_{g\perp}$ AND $F_{g//}$

**1. When an object moves up a slope with a known angle**



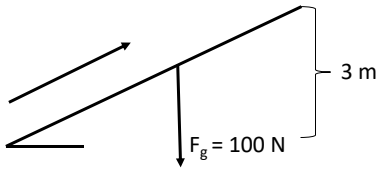

$$\begin{aligned} W_g &= F_g \Delta x \cos\theta \\ &= (100)(4)\cos 120° \\ &= -200\ J \end{aligned}$$

**2. When an object moves down a slope with a known angle**



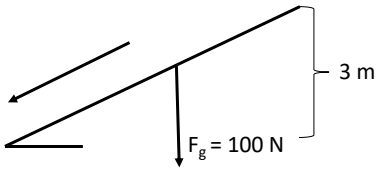

$$\begin{aligned} W_g &= F_g \Delta x \cos\theta \\ &= (100)(4)\cos 60° \\ &= 200\ J \end{aligned}$$

**3. When an object moves up a slope without a given angle, but with specified height**




$$\begin{aligned} W_g &= F_g \Delta x \cos\theta \\ &= (100)(3)\cos 180° \\ &= -300\ J \end{aligned}$$

**4. When an object moves down a slope without a given angle, but with specified height**




$$\begin{aligned} W_g &= F_g \Delta x \cos\theta \\ &= (100)(3)\cos 0° \\ &= 300\ J \end{aligned}$$

# MOTION IN 1D



## VARIABLES

| | | |
|---|---|---|
| u | $v_i$ | initial velocity |
| v | $v_f$ | final velocity |
| a | a | acceleration |
| s | Δx / Δy | displacement |
| t | Δt | change in time |

## EQUATIONS OF MOTION

| IEB preferred | Alternative | Leaves out |
|---|---|---|
| $v = u + at$ | $v_f = v_i + a\Delta t$ | $s$ or $\Delta x$ |
| $s = ut + \frac{1}{2}at^2$ | $\Delta x = v_i\Delta t + \frac{1}{2}a\Delta t^2$ | $v$ or $v_f$ |
| $v^2 = u^2 + 2as$ | $v_f^2 = v_i^2 + 2a\Delta x$ | $t$ or $\Delta t$ |
| $s = \frac{1}{2}(u + v)t$ | $\Delta x = \frac{1}{2}(v_i + v_f)\Delta t$ | $a$ |

**Steps to using the equations:**

a) Draw a diagram of the motion of the object.
b) Identify each stage of the motion **(where the acceleration has changed)**.
c) Choose a positive direction and use the same convention throughout.
d) Record the information given and value required by writing next to each variable. Check the unit and direction.
e) Select correct equation and solve for unknown.
f) Include units and direction in your answer.

**Remember:**
'starting from rest' means: u or $v_i$ = 0
'comes to a stop' means: v or $v_f$ = 0
Slowing down means: acceleration is negative (a < 0), while still moving in a positive direction.
Constant velocity means: a =0, u = v or $v_i = v_f$
Use a new set of variables for each stage of the motion.
Conversion of units: 1 $m.s^{-1}$ = 3,6 $km.h^{-1}$.

**Calculations:**

A racing car starting from rest on the grid, travels straight along the track and reaches the 400 m mark after 8,6 s.
a) What was its average acceleration?

| | | |
|---|---|---|
| u | $v_i$ | 0 |
| v | $v_f$ | / |
| a | a | ? |
| s | Δx | 400 m |
| t | Δt | 8,6 s |

Let forward be positive.

$$\Delta x = v_i\Delta t + \frac{1}{2}at^2$$
$$400 = (0)(8,6) + \frac{1}{2}a8,6^2$$
$$a = 10,82\ \text{m}\cdot\text{s}^{-2}\ \text{forward}$$

b) What was its velocity at the 400 m mark?

$$v_f = v_i + a\Delta t$$
$$v_f = 0 + (10,82)(8,6)$$
$$v_f = 93,05\ \text{m}\cdot\text{s}^{-1}\ \text{forward}$$

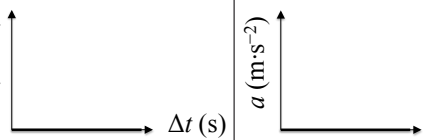
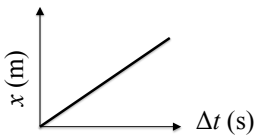
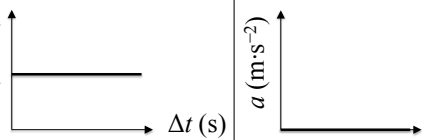
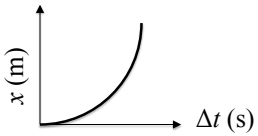
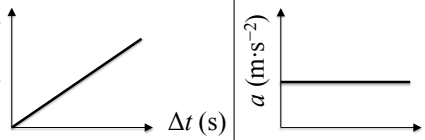
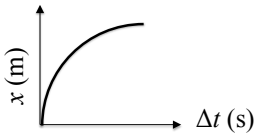
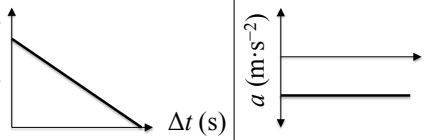
c) At the 400 m mark, the brakes are applied and the car slowed down at 2 $m{\cdot}s^{-2}$ to come to rest. Calculate the time it took for the car to stop.

**NB! New stage of motion.**
**Find the new value of each variable.**

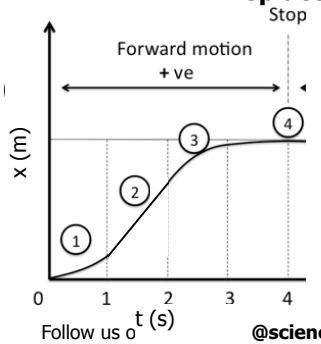
| | | |
|---|---|---|
| u | $v_i$ | 93,05 $m{\cdot}s^{-1}$ |
| v | $v_f$ | 0 |
| a | a | -2 $m{\cdot}s^{-2}$ |
| s | Δx | / |
| t | Δt | ? |

Let forward be positive.

$$v_f = v_i + a\Delta t$$
$$0 = 93,05 - 2t$$
$$t = 46,53\ \text{s}$$

| Position vs Time | Velocity vs Time | Acceleration vs Time |
|---|---|---|
| Stationary (velocity = 0 $m{\cdot}s^{-1}$) | | |
|  |  |  |
| Constant velocity (acceleration = 0 $m{\cdot}s^{-2}$) | | |
|  |  |  |
| Increasing velocity (constant positive acceleration) | | |
|  |  |  |
| Decreasing velocity (constant negative acceleration) | | |
|  |  |  |

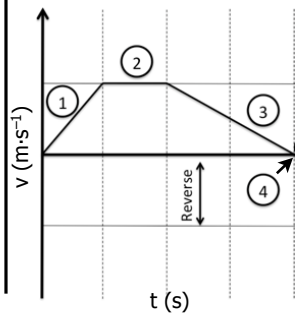
### Displacement-Time




- 1 is positive acceleration
- 2 is constant velocity
- 3 is negative acceleration
- 4 is at rest

**GRADIENT:** Velocity
**AREA BELOW GRAPH:** n/a

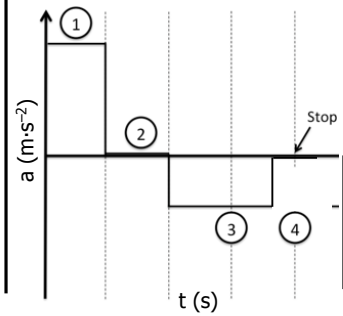
### Velocity-Time




- 1 is positive acceleration
- 2 is constant velocity
- 3 is negative acceleration
- 4 is at rest, v = 0 $m.s^{-1}$

**GRADIENT:** Acceleration
**AREA BELOW GRAPH:** ΔDisplacement

### Acceleration-Time




- 1 is positive acceleration
- 2 is constant velocity (a = 0)
- 3 is negative acceleration
- 4 is at rest or constant v

**GRADIENT:** n/a
**AREA BELOW GRAPH:** ΔVelocity

# VERTICAL PROJECTILE MOTION



## PROJECTILE MOTION

A projectile is an object that moves freely under the influence of gravity only. It is not controlled by any mechanism (pulley or motor). The object is in free fall, but may move upwards (thrown up) or downwards.

**Forces on a projectile**

In the absence of friction, the gravitational force of the earth is the **only** force acting on a free falling body. This force always acts downwards.

Because the gravitational force is always downward, a projectile that is moving upward, must slow down. When a projectile is moving downward, it moves in the direction of the gravitational force, therefore it will speed up.

**Acceleration due to gravity**

All free falling bodies near the surface of the earth have the same acceleration due to gravity. This acceleration is 9,8 $m{\cdot}s^{-2}$ downward.

Ignoring air resistance/friction; If a marble and a rock are released from the same height at the same time, they will strike the ground simultaneously, and their final velocity will be the same.

**Their momentum** (mv) **and kinetic energy (½mv²) are not the same, due to a difference in mass.**

If two objects are released from different heights, they have the same acceleration, but they strike the ground at different times and have different velocities.

$$v_f = v_i + a\Delta t$$

$$v_f^2 = v_i^2 + 2a\Delta y$$

$$\Delta y = v_i\Delta t + \frac{1}{2}a\Delta t^2$$

$$\Delta y = \left(\frac{v_i + v_f}{2}\right)\Delta t$$

$\Delta y$ = displacement (m)

$\Delta t$ = time (s)

$v_i$ = initial velocity ($m{\cdot}s^{-1}$)

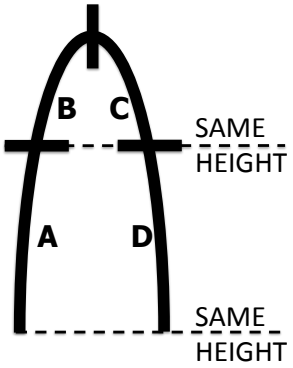
$v_f$ = final velocity ($m{\cdot}s^{-1}$)

a = acceleration ($m{\cdot}s^{-2}$) (9,8 $m{\cdot}s^{-2}$ downwards)

**REMEMBER:**
1. Draw a sketch diagram
2. Write down given variables
3. Choose positive direction
4. Solve

## PARTS OF PROJECTILE PATH

Only vertical movement (up and down) is considered, no horizontal movement is taken into account. The path of projectile motion can be analysed using the 4 sections as shown below. The combination of these 4 parts will depend on the actual path travelled by the projectile. Example: Dropped projectile is sections C and D only. Object thrown upwards and falls on roof is sections A to C.




**Time:**

$t_A = t_D$

$t_B = t_C$

**Displacement:**

$\Delta y_A = \Delta y_D$

$\Delta y_B = \Delta y_C$

**Velocity:**

$v_{iA} = v_{fD}$

$v_{fA} = v_{iD}$

$v_{iB} = v_{fC}$

$V_{fB} = V_{iC} = 0\ m{\cdot}s^{-1}$

**EXAMPLE:**

An object is projected vertically upwards. 4 seconds later, it is caught at the same height (point of release) on its way downwards. Determine how long it took the ball to pass a height of 8 m in the upward direction. Choose downward as positive direction.

$\text{total time} = 4\ s$

$\therefore t_{up} = 2\ s$

$v_f = v_i + a\Delta t$

$0 = v_i + (9{,}8)(2)$

$v_i = -19{,}6$

$\therefore v_i = 19{,}6\ m \cdot s^{-1}\ up$

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$\Delta y = v_i\Delta t + \frac{1}{2}at^2$

$-8 = -19{,}6t + \frac{1}{2}(9{,}8)t^2$

$0 = 4{,}9t^2 - 19{,}6t + 8$

$$t = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

$$t = \frac{-(-19{,}6) \pm \sqrt{(-19{,}6)^2 - 4(4{,}9)(8)}}{2(4{,}9)}$$

$t = 0{,}46\ s \quad OR \quad 3{,}54^*$

$\therefore t = 0{,}46\ s$

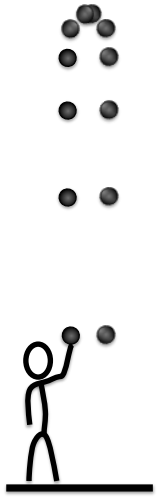
*time for downward direction

## GRAPHS OF PROJECTILE MOTION

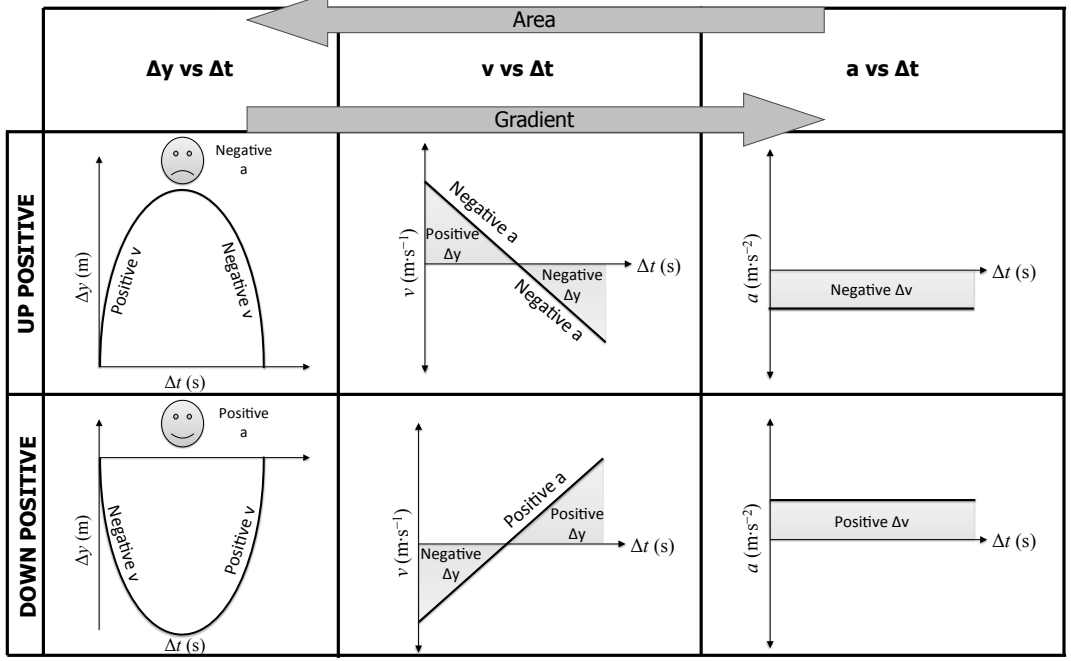
**Graph manipulation:**

Change in positive direction: Flip graph along x-axis

Change in reference position: Shift x-axis (Δy-Δt only)



**(Eg. A ball is thrown into the air and is caught at the same height.)**

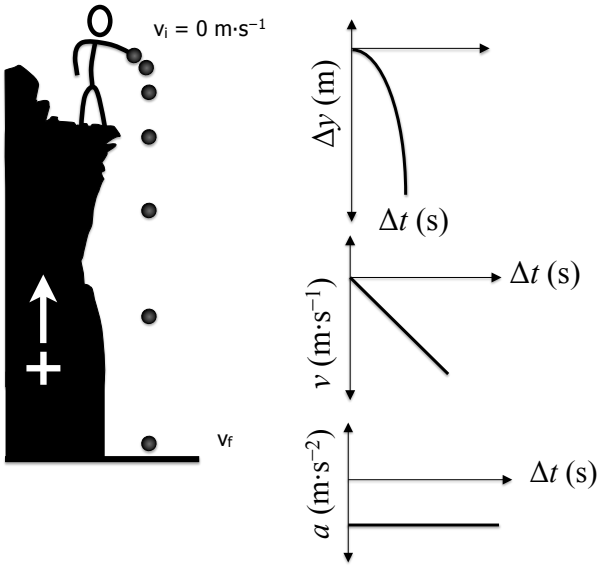


# PATH OF A PROJECTILE

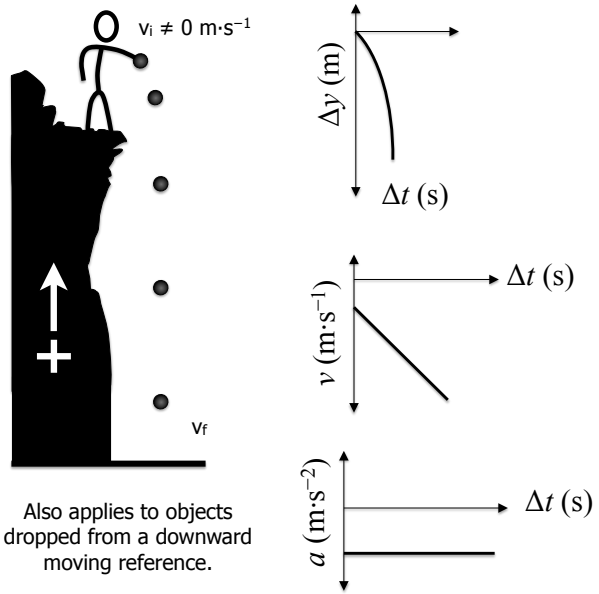
**ALL EXAMPLES:**
**UP POSITIVE, POINT OF RELEASE IS REFERENCE**

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## OBJECT DROPPED FROM HEIGHT (C+D)

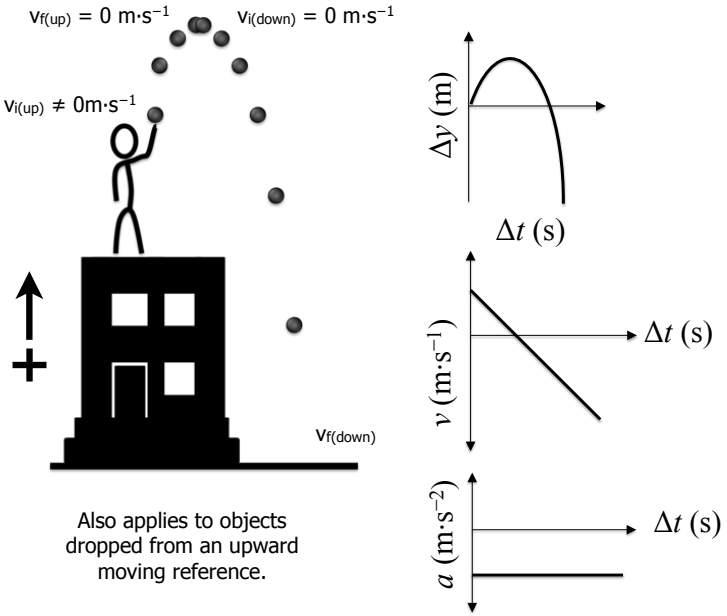



## OBJECT THROWN DOWN FROM HEIGHT (D)



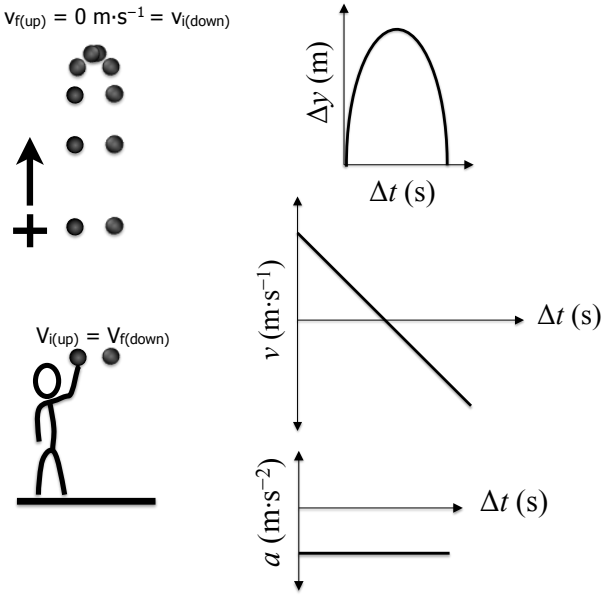

Also applies to objects dropped from a downward moving reference.

## OBJECT THROWN UP FROM HEIGHT (B+C+D)

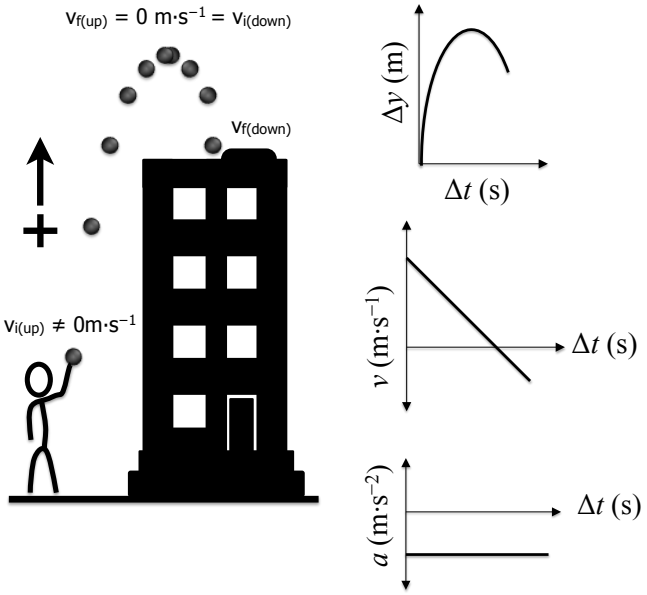



Also applies to objects dropped from an upward moving reference.

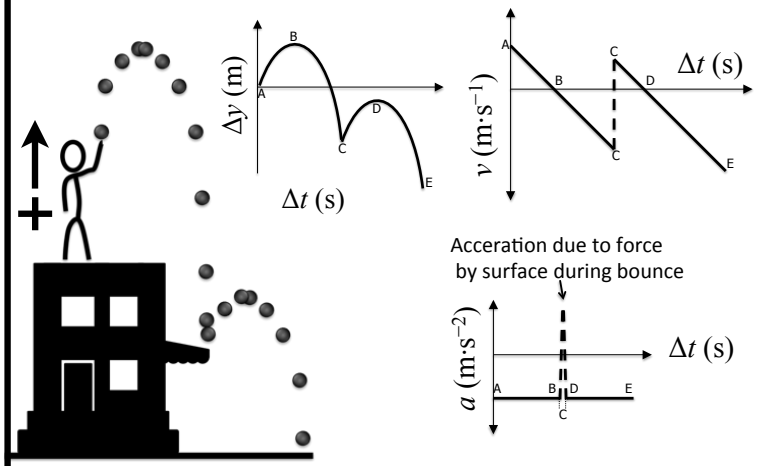
## OBJECT THROWN UP AND CAUGHT (A+B+C+D)




## OBJECT THROWN UP, LANDS AT HEIGHT (A+B+C)




## OBJECT THROWN UP FROM HEIGHT, BOUNCES (B+C+D)




If the collision is perfectly elastic, the downward velocity before the bounce and the upward velocity after the bounce is equal in magnitude.

Treat the 2 projectile paths (before and after bounce) as separate paths.

# SPECIAL PROJECTILE PATHS



## HOT AIR BALLOON



When an object is dropped from a moving reference (hot air balloon), the initial velocity will be equal to that of the reference. The acceleration of the object will be downwards at 9,8 $m{\cdot}s^{-2}$, regardless of the acceleration of the reference.

**EXAMPLE:**

A hot air balloon ascends with a constant velocity of 5 $m{\cdot}s^{-1}$. A ball is dropped from the hot air balloon at a height of 50 m and falls vertically towards the ground. Determine (a) the distance between the hot air balloon and ball after 2 seconds and (b) the velocity of the ball when it reaches the ground.

(a) Take downwards as positive:

Distance travelled by balloon :

$$\Delta y = v_i\Delta t + \tfrac{1}{2}a\Delta t^2$$
$$= (-5)(2) + \tfrac{1}{2}(0)(2^2)$$
$$= -10$$
$$\therefore \Delta y = 10 \text{ m up}$$

Distance travelled by ball :

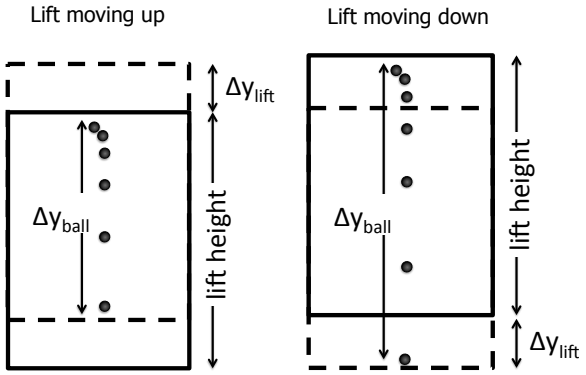
$$\Delta y = v_i\Delta t + \tfrac{1}{2}a\Delta t^2$$
$$= (-5)(2) + \tfrac{1}{2}(9{,}8)(2^2)$$
$$= -10 + 19{,}6$$
$$\therefore \Delta y = 9{,}6 \text{ m down}$$

$$\therefore \text{ total distance} = 10 + 9{,}6$$
$$= 19{,}6 \text{ m apart}$$

(b) Take downwards as positive:

$$v_f^2 = v_i^2 + 2a\Delta y$$
$$v_f^2 = (-5^2) + 2(9{,}8)(50)$$
$$v_f = \sqrt{25 + 980}$$
$$v_f = 31{,}70 \text{ m}\cdot\text{s}^{-1} \text{ downwards}$$

## LIFT




$$\Delta y_{ball} = \text{lift height} + \Delta y_{lift}$$

**EXAMPLE:**

A lift accelerates upwards at a rate of 1,4 $m{\cdot}s^{-2}$. As the lift starts to move, a lightbulb falls from the ceiling of the lift. Determine how long it takes the lightbulb to reach the lift's floor. The height from the ceiling of the lift to its floor is 3m.

Take downwards as positive:

movement of lift :

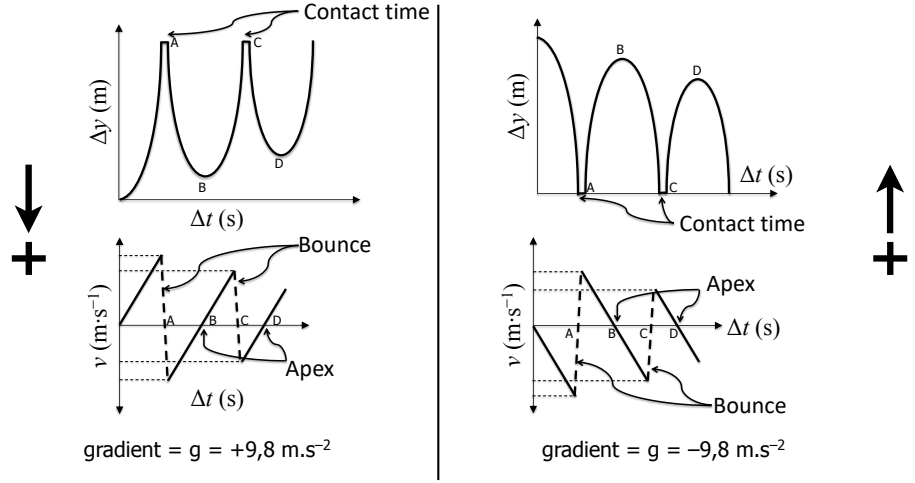
$$\Delta y_{lift} = v_i\Delta t + \tfrac{1}{2}a\Delta t^2$$
$$y_{lift} = (0)t + \tfrac{1}{2}(-1{,}4)t^2$$
$$\therefore y_{lift} = -0{,}7t^2$$

movement of bulb :

$$\Delta y_{bulb} = v_i\Delta t + \tfrac{1}{2}a\Delta t^2$$
$$3 + y_{lift} = (0)t + \tfrac{1}{2}(9{,}8)t^2$$
$$3 - 0{,}7t^2 = 4{,}9t^2$$
$$3 = 5{,}6t^2$$
$$\therefore t = 0{,}73s$$

Simultaneous equation is needed because there are 2 unknown variables:
- Distance that lift moved
- Time to reach floor

## BOUNCING BALL – Ball falls from rest and bounces

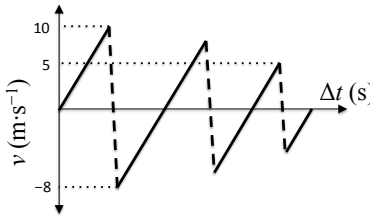



gradient = g = +9,8 $m.s^{-2}$

gradient = g = –9,8 $m.s^{-2}$

**EXAMPLE:**

The velocity-time graph below represents the bouncing movement of a 0,1 kg ball. Use the graph to answer the questions that follow:




a) Which direction of movement is positive?
**Downwards**

b) How many times did the ball bounce?
**3 times**

c) What does the gradient of the graph represent?
**Acceleration of the ball**

d) Are the collisions between the ball and ground elastic or inelastic?
**After each bounce there is a decrease in magnitude of the velocity of the ball, and therefore a change in kinetic energy. The collisions are inelastic as kinetic energy is not conserved.**

e) If the ball is in contact with the ground for a duration of 0,08 s, determine the impulse on the ball

$$\text{Impulse} = \Delta p$$
$$= m(v_f - v_i)$$
$$= (0{,}1)(-8 - 10)$$
$$= -1{,}8$$
$$\therefore \text{Impulse} = 1{,}8 \text{ N}\cdot\text{s upwards}$$

f) Predict why the ball stopped moving.
**it was most likely caught**

# ELECTRICITY

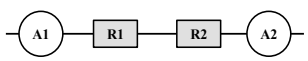


| SERIES | PARALLEL |
|---|---|
| If resistors are added in series, the total resistance will increase and the **total** current will decrease provided the emf remains constant. | If resistors are added in parallel, the total resistance will decrease and the **total** current will increase, provided the emf remains constant. |

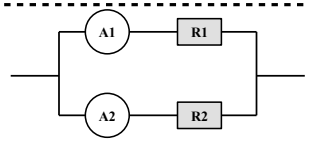
**CURRENT** is **the rate of flow of charge**.

$$I = \frac{q}{t}$$

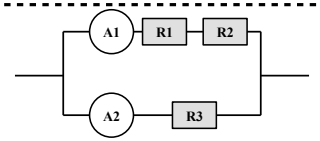
**I** is the current strength, **Q** the charge in coulombs and **t** the time in seconds. SI unit is ampere (A).




$I_T = I_1 = I_2$




$I_T = I_1 + I_2$




$I_T = I_1 + I_2$

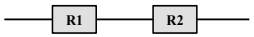
$I_1 = I_{R1} = I_{R2}$

**RESISTANCE** is defined as the **material's opposition to the flow of electric current.**

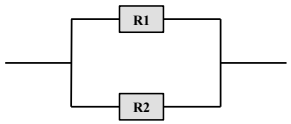
$$V = IR$$

**R** is the electrical resistance of the conducting material, resisting the flow of charge through it.

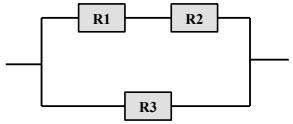
**Resistance (R)** is the quotient of the **potential difference (V)** across a conductor and the **current (I)** in it. The unit of resistance is called the **ohm (Ω)**.




$R_s = R_1 + R_2$




$$\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2}$$




$$\frac{1}{R_p} = \frac{1}{R_1 + R_2} + \frac{1}{R_3}$$

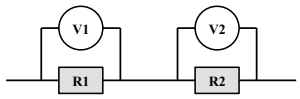
**POTENTIAL DIFFERENCE** (p.d.) is **the work done per unit positive charge** to move the charge from one point to another. It is often referred to as voltage.

$$V = \frac{W}{Q}$$

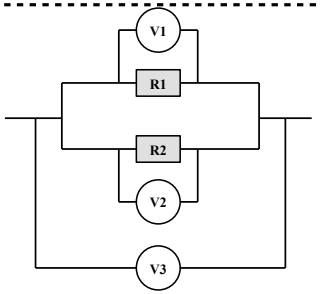
**V** is Potential difference in V (volts), **W** is Work done or energy transferred in J (joules) and **Q** is Charge in C (coulombs).

**NOTE:**

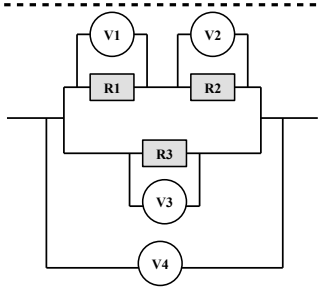
1. Emf ( ε ): voltage across cells when no current is flowing (open circuit).
2. $V_{term}$ or pd: voltage across cells when current is flowing.




$V_s = V_1 + V_2$



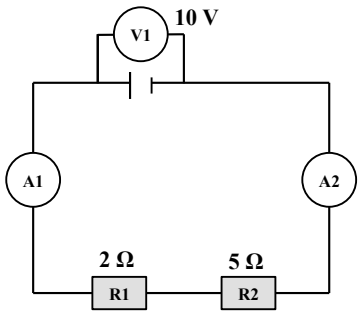

$V_p = V_1 = V_2 = V_3$




$V_p = V_3 = V_4 = (V_1 + V_2)$

## CALCULATIONS (NO INTERNAL RESISTANCE)

### Series circuit



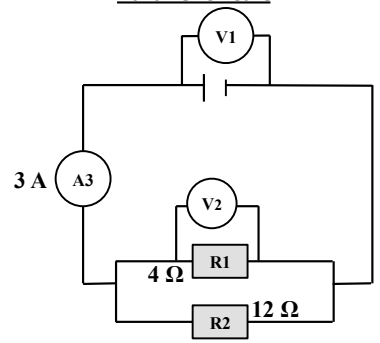

a) Determine the total resistance.

$$\begin{aligned} R_{tot} &= R_1 + R_2 \\ &= 2 + 5 \\ &= 7\ \Omega \end{aligned}$$

b) Determine the reading on A1 and A2.

$$\begin{aligned} V &= IR \\ 10 &= I(7) \\ I &= 1{,}43\ \text{A} \\ \therefore \text{A1} = \text{A2} &= 1{,}43\ \text{A} \end{aligned}$$

### Parallel circuit




a) Determine the total resistance.

$$\begin{aligned} \frac{1}{R_p} &= \frac{1}{R_1} + \frac{1}{R_2} \\ &= \frac{1}{4} + \frac{1}{12} \\ &= \frac{1}{3} \\ \therefore R_p &= 3\Omega \end{aligned}$$

b) Determine the reading on V1 and V2.

$$\begin{aligned} V_1 &= IR \\ &= (3)(3) \\ &= 9\ \text{V} \\ \therefore \text{V1} = \text{V2} &= 9\ \text{V} \end{aligned}$$

### Combination circuits

Consider the circuit given. (Internal resistance is negligible)

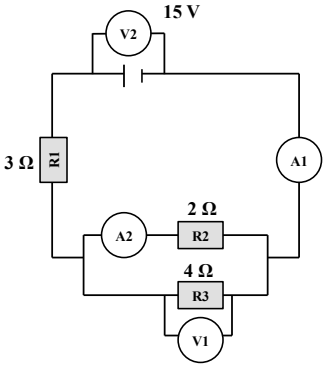
Calculate:

a) the effective resistance of the circuit.

b) the reading on ammeter A1.

c) the reading on voltmeter V1.

d) the reading on ammeter A2.




a)

$$\begin{aligned} \frac{1}{R_P} &= \frac{1}{R_2} + \frac{1}{R_3} \\ &= \frac{1}{2} + \frac{1}{4} \\ &= \frac{3}{4} \\ \therefore R_p &= \frac{4}{3} = 1{,}33\ \Omega \end{aligned}$$

$$\begin{aligned} R_{tot} &= R_{3\Omega} + R_P \\ &= 3 + 1{,}33 \\ &= 4{,}33\ \Omega \end{aligned}$$

b)

$$\begin{aligned} R_{tot} &= \frac{V_{tot}}{I_1} \\ 4{,}33 &= \frac{15}{I_1} \\ I_1 &= 3{,}46\ \text{A} \end{aligned}$$

c)

$$\begin{aligned} R_P &= \frac{V_1}{I_1} \\ 1{,}33 &= \frac{V_1}{3{,}46} \\ V_1 &= 4{,}60\ \text{V} \end{aligned}$$

d)

$$\begin{aligned} R_{2\Omega} &= \frac{V_1}{I_2} \\ 2 &= \frac{4{,}60}{I_2} \\ I_2 &= 2{,}30\ \text{A} \end{aligned}$$

# ELECTRICITY



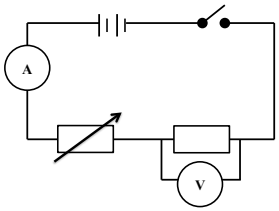
## OHM'S LAW

**Current through a conductor is directly proportional to the potential difference across the conductor at constant temperature.**

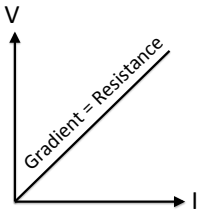
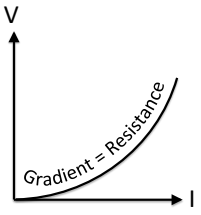
$$R = \frac{V}{I}$$

How to prove Ohm's law:

The current in the circuit is changed using the rheostat, thus current is the independent variable and potential difference is the dependent variable. It is important that the temperature of the resistor is kept constant.




The resultant graph of potential difference vs current indicates if the conductor is ohmic or non-ohmic.

| Ohmic conductor | Non-ohmic conductor |
|---|---|
| • An Ohmic conductor is a conductor that obeys Ohm's law at all temperatures.<br>• Constant ratio for $\frac{V}{I}$.<br>• E.g. Nichrome wire | • A Non-ohmic conductor is a conductor that does not obey Ohm's law at all temperatures.<br>• Ratio for $\frac{V}{I}$ change with change in temperature.<br>• E.g. Light bulb |
|  |  |





## POWER

In general, **power is the rate at which work is done**, however, the electrical power dissipated in a device is also equal to the **product of the potential difference across the device and the current flowing through it.**

$$P = \frac{W}{\Delta t}$$

$$P = I^2R$$

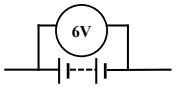
$$P = VI$$

$$P = \frac{V^2}{R}$$

P = power (W)
W = work (J)
Δt = time (s)
I = current (A)
V = potential difference (V)
R = resistance (Ω)

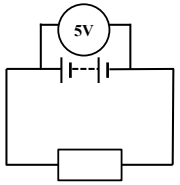
## INTERNAL RESISTANCE

The potential difference across a battery not connected in a circuit is the emf of the battery.



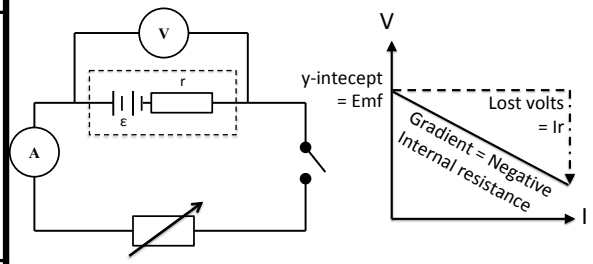

**Emf is the total energy supplied per coulomb of charge by the cell.**

When connected in a circuit the potential difference drops due to the internal resistance of the cells.




In reality all cells have internal resistance (r). Internal resistors are always considered to be connected in series with the rest of the circuit.

**Determining the emf and internal resistance of a cell**




| | |
|---|---|
| **Independent variable** | Current (I) |
| **Dependent variable** | Potential difference (V) |
| **Controlled variable** | Temperature |

## COST OF ELECTRICITY

Electricity is paid for in terms of the amount of energy used by the consumer. Electrical energy is measured in joules (J) but is sold in units called kilowatt hours (kWh).

1 kWh is the amount of energy used when 1 kilowatt of electricity is used for 1 hour.

**Note:**
P in kW
t in hours

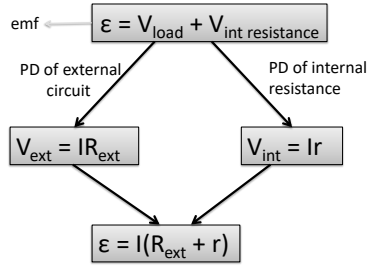
Cost of electricity = power × time × cost per unit

**Example**

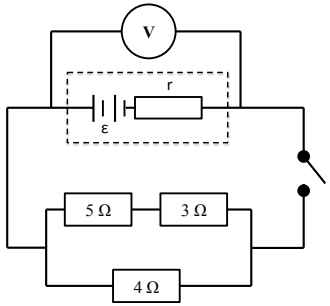
A geyser produces 1200 W of power. Calculate the cost of having the geyser switched on for 24 hours, if the price of electricity is R1,55 per kWh.

$$\begin{aligned} \text{Cost} &= \text{power} \times \text{time} \times \text{cost per kWh} \\ &= (1{,}2)(24)(1{,}55) \\ &= \text{R}44{,}64 \end{aligned}$$

## CALCULATIONS (WITH INTERNAL RESISTANCE)




**EXAMPLE:**




When the switch is open the reading on the voltmeter is 12 V.
When the switch is closed, the current through the 3 Ω resistor is 1 A.

a) Calculate the total current of the circuit.
b) Calculate the internal resistance of the battery.
c) How will the voltmeter reading change when the 4 Ω resistor is removed?

a)
$$\begin{aligned} R_{top} &= R_{5\Omega} + R_{3\Omega} \\ &= 5 + 3 \\ &= 8\ \Omega \end{aligned}$$

$$\begin{aligned} R_{top} &: R_{4\Omega} \\ 8 &: 4 \\ 2 &: 1 \\ \therefore I_{top} &: I_{4\Omega} \\ 1 &: 2 \end{aligned}$$

$$\begin{aligned} I_{4\Omega} &= 2I_{top} \\ &= 2(1) \\ &= 2\ \text{A} \end{aligned}$$

$$\begin{aligned} I_{tot} &= I_{top} + I_{4\Omega} \\ &= 1 + 2 \\ &= 3\ \text{A} \end{aligned}$$

b)
$$\begin{aligned} \frac{1}{R_p} &= \frac{1}{R_{top}} + \frac{1}{R_{4\Omega}} \\ &= \frac{1}{8} + \frac{1}{4} \\ &= \frac{3}{8} \end{aligned}$$

$$R_p = \frac{8}{3} = 2{,}67\ \Omega$$

$$\begin{aligned} \varepsilon &= I(R + r) \\ 12 &= 3(2{,}67 + r) \\ r &= 1{,}33\ \Omega \end{aligned}$$

c) When the 4 Ω resistor is removed, the external resistance increases and the current decreases. **($I \propto 1/R$)**. Emf and internal resistance are constant, therefore a decrease in $V_{int}$ (Ir) will result in an increase in external PD (Voltmeter reading)

**$V = \varepsilon - Ir$**

# ELECTROSTATICS



## FLASHBACK!!

**Principle of conservation of charge.**

$$Q_{new} = \frac{Q_1 + Q_2}{2}$$

**Principle of charge quantization.**

$$N_{e^-} = \frac{Q}{q_e}$$

Unit of charges:

| Prefix | Conversion |
|---|---|
| centi– (cC) | $\times 10^{-2}$ |
| milli– (mC) | $\times 10^{-3}$ |
| micro– (μC) | $\times 10^{-6}$ |
| nano– (nC) | $\times 10^{-9}$ |
| pico– (pC) | $\times 10^{-12}$ |

## COULOMB'S LAW

Two point charges in free space or air exert forces on each other. The force is directly proportional to the product of the charges and inversely proportional to the square of the distance between the charges.

This can be expressed mathematically as:

$$F = \frac{kq_1q_2}{r^2}$$

F = force of attraction between charges $q_1$ and $q_2$ (N)
k = Coulomb's constant ($9\times10^9$ N·m$^2$·C$^{-2}$)
Q = magnitudes of charge (C)
r = distance between charges (m)

## RATIOS

In ratio questions, the same process is used as with Newton's Law of Universal Gravitation.

**EXAMPLE:**
Two charges experience a force F when held a distance r apart. How would this force be affected if one charge is doubled, the other charge is tripled and the distance is halved.

$$F = \frac{kq_1q_2}{r^2}$$
$$= \frac{k(2q_1)(3q_2)}{(\frac{1}{2}r)^2}$$
$$= \frac{6}{\frac{1}{4}}\frac{kq_1q_2}{r^2}$$
$$= 24\left(\frac{kq_1q_2}{r^2}\right)$$
$$= 24F$$

## CALCULATIONS- Electrostatic force

Electrostatic force is a vector, therefore all vector rules can be applied:
- Direction specific
- Can be added or subtracted

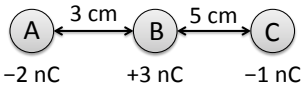
The force can be calculated using

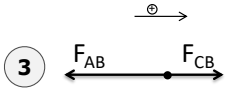
$$F = \frac{kq_1q_2}{r^2}$$

- Substitute charge magnitude only.
- Direction determined by nature of charge (like repel, unlike attract).
- Both objects experience the same force (Newton's Third Law of Motion).

### 1 Dimensional

Determine the resultant electrostatic force on $Q_B$.



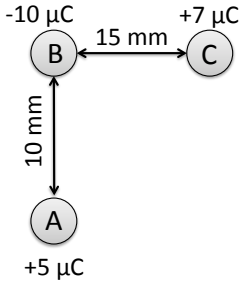

**1** $F_{AB} = \frac{kq_Aq_B}{r^2}$
$= \frac{9\times10^9(2\times10^{-9})(3\times10^{-9})}{(3\times10^{-2})^2}$
$= 6\times10^{-5}$ N left (A attracts B)

**2** $F_{CB} = \frac{kq_Cq_B}{r^2}$
$= \frac{9\times10^9(1\times10^{-9})(3\times10^{-9})}{(5\times10^{-2})^2}$
$= 1{,}08\times10^{-5}$ N right (C attracts B)

**4** $F_{net} = F_{AB} + F_{CB}$
$= (-6\times10^{-5}) + (1{,}08\times10^{-5})$
$= -4{,}92\times10^{-5}$
$\therefore F_{net} = 4{,}92\times10^{-5}$ N left

### 2 Dimensional

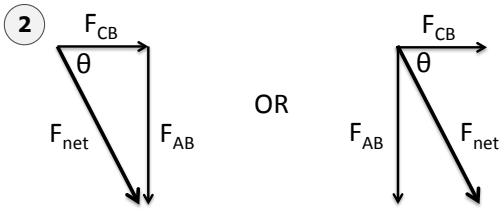
Determine the resultant electrostatic force on $Q_B$.




**1** $F_{AB} = \frac{kq_Aq_B}{r^2}$
$= \frac{9\times10^9(5\times10^{-6})(10\times10^{-6})}{(10\times10^{-3})^2}$
$= 4\ 500$ N down (A attracts B)

$F_{CB} = \frac{kq_Cq_B}{r^2}$
$= \frac{9\times10^9(7\times10^{-6})(10\times10^{-6})}{(15\times10^{-3})^2}$
$= 2\ 800$ N right (C attracts B)

**2**




**3** PYTHAGORAS :
$F_{net}^2 = F_{AB}^2 + F_{BC}^2$
$F_{net} = \sqrt{4\ 500^2 + 2\ 800^2}$
$F_{net} = 5\ 300$ N

**4** $\tan\theta = \frac{o}{a}$
$\theta = \tan^{-1}\frac{F_{AB}}{F_{CB}}$
$\theta = \tan^{-1}\frac{4\ 500}{2\ 800}$
$\theta = 58{,}11°$
$\therefore F_{net} = 5\ 300$ N at 58,11° clockwisefrom the positive x – axis

# ELECTROSTATICS



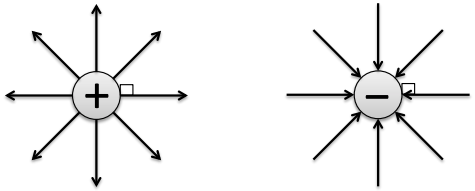
## ELECTRIC FIELDS

An electric field is a region of space in which an electric charge experiences a force.

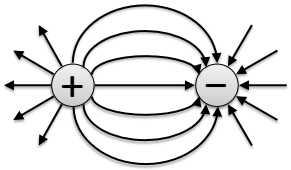
The direction of the electric field at a point is the direction that a positive test charge (+1C) would move if placed at that point.

**REMEMBER:** Field lines leave a conducting surface at 90 °

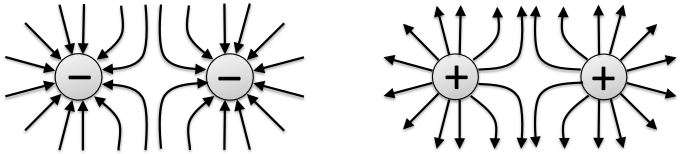
**Single point charges**



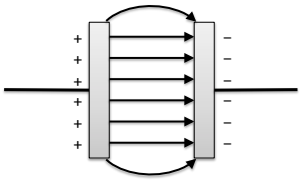
**Unlike charges**



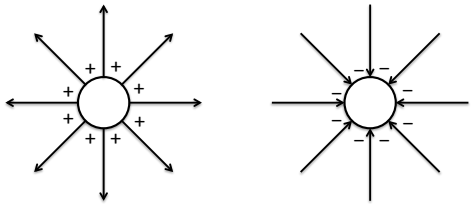
**Like charges**



**Parallel plates**



**Charged hollow spheres**



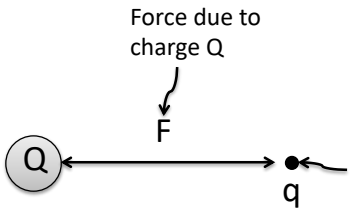
## ELECTRIC FIELD STRENGTH

**The magnitude of an electric field at any point in space is the force per unit charge experienced by a positive test charge at that point.**

$$E = \frac{F}{q}$$

E = electric field strength ($N \cdot C^{-1}$)
F = force on charge q (N)
q = charge (C)

**q is the charge that experiences the force.**




**EXAMPLE:**

Charge A experiences a force of 2 N due to charge B. Determine the electric field strength at point B.




$$E = \frac{F}{q}$$
$$= \frac{2}{2 \times 10^{-6}}$$
$$= 4 \times 10^{6}\ \text{N} \cdot \text{C}^{-1} \text{ to the right}$$

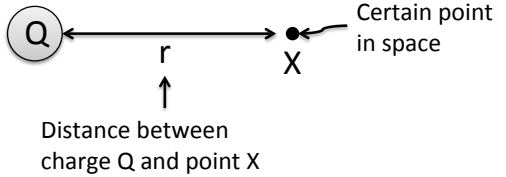
**DIRECTION OF E:**

**Direction that charge q would move IF it was positive.**

$$E = \frac{kQ}{r^2}$$

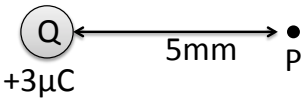
E = electric field strength ($N \cdot C^{-1}$)
k = Coulomb's constant ($9 \times 10^{9}\ N \cdot m^2 \cdot C^{-2}$)
Q = charge (C)
r = distance from charge Q (m)

**Q is the charge that creates the electric field.**




**EXAMPLE:**

Determine the electric field strength at point P due to charge Q.




$$E = \frac{kQ}{r^2}$$
$$= \frac{9 \times 10^{9}(3 \times 10^{-6})}{(5 \times 10^{-3})^2}$$
$$= 1{,}08 \times 10^{9}\ \text{N} \cdot \text{C}^{-1} \text{ to the right}$$

**DIRECTION OF E:**

**Direction that point in space ( X ) would move IF it was positive.**

**NOTE:**

**Electric field strength is a VECTOR. All vector rules and calculations apply. (linear addition, 2D arrangement, resultant vectors, etc.)**

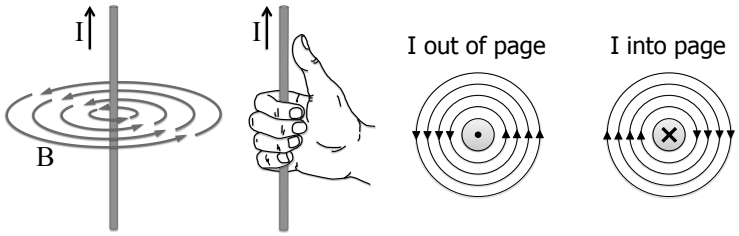
# ELECTROMAGNETISM



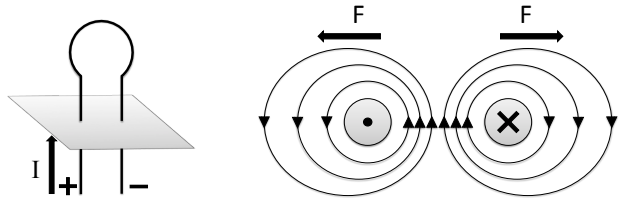
## INDUCTION OF A MAGNETIC FIELD

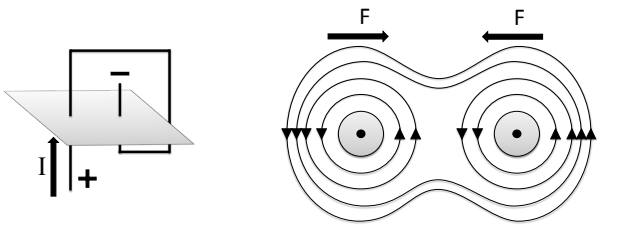
When current passes through a conductor, a magnetic field is induced around the wire.

The direction of the magnetic field can be determined by the **right hand thumb rule**. For a straight, single wire, point the thumb of your right hand in the direction of the conventional current and your curled fingers will point in the direction of the magnetic field around the wire.

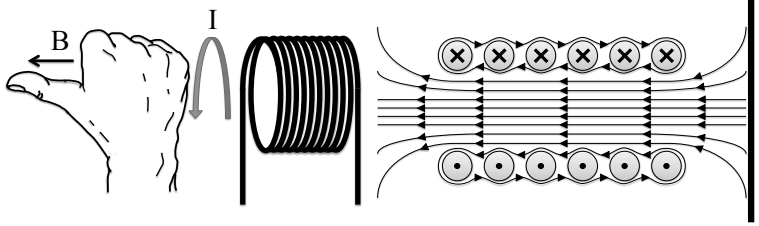



For a wire loop, the magnetic field is the sum of the individual magnetic fields around the single wires at each end. Use the right hand rule for a single wire at each end of the loop.




For a solenoid, curl your fingers around the solenoid in the direction of the conventional current and your thumb will point in the direction of the North pole. This is know as the **right hand solenoid rule.**



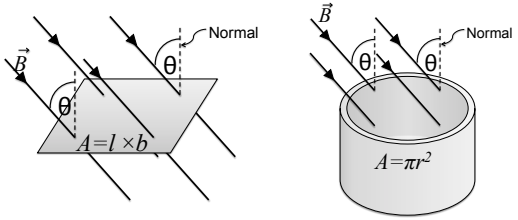

## INDUCTION OF AN ELECTRIC CURRENT

When a magnet is brought close to a metal wire, it causes movement of charge in the wire. As a result, an EMF is induced in the wire. Only a **change in magnetic flux** will induce a current.

The magnetic flux is the result of the product of the perpendicular component of the magnetic field and the cross-sectional area the field lines pass through. **Magnetic flux density (B) is a representation of the magnitude and direction of the magnetic field.**

$$\phi = BA\cos\theta$$

ϕ= magnetic flux (Wb)
B= magnetic flux density (T)
A= area ($m^2$)
θ= angle between magnetic field line and normal




**Faraday's law states that the emf induced is directly proportional to the rate of change of magnetic flux (flux linkage).**

**Magnetic flux linkage is the product of the number of turns on the coil and the flux through the coil.**

NOTE THAT NO CALCULATIONS ARE REQUIRED, ONLY RELATIONSHIP BETWEEN VARIABLES

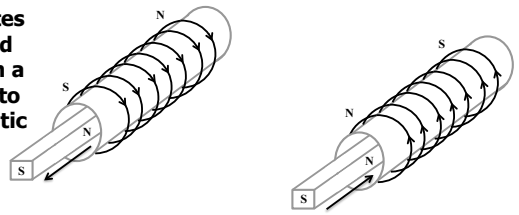
$$\varepsilon = \frac{-N\Delta\phi}{\Delta t}$$

ε = emf (V)
N= number of turns/windings in coil
Δϕ= change in magnetic flux (Wb)
Δt= change in time (s)

## DIRECTION OF INDUCED CURRENT

As a bar magnet moves into a solenoid, the needle of the galvanometer is deflected away from the 0 mark. As the bar magnet is removed, the needle deflects in the opposite direction. The magnetic energy is converted to electrical energy. The direction of the induced current can be determined using **Lenz's law**.

**Lenz's Law states that the induced current flows in a direction so as to set up a magnetic field to oppose the change in magnetic flux.**

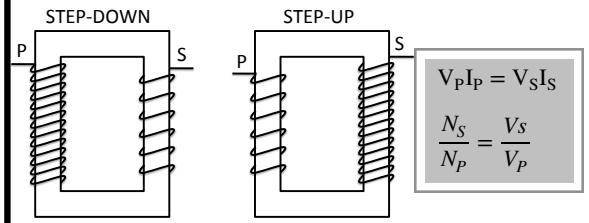



## TRANSFORMERS

Transformers can be used to increase (step-up transformer) or decrease (step-down transformer) the potential difference of alternating current through **mutual induction**.

When alternating current flows through the primary coil, a changing magnetic field is induced. The changing magnetic field induces a changing electric field in the secondary coil, therefore inducing alternating current in the secondary coil. Direct current can not be stepped up or down, as there is no change in magnetic field. The coils have to be wrapped around a soft iron core.

The ratio between the number of windings in the primary and secondary coil, will determine the ratio between the primary and secondary coil potential difference. In an ideal transformer, the input power is equal to the output power.




$$V_P I_P = V_S I_S$$

$$\frac{N_S}{N_P} = \frac{V_S}{V_P}$$

## FORCE ON A STRAIGHT CONDUCTOR

When a current-carrying conductor is placed in a magnetic field, the conductor will experience a force.

NOTE THAT NO CALCULATIONS ARE REQUIRED, ONLY RELATIONSHIP BETWEEN VARIABLES

$$F = I\ell B\sin\theta$$

F = Force on current-carrying conductor (N)
I = Current strength in conductor (A)
ℓ = Length of conductor (m)
B = magnetic flux density/ field strength (T)
θ = Angle between conductor and magnetic field

To increase the force on a conductor:

- Increase the length of the conductor (multiple loops)
- Increase the current through/emf across the conductor
- Increase the strength of the magnetic field
- Place the conductor perpendicular to the magnetic flux (sin 90°)

# ELECTRODYNAMICS

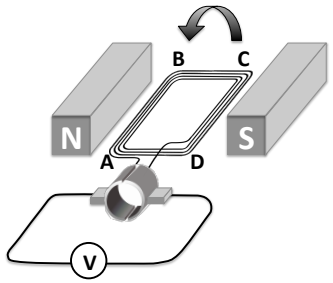


## GENERATORS

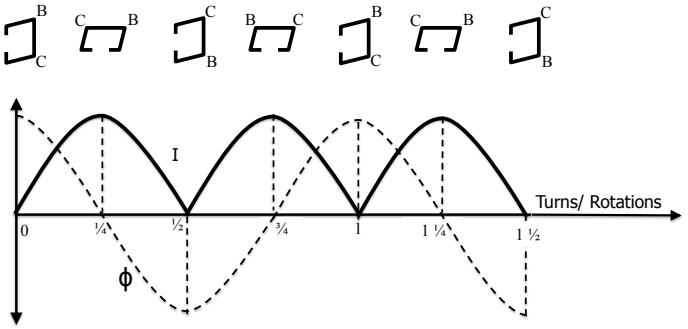
Generators convert mechanical energy into electrical energy. A generator works on the principle of mechanically rotating a conductor in a magnetic field. This creates a changing flux which induces an emf in the conductor.

### Direct (Not IEB)

A direct current generator uses a **split ring** commutator to connect the conductor to the external circuit instead of a slip ring.

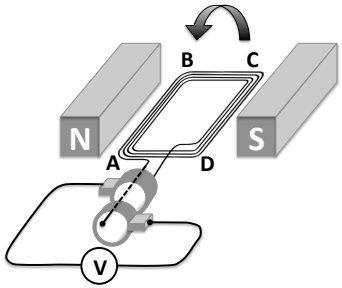



The current in the external circuit does not change direction and is known as direct current (DC).

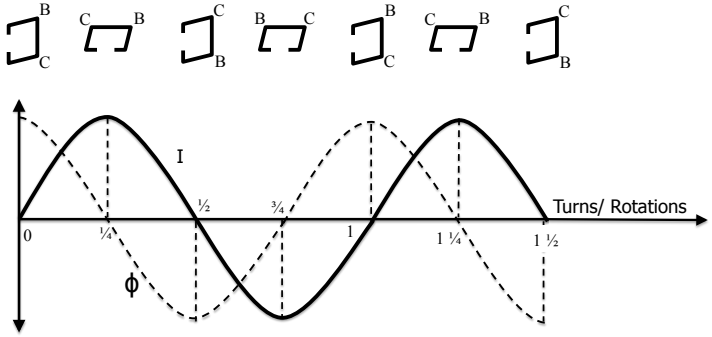



### Alternating

The alternating current generator is connected to the external circuit by 2 **slip rings** which are connected to the conductor. The slip rings make contact with brushes which are connected to the external circuit.

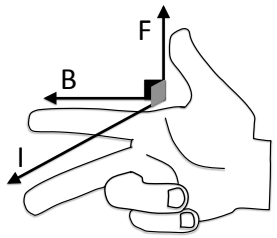


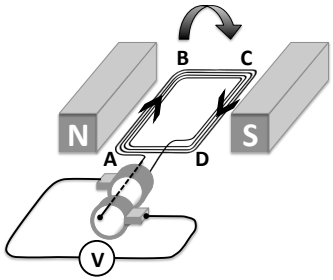

The direction of the current changes with every half-turn of the coil. The current that is produced is known as alternating current (AC).

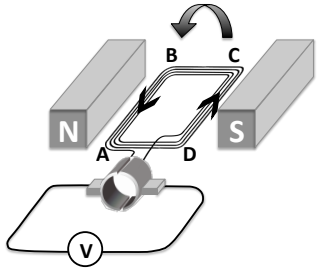



## FLEMING'S RIGHT HAND-DYNAMO (GENERATOR) RULE

The Right hand Rule is used to predict the direction of the induced emf in the coil. Using your right hand, hold your first finger, second finger and thumb 90° to each other. Point your first finger in the direction of the magnetic field (N to S), your thumb in the direction of the motion (or force) of the conductor. The middle finger will point in the direction of the induced current.




## INCREASING THE INDUCED EMF

$$\varepsilon = \frac{-N\Delta\phi}{\Delta t}$$

From the equation, the induced emf can be increased by

- Increasing the number of turns in the coil.
- Increasing the area of the coil.
- Increasing the strength of the magnets.
- Decreasing the time it takes to change the magnetic flux.

# ELECTRODYNAMICS

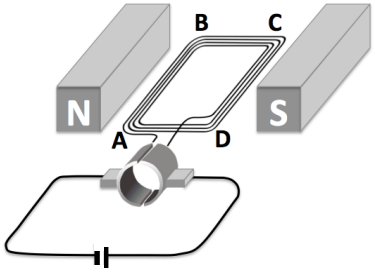


## MOTORS

Electric motors convert electrical energy to mechanical energy. It consists of a current carrying armature, connected to a source by a commutator and brushes and placed in a magnetic field.

### Direct

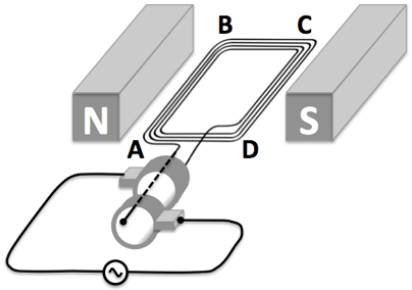
A direct current motor uses a **split ring** commutator to connect the conductor to the external circuit instead of a slip ring.




The split ring commutator allows the current in the coil to alternate with every half turn, which allows the coil to continue to rotate in the same direction.

### Alternating (Not IEB)

The alternating current motor is connected to the external circuit by a **slip ring**. The slip ring makes contact with brushes which are connected to the external circuit attached to an alternating current source.

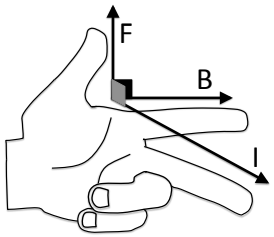


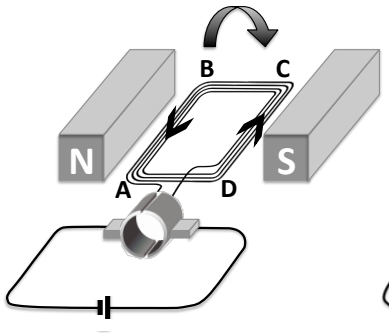

The direction of the current in the coil is constantly changing, which allows the coil to continue to rotate in the same direction.

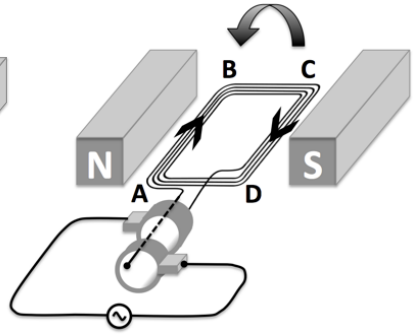
When a charge moves in a magnetic field it experiences a force. The force experienced on both sides of the armature creates torque which makes it turn. The direction of the force can be explained using the left hand rule.

## FLEMING'S LEFT HAND MOTOR RULE

The Left hand Rule is used to predict the direction of the movement of the coil in the motor. Using your left hand, hold your first finger, second finger and thumb 90° to each other. Point your first finger in the direction of the magnetic field, your second finger in the direction of the conventional current and your thumb will then point in the direction of the force.

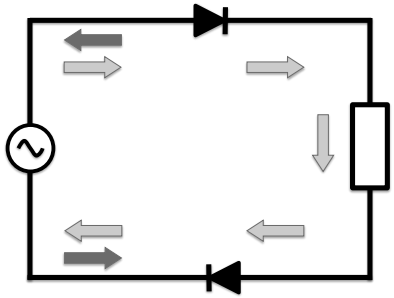


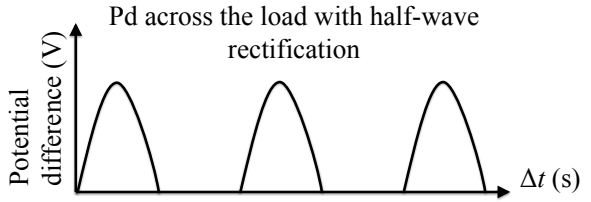

## DIODES

**Diodes are components that only allow current to flow in one direction**. A single diode produces half wave rectification where either the positive or negative current is able to pass through, while the other half is blocked, producing a pulsating output in one direction. This is known as half-wave rectification, as the only half of the original wavefront passes through the load. The average potential difference of the output is lower.

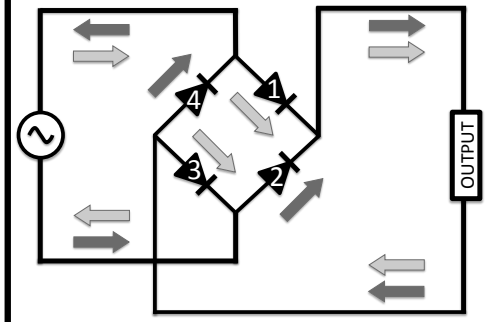


**LIGHT GREY- FORWARD BIAS:**
Allows current to pass through.

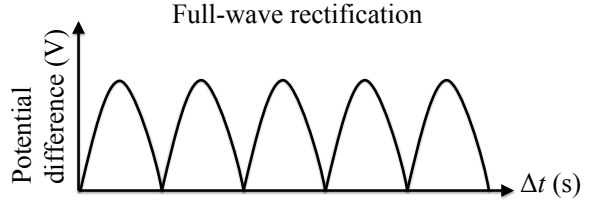
**DARK GREY- REVERSE BIAS:**
Does not allow current to pass through.




For full wave-rectification a bridge rectifier is used. Full wave rectification converts both positive and negative currents to the same direction, producing an output with a higher average potential difference that flows in one direction only (DC).




Forward bias is applicable to diodes 1 + 3, allowing current to pass through. When the current direction reverses, diodes 2 + 4 are forward biased. The current through the output is always in the same direction, hence DC.

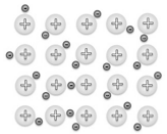


# PHOTOELECTRIC EFFECT



## PARTICLE NATURE OF LIGHT

The photoelectric effect occurs when light is shone on a metal's surface and this causes the metal to emit electrons.



Metals are bonded in such a way that they share their valence electrons in a sea of delocalized electrons. In order to get an electron to be removed from the surface of a metal, it has to be provided with enough energy in order to escape the bond. Each electron has to receive a photon of a minimum energy content.

The energy that light provides enables the electron to escape from the surface and this phenomenon is called photoelectric effect.

## PHOTON ENERGY

Photons are "little packets" of energy called quanta, which act as particles. The energy of the photon (light packet) can be calculated in one of two ways:

$$E = hf \quad \text{OR} \quad E = \frac{hc}{\lambda}$$

E = energy of the photon measured in joules (J)
h = Planck's constant, $6{,}63 \times 10^{-34}$ (J·s)
f = frequency measured in hertz (Hz)
$\lambda$ = wavelength measured in meters (m)
c = speed of light, $3 \times 10^{8}$ ($m \cdot s^{-1}$)

## THRESHOLD FREQUENCY ($f_0$), WORK FUNCTION ($W_0$) AND ELECTRON ENERGY

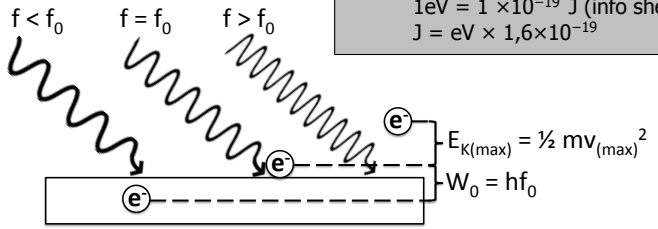
The frequency required to provide enough energy to emit an electron is called the threshold frequency ($f_0$). **The threshold frequency ($f_0$) is the minimum frequency of incident radiation at which electrons will be emitted from a particular metal. The work function ($W_0$) is the minimum amount of energy needed to emit an electron from the surface of a metal**. The work function is material specific.

If the energy of the photons exceed the work function (i.e. the frequency of light exceeds the threshold frequency), the excess energy is transferred to the liberated electron in the form of kinetic energy only.

The kinetic energy of each electron can be determined by:

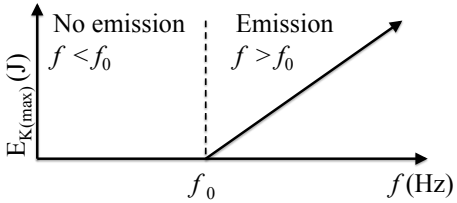
$$E = W_0 + E_{K(max)} = hf + \frac{1}{2}m_e V^2$$

**NOTE:**
Sometimes work function is given in eV. Convert from eV to J:
1eV = $1 \times 10^{-19}$ J (info sheet)
J = eV × $1{,}6 \times 10^{-19}$

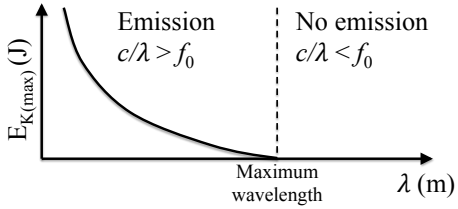



## FREQUENCY AND WAVELENGTH

An increase in frequency will increase the kinetic energy of the electrons. On a graph of $E_{k(max)}$ vs frequency, the x-intercept indicates the threshold frequency.

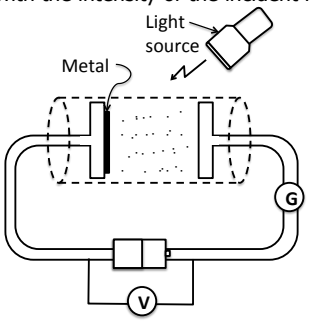


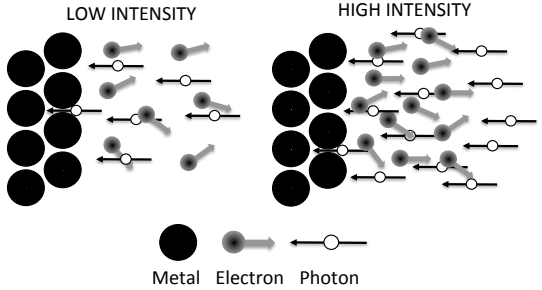

Similarly, on the graph of $E_{k(max)}$ vs wavelength, the x-intercept indicates the maximum wavelength of light that can emit an electron. **Wavelength is inversely proportional to frequency and energy**.




## INTENSITY AND FREQUENCY

Increasing the intensity (brightness) of the light (radiation) means that there are more photons from the same frequency. This will result in more electrons with the same amount of energy being emitted. Thus the number of electrons emitted per second increases with the intensity of the incident radiation. I = Q/t




Note that the energy of the electrons remain the same. If the frequency of the incident radiation is below the cut-off frequency, then increasing the intensity of the radiation has no effect, i.e. it does not cause electrons to be ejected. To increase the energy, the frequency of the radiant light needs to be increased, to reach the threshold frequency.

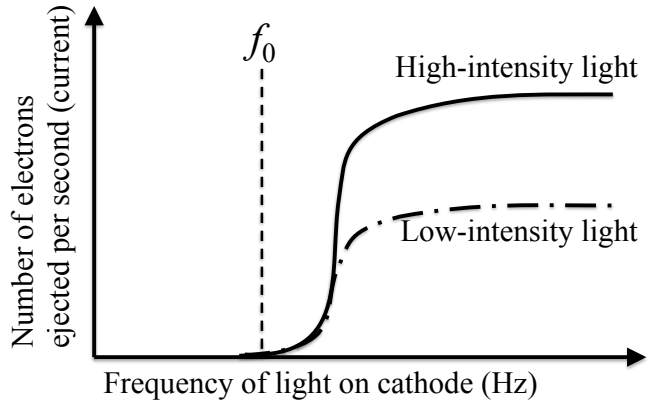
INCREASE **INTENSITY** AT CONSTANT FREQUENCY = INCREASE **AMOUNT** OF EMITTED ELECTRONS

INCREASE **FREQUENCY** AT CONSTANT INTENSITY = INCREASE **KINETIC ENERGY** OF EMITTED ELECTRONS

## INTENSITY, FREQUENCY AND CURRENT

The higher the intensity of the radiation, the more electrons are emitted per second. Therefore an increased intensity will increase the current produced (ammeter reading will increase).

The higher the frequency, the more kinetic energy is provided to the same number of electrons. The rate of electron flow STAYS THE SAME (constant ammeter reading).



# EMISSION SPECTRA



## CONTINUOUS SPECTRUM

When white light shines through a prism, the light is dispersed into a spectrum of light (phenomenon is called refraction). It is called the continuous spectrum. White light is made up of all the colours of the spectrum, and when dispersed we are able to see all the components of white light. This is the same range as the visible spectrum, which we see as a rainbow.

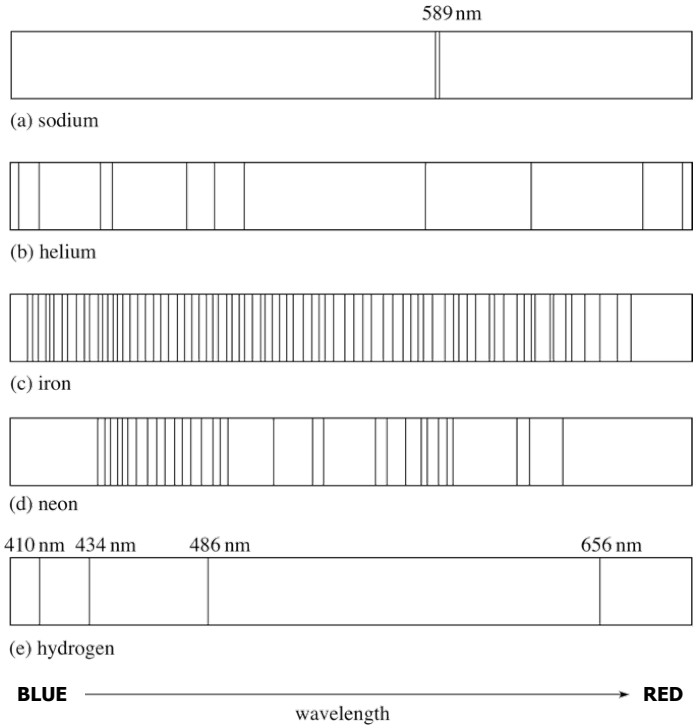
| R | O | Y | G | B | I | V |
|---|---|---|---|---|---|---|
| red | orange | yellow | green | blue | indigo | violet |

The white light is emitted from a bulb or any incandescent source, therefore the continuous spectrum is an emission spectrum.

## ATOMIC EMISSION SPECTRA

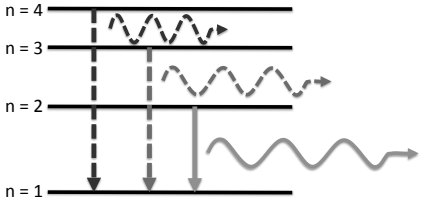
When an element in the gaseous phase is heated, it emits light. If the light produced is passed through a prism, a spectrum is produced. However, this spectrum is not continuous, but consists of only some lines of colour. This is known as **line emission spectrum** and is unique for each element.

Each element has their own light signature as no two elements have the same spectrum, like a bar code or finger print.




## ENERGY LEVELS

The lines on the atomic spectrum (line emission spectrum) are as a result of electron transitions between energy levels. As electrons gain energy (from heat, electricity or any other source) they move to a higher state of energy, hence a higher energy level, further away from the nucleus. As the element cools the electrons drop back down to the lower energy state and a position closer to the nucleus. As they do this they emit the absorbed energy in the form of light (photons). Therefore, each electron gives off a frequency of light which corresponds with the line emission spectrum.




Electrons in the n = 1 energy level are closest to the nucleus and have the lowest potential energy. Electrons in the energy level furthest from the nucleus (eg. n = 4) has the highest potential energy. If an electron is free from the atom then it has zero potential energy. The potential energy is always given as a negative value due to a decrease in potential as the electrons get close to the nucleus.

As the electrons transition from their energized state back to their normal state they give off energy that is equal to the difference in potential energy between the energy levels.

$$\Delta E = E_2 - E_1$$

$\Delta E$ = difference in potential energy between two energy levels

$E_2$ = the highest energy state

$E_1$ = the lowest energy state

**NB:** Remember to use NEGATIVES for the values when substituting $E_1$ and $E_2$ individually

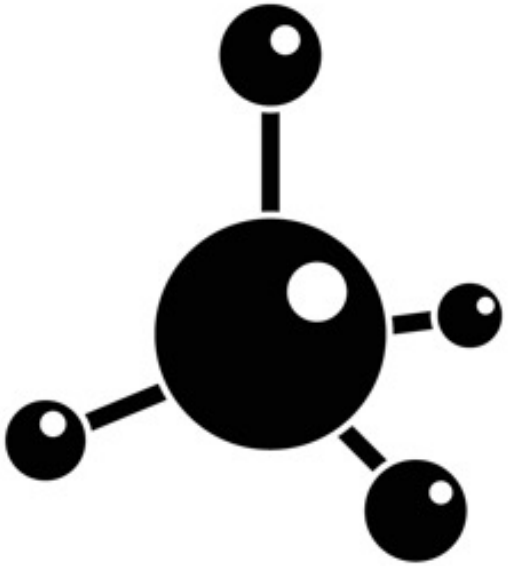
The amount of energy that is released relates directly to a specific frequency or wavelength (thus colour) of light.

$$E = hf \qquad E = \frac{hc}{\lambda}$$

**EXAMPLE:**
A sample of hydrogen gas is placed in a discharge tube. The electron from the hydrogen atom emits energy as it transitions from energy level $E_6$ ($-0{,}61\times10^{-19}$ J) to $E_2$ ($-5{,}46\times10^{-19}$). Determine the wavelength of light emitted.

$$\Delta E = E_6 - E_2$$
$$= -0{,}61\times10^{-19} - (-5{,}46\times10^{-19})$$
$$= 4{,}85\times10^{-19}\ \text{J}$$

$$E = \frac{hc}{\lambda}$$
$$4{,}85\times10^{-19} = \frac{(6{,}63\times10^{-34})(3\times10^{8})}{\lambda}$$
$$\lambda = 4{,}1\times10^{-7} = 410\ \text{nm}$$



# Chemistry



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# EXAMINATION DATA SHEET FOR THE PHYSICAL SCIENCES (CHEMISTRY)

## TABLE 1 PHYSICAL CONSTANTS

| NAME | SYMBOL | VALUE |
|---|---|---|
| Magnitude of charge on electron | e | $1,6 \times 10^{-19}$ C |
| Mass of an electron | $m_e$ | $9,1 \times 10^{-31}$ kg |
| Standard pressure | $p^{\theta}$ | $1,01 \times 10^{5}$ Pa |
| Molar gas volume at STP | $V_m$ | 22,4 $dm^3 \cdot mol^{-1}$ |
| Standard temperature | $T^{\theta}$ | 273 K |
| Avogadro's constant | $N_A$ | $6,02 \times 10^{23}$ $mol^{-1}$ |
| Faraday's constant | F | 96 500 $C \cdot mol^{-1}$ |

## TABLE 2 CHEMISTRY FORMULAE

| | | |
|---|---|---|
| $n = \frac{m}{M}$ | $n = \frac{N}{N_A}$ | $n = \frac{V}{V_m}$ |
| $c = \frac{n}{V}$ OR $c = \frac{m}{MV}$ | $K_w = [H_3O^+] \cdot [OH^-] = 1 \times 10^{-14}$ at 25 °C (298 K) | |
| $q = It$<br>$q = nF$ | $E^{\theta}_{cell} = E^{\theta}_{cathode} - E^{\theta}_{anode}$<br>$E^{\theta}_{cell} = E^{\theta}_{oxidising\ agent} - E^{\theta}_{reducing\ agent}$ | |

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**TABLE 3 PERIODIC TABLE**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 2,1 **H** 1 | | | | | | | | | | | | | | | | | 2 **He** 4 |
| 2 | 3 1,0 **Li** 7 | 4 1,5 **Be** 9 | | | | | | | | | | | 5 2,0 **B** 10,8 | 6 2,5 **C** 12 | 7 3,0 **N** 14 | 8 3,5 **O** 16 | 9 4,0 **F** 19 | 10 **Ne** 20 |
| 3 | 11 0,9 **Na** 23 | 12 1,2 **Mg** 24,3 | | | | | | | | | | | 13 1,5 **Aℓ** 27 | 14 1,8 **Si** 28 | 15 2,1 **P** 31 | 16 2,5 **S** 32 | 17 3,0 **Cℓ** 35,5 | 18 **Ar** 40 |
| 4 | 19 0,8 **K** 39 | 20 1,0 **Ca** 40 | 21 1,3 **Sc** 45 | 22 1,5 **Ti** 48 | 23 1,6 **V** 51 | 24 1,6 **Cr** 52 | 25 1,5 **Mn** 55 | 26 1,8 **Fe** 56 | 27 1,8 **Co** 59 | 28 1,8 **Ni** 59 | 29 1,9 **Cu** 63,5 | 30 1,6 **Zn** 65,4 | 31 1,6 **Ga** 70 | 32 1,8 **Ge** 72,6 | 33 2,0 **As** 75 | 34 2,4 **Se** 79 | 35 2,8 **Br** 80 | 36 **Kr** 84 |
| 5 | 37 0,8 **Rb** 85,5 | 38 1,0 **Sr** 88 | 39 1,2 **Y** 89 | 40 1,4 **Zr** 91 | 41 1,6 **Nb** 93 | 42 1,8 **Mo** 96 | 43 1,9 **Tc** 99 | 44 2,2 **Ru** 101 | 45 2,2 **Rh** 103 | 46 2,2 **Pd** 106 | 47 1,9 **Ag** 108 | 48 1,7 **Cd** 112 | 49 1,7 **In** 115 | 50 1,8 **Sn** 119 | 51 1,9 **Sb** 121 | 52 2,1 **Te** 128 | 53 2,5 **I** 127 | 54 **Xe** 131 |
| 6 | 55 **Cs** 133 | 56 **Ba** 137,3 | | 72 **Hf** 178,5 | 73 **Ta** 181 | 74 **W** 184 | 75 **Re** 186 | 76 **Os** 190 | 77 **Ir** 192 | 78 **Pt** 195 | 79 **Au** 197 | 80 **Hg** 200,6 | 81 **Tℓ** 204,4 | 82 **Pb** 207 | 83 **Bi** 209 | 84 **Po** – | 85 **At** – | 86 **Rn** – |
| 7 | 87 **Fr** | 88 **Ra** | | | | | | | | | | | | | | | | |

**Atomic number (Z)** — 1 2,1 **H** 1 — **Electro-negativity**

**Relative atomic mass**

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 57 **La** | 58 **Ce** | 59 **Pr** | 60 **Nd** | 61 **Pm** | 62 **Sm** | 63 **Eu** | 64 **Gd** | 65 **Tb** | 66 **Dy** | 67 **Ho** | 68 **Er** | 69 **Tm** | 70 **Yb** | 71 **Lu** |
| 89 **Ac** | 90 **Th** | 91 **Pa** | 92 **U** | 93 **Np** | 94 **Pu** | 95 **Am** | 96 **Cm** | 97 **Bk** | 98 **Cf** | 99 **Es** | 100 **Fm** | 101 **Md** | 102 **No** | 103 **Lw** |

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## TABLE 4 STANDARD ELECTRODE POTENTIALS

| Half-reaction | E°/volt |
|---|---|
| $Li^+ + e^- \rightleftharpoons Li$ | –3,05 |
| $K^+ + e^- \rightleftharpoons K$ | –2,93 |
| $Cs^+ + e^- \rightleftharpoons Cs$ | –2,92 |
| $Ba^{2+} + 2e^- \rightleftharpoons Ba$ | –2,90 |
| $Sr^{2+} + 2e^- \rightleftharpoons Sr$ | –2,89 |
| $Ca^{2+} + 2e^- \rightleftharpoons Ca$ | –2,87 |
| $Na^+ + e^- \rightleftharpoons Na$ | –2,71 |
| $Mg^{2+} + 2e^- \rightleftharpoons Mg$ | –2,37 |
| $A\ell^{3+} + 3e^- \rightleftharpoons A\ell$ | –1,66 |
| $Mn^{2+} + 2e^- \rightleftharpoons Mn$ | –1,18 |
| $2H_2O + 2e^- \rightleftharpoons H_2(g) + 2OH^-$ | –0,83 |
| $Zn^{2+} + 2e^- \rightleftharpoons Zn$ | –0,76 |
| $Cr^{3+} + 3e^- \rightleftharpoons Cr$ | –0,74 |
| $Fe^{2+} + 2e^- \rightleftharpoons Fe$ | –0,44 |
| $Cd^{2+} + 2e^- \rightleftharpoons Cd$ | –0,40 |
| $Co^{2+} + 2e^- \rightleftharpoons Co$ | –0,28 |
| $Ni^{2+} + 2e^- \rightleftharpoons Ni$ | –0,25 |
| $Sn^{2+} + 2e^- \rightleftharpoons Sn$ | –0,14 |
| $Pb^{2+} + 2e^- \rightleftharpoons Pb$ | –0,13 |
| $Fe^{3+} + 3e^- \rightleftharpoons Fe$ | –0,04 |
| $2H^+ + 2e^- \rightleftharpoons H_2(g)$ | 0,00 |
| $S + 2H^+ + 2e^- \rightleftharpoons H_2S(g)$ | +0,14 |
| $Sn^{4+} + 2e^- \rightleftharpoons Sn^{2+}$ | +0,15 |
| $SO_4^{2-} + 4H^+ + 2e^- \rightleftharpoons SO_2(g) + 2H_2O$ | +0,17 |
| $Cu^{2+} + 2e^- \rightleftharpoons Cu$ | +0,34 |
| $2H_2O + O_2 + 4e^- \rightleftharpoons 4OH^-$ | +0,40 |
| $SO_2 + 4H^+ + 4e^- \rightleftharpoons S + 2H_2O$ | +0,45 |
| $I_2 + 2e^- \rightleftharpoons 2I^-$ | +0,54 |
| $O_2(g) + 2H^+ + 2e^- \rightleftharpoons H_2O_2$ | +0,68 |
| $Fe^{3+} + e^- \rightleftharpoons Fe^{2+}$ | +0,77 |
| $Hg^{2+} + 2e^- \rightleftharpoons Hg$ | +0,79 |
| $NO_3^- + 2H^+ + e^- \rightleftharpoons NO_2(g) + H_2O$ | +0,80 |
| $Ag^+ + e^- \rightleftharpoons Ag$ | +0,80 |
| $NO_3^- + 4H^+ + 3e^- \rightleftharpoons NO(g) + 2H_2O$ | +0,96 |
| $Br_2 + 2e^- \rightleftharpoons 2Br^-$ | +1,09 |
| $Pt^{2+} + 2e^- \rightleftharpoons Pt$ | +1,20 |
| $MnO_2 + 4H^+ + 2e^- \rightleftharpoons Mn^{2+} + 2H_2O$ | +1,21 |
| $O_2 + 4H^+ + 4e^- \rightleftharpoons 2H_2O$ | +1,23 |
| $Cr_2O_7^{2-} + 14H^+ + 6e^- \rightleftharpoons 2Cr^{3+} + 7H_2O$ | +1,33 |
| $C\ell_2(g) + 2e^- \rightleftharpoons 2C\ell^-$ | +1,36 |
| $Au^{3+} + 3e^- \rightleftharpoons Au$ | +1,42 |
| $MnO_4^- + 8H^+ + 5e^- \rightleftharpoons Mn^{2+} + 4H_2O$ | +1,51 |
| $H_2O_2 + 2H^+ + 2e^- \rightleftharpoons 2H_2O$ | +1,77 |
| $F_2(g) + 2e^- \rightleftharpoons 2F^-$ | +2,87 |

**Increasing oxidising ability** ↓

**Increasing reducing ability** ↑

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| | |
|---|---|
| **Quantitative Chemistry** | **Molar mass:** Mass in grams of one mole of that substance<br>**Solution:** Homogeneous mixture of solute and solvent<br>**Solute:** Substance that is dissolved in the solution<br>**Solvent:** Substance in which another substance is dissolved, forming a solution<br>**Concentration:** Amount of solute per unit volume of solution<br>**Standard solution:** Solution of known concentration<br>**Yield:** A measure of the extent of a reaction, generally measured by comparing the amount of product against the amount of product that is possible |
| **Chemical Bonding** | **Intramolecular bond:** A bond which occurs between atoms within molecules<br>**Electronegativity:** A measure of the tendency of an atom to attract a bonding pair of electrons<br>**Covalent bond:** A sharing of at least one pair of electrons by two non-metal atoms<br>**Non-polar covalent (pure covalent):** An equal sharing of electrons<br>**Polar covalent:** Unequal sharing of electrons leading to a dipole forming (as a result of electronegativity difference)<br>**Ionic bond:** A transfer of electrons and subsequent electrostatic attraction<br>**Metallic bonding:** A metallic bond is between a positive kernel and a sea of delocalized electrons<br>**Intermolecular force**: A weak force of attraction between molecules, ions, or atoms of noble gases |
| **Energy Change and Rates of Reaction** | **Heat of reaction (ΔH)**: The net change of chemical potential energy of the system<br>**Exothermic reactions:** Reactions which transform chemical potential energy into thermal energy<br>**Endothermic reactions:** Reactions which transform thermal energy into chemical potential energy<br>**Activation energy:** The minimum energy required to start a chemical reaction OR The energy required to form the activated complex<br>**Activated complex:** A high energy, unstable, temporary transition state between the reactants and products<br>**Reaction rate:** Change in concentration per unit time of either a reactant or product<br>**Catalyst:** Substance that increases the rate of the reaction but remains unchanged at the end of the reaction |
| **Chemical Equilibrium** | **Closed system:** A system in which mass is conserved inside the system but energy can enter or leave the system freely<br>**Open system:** A system in which both energy and matter can be exchanged between the system and its surroundings<br>**Le Chatelier's Principle:** When an external stress (change in pressure, temperature or concentration) is applied to a system in dynamic chemical equilibrium, the equilibrium point will change in such a way as to counteract the stress<br>**Yield:** A measure of the extent of a reaction, generally measured by comparing the amount of product against the amount of product that is possible |
| **Acids and Bases** | **Lowry-Brønsted theory:**<br>**Base**: a proton ($H^+$ ion) acceptor<br>**Acid:** a proton ($H^+$ ion) donor<br>**Ionisation:** The reaction of a molecular substance with water to produce ions<br>**Dissociation**: The splitting of an ionic compound into its ions<br>**Strong acids:** An acid that ionises completely in an aqueous solution<br>**Strong bases:** A base that dissociates completely in an aqueous solution<br>**Weak acids:** An acid that only ionises partially in an aqueous solution<br>**Weak bases:** A base that only dissociates/ionises partially in an aqueous solution<br>**Amphoteric (Amphiprotic):** A substance that can act as either an acid or a base<br>**Salt:** A substance in which the hydrogen of an acid has been replaced by a cation<br>**Hydrolysis of a salt:** A reaction of an ion (from a salt) with water<br>**Neutralization/equivalence point:** The point where an acid and a base have reacted so neither is in excess |
| **Electrochemistry** | **Redox:** A reaction involving the transfer of electrons<br>**Oxidation:** A loss of electrons<br>**Reduction:** A gain of electrons<br>**Oxidising agent:** A substance that accepts electrons.<br>**Reducing agent:** A substance that donates electrons.<br>**Anode**: The electrode where oxidation takes place<br>**Cathode:** The electrode where reduction takes place<br>**Electrolyte:** A substance that can conduct electricity by forming free ions when molten or dissolved in solution |
| **Organic Chemistry** | **Functional group:** an atom or a group of atoms that form the centre of chemical activity in the molecule<br>**Hydrocarbon:** a compound containing only carbon and hydrogen atoms<br>**Homologous series:** a series of similar compounds which have the same functional group and have the same general formula, in which each member differs from the previous one by a single $CH_2$ unit<br>**Saturated compound:** a compound in which all of the bonds between carbon atoms are single bonds<br>**Unsaturated compound:** a compound in which there is at least one double and/ triple bond between carbon atoms<br>**Structural isomer: C**ompounds that have the same molecular formula but different structural formulae |

# ORGANIC MOLECULES



Organic molecules contain carbon atoms, with the exception of $CO_2$,, CO, diamond graphite, carbonates (or bicarbonates), carbides and cyanides. These compounds can be in the gaseous, liquid, or solid phase. All living matter contains organic compounds.

## UNIQUENESS OF CARBON

Carbon is very unique and is the basic building block of all organic compounds. Carbon's atoms have a valency of four in a tetrahedral arrangement. This means it is able to **make four bonds**. It forms strong carbon to carbon bonds and permits long chains to form. The is called **catenation**.

Carbon atoms can form single or double bonds.

C — C  C ═ C

**NOTE:**

Carbon atoms have to form 4 bonds, but not necessarily with 4 other atoms

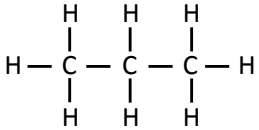
## HYDROCARBONS

A hydrocarbon is a compound that contains only carbon and hydrogen atoms. These compounds can be saturated (single bonds) and unsaturated (double or triple bonds).

**Hydrocarbon:** A compound containing only carbon and hydrogen atoms.

**Saturated compound:**

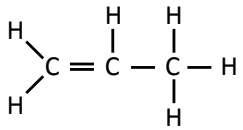
A compound in which all of the bonds between carbon atoms are single bonds.



(Alkanes)

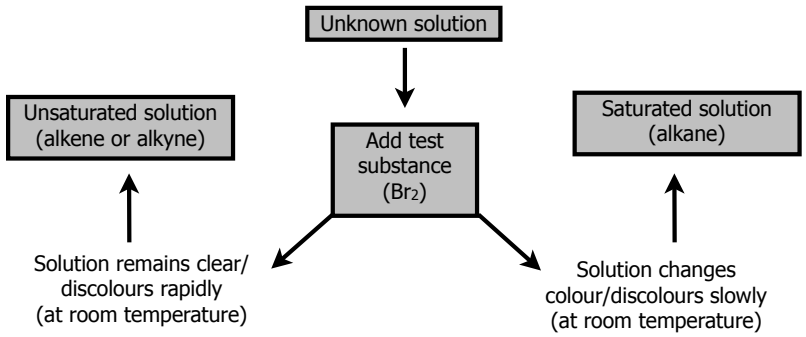
**Unsaturated compound:**

A compound in which there is at least one double and/or triple bond between carbon atoms.



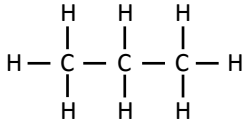
(Alkenes and alkynes)

**Saturation test with $Br_2$ (aq)**



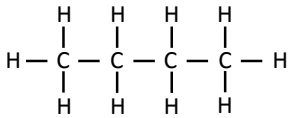
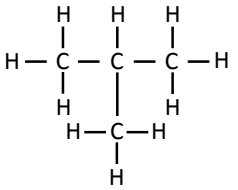
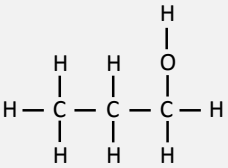
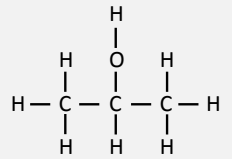
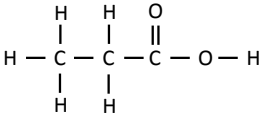
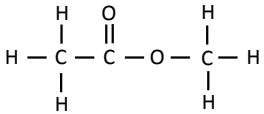

## REPRESENTING ORGANIC COMPOUNDS

We use a variety of ways to draw or write organic compounds. We either make use of the molecular formula, condensed formula or we use full structural formulae.

| | | |
|---|---|---|
| **Structural formula** | Atoms are represented by their chemical symbols and lines are used to represent ALL of the bonds between the atoms. |  |
| **Condensed formula** | The way in which atoms are bonded but NOT ALL bond lines are shown. | $CH_3CH_2CH_3$ |
| **Molecular formula** | This is a chemical formula that indicates the type of atoms and the correct number of each in a molecule. | $C_3H_8$ |

## ISOMERS

**Structural Isomers: Compounds having the same molecular formula but different structural formulae.**

| | | | |
|---|---|---|---|
| **Chain isomers** | These have the same molecular formula but different types of chain structures (i.e. branching) | butane  | methylpropane  |
| **Positional isomers** | These have the same molecular formula but the same functional group is in a different position on the parent chain. | propan-1-ol  | propan-2-ol  |
| **Functional isomers** | These have the same molecular formula but a different functional group. **Carboxylic acids** and **esters** are functional isomers. | propanoic acid  | methyl ethanoate  |

# ORGANIC MOLECULES- NAMING



All organic compounds belong to a specific group which allows us to identify or name the compound. The group that compounds belong to, known as the **homologous series**, depends on the the **functional group** of the compound.

**Homologous series:** A series of similar compounds which have the same functional group and have the same general formula, in which each member differs from the previous one by a single $CH_2$ unit.
**Functional group:** An atom or a group of atoms that form the centre of chemical activity in the molecule.
**General formula:** A formula that is applicable to all members of a homologous series.

## NAMING ORGANIC COMPOUNDS

Every distinct compound has a unique name, and there is only one possible structure for any IUPAC (International Union of Pure and Applied Chemistry) name. The IUPAC method for naming is a set pattern. It indicates the **longest chain** (the longest continuous chain), the **functional group** and names of **substituent groups (side chains)** or atoms attached to the longest chain.

### Three parts of an IUPAC name:

**Substituent Prefix** — **Root name** — **Functional group suffix**

The **root name** indicates the number of carbon atoms in the longest chain. This chain **must contain the functional group**. The **prefix** indicates the **number and location** of atoms or groups (substituents) attached to the longest chain. The **suffix** identifies the **functional group.**

### Steps to naming organic compounds:

1. Identify the longest continuous carbon chain which must contain the functional group.
2. Number the longest carbon chain beginning at the carbon (carbon 1) nearest to the functional group with the alkyl substituents on the lowest numbered carbon atoms of the longest chain.
3. Name the longest chain according to the number of carbons in the chain. (**the root name**)
4. The **suffix** of the compound name is dependent on the functional group.
5. Identify and name substituents (alkyl and halogen substituents), indicating the position of the substituent
6. For several identical side chains use the prefix di-, tri-, tetra-
7. Arrange substituents in alphabetical order in the name of the compound, ignore the prefix di-, tri-, tetra- **(substituent prefix)**
8. Indicate position using numbers.

| Number of carbon atoms in main chain | Root name |
|---|---|
| 1 | meth– |
| 2 | eth– |
| 3 | prop– |
| 4 | but– |
| 5 | pent– |
| 6 | hex– |
| 7 | hept– |
| 8 | oct– |

| Number of substituents | Substituent prefix |
|---|---|
| 2 | **di** (eg. dimethyl) |
| 3 | **tri** (eg. triethyl) |
| 4 | **tetra** (eg. tetramethyl) |

**NOTE:**
A maximum of THREE substituent chains (alkyl substituents) are allowed on the main chain

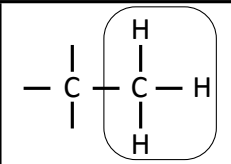
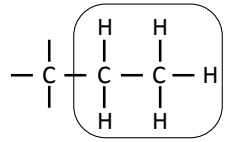
**NOTE:**
**comma between numbers**
number , number
**dash between letter and number**
letter – number – letter

**NB SAG REQUIREMENT:**

**For DIOLS**
the "e" before the suffix is **not** removed
e.g. butane–1,2–diol ✓ BUT butan–1,2–diol ✗

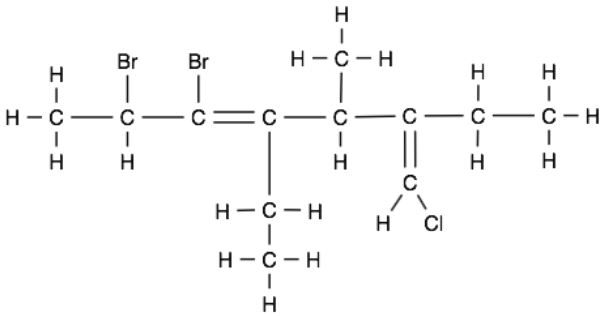
**For DIENES:**
an "a" must be **added** before the suffix
e.g. buta–1,3–diene ✓ BUT but–1,3–diene ✗

**GENERAL RULE:**
There must be **1 vowel** and **1 consonant** on either side of the numbers. There may not be 2 vowels or 2 consonants.

| Substituent | Formula | Structural formula | Name |
|---|---|---|---|
| Alkyl | $CH_3$– |  | methyl– |
| | $CH_3CH_2$– |  | ethyl– |
| Halogen | X– |  | X repesents a halogen:<br>Fluorine: fluoro–<br>Chlorine: chloro–<br>Bromine: bromo–<br>Iodine: iodo– |

**EXAMPLE:**

Write down the name of the molecule below:

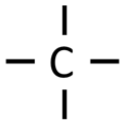
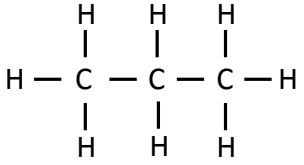
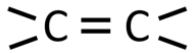
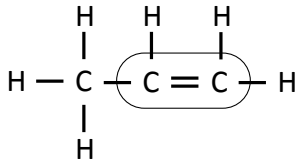
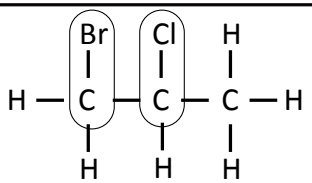
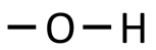
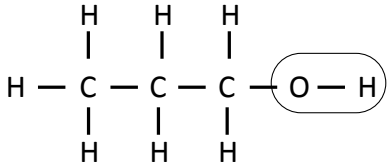
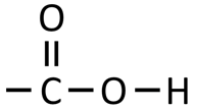
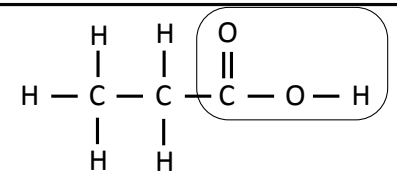
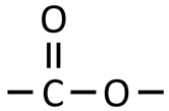
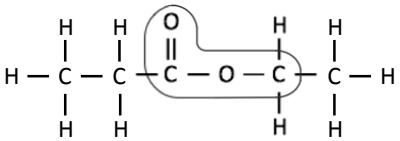


| Substituents | Main chain | Functional group |
|---|---|---|
| 1–**c**hloro | 7 = hept | 1,4–diene |
| 2,4–di**e**thyl | | |
| 3–**m**ethyl | | |
| 5,6–di**b**romo | | |

5,6–dibromo–1–chloro–2,4–diethyl–3–methylhepta–1,4–diene

# Organic Functional Groups



| Homologous series and General formula | Functional group | Suffix | Examples | | | Properties |
|---|---|---|---|---|---|---|
| | | | Structural formula | Condensed formula | Name | |
| Alkanes<br>$C_nH_{2n+2}$ | Saturated hydrocarbon<br>  | -ane |  | $CH_3CH_2CH_3$ | prop**ane** | **Polarity:** Non-Polar<br>**IMF:** Weak London<br>**Reactions**: Substitution, Elimination, Combustion |
| Alkenes<br>$C_nH_{2n}$ | Double carbon-carbon bonds<br>  | -ene |  | $CH_3CH{=}CH_2$ | prop**ene** | **Polarity:** Non-polar<br>**IMF:** London<br>**Reactions:** Addition, combustion |
| Haloalkane/<br>Haloalkene<br>(Alkyl halide) | Halogen atom bonded to a carbon atom<br>  | fluoro–<br>chloro–<br>bromo–<br>iodo– |  | $CH_2BrCHClCH_3$ | 1–bromo–2–chloropropane | **Polarity:** Polar<br>**IMF:** Dipole–Dipole<br>**Reactions:** Elimination, Substitution |
| Alcohols<br>$C_nH_{2n+2}O$ | Hydroxyl group<br>  | -ol |  | $CH_3CH_2CH_2$**OH** | propan–1–**ol** | **Polarity:** Polar<br>**IMF:** Strong Hydrogen bonds<br>**Reactions:** Substitution, Elimination, Esterification, Combustion |
| Carboxylic acids<br>$C_nH_{2n}O_2$ | Carboxyl group<br>  | -oic acid |  | $CH_3CH_2$**COOH** | propan**oic acid** | **Polarity:** Polar<br>**IMF:** Strong Hydrogen bonds<br>**Reactions:** Esterification |
| Esters<br>–COO– | Ester group<br>  | -yl -oate<br>(alch.) (carbox.) |  | $CH_3CH_2$**COOC**$H_2CH_3$<br>(carbox.) (alch.) | eth**yl** propan**oate** | **Polarity:** Polar<br>**IMF:** Dipole–Dipole<br>**Reactions:** Formed by esterification |

# ORGANIC INTERMOLECULAR FORCES



Intermolecular forces are forces that exist between molecules in the solid, liquid and gaseous phases. They are electrostatic attractive forces. The strength of the IMF will determine the freedom of the particles, determining the phase of the substance (solid, liquid, gas).

**Intermolecular force are a weak force of attraction between molecules, ions or atoms of noble gases**

The types of intermolecular forces that exists between different types of organic molecules and the strength of the intermolecular forces will affect the physical properties of a molecule.

| TYPES OF IMF | | | |
|---|---|---|---|
| | **Hydrogen Bonds** | • Strongest of all the intermolecular forces<br>• Act over shorter distances.<br>• Between molecules that are strongly polar that contain hydrogen bonded to a small highly electronegative atom such as **N, O or F.** | Alcohols (1 bonding site)<br>Carboxylic Acids (2 bonding sites) |
| | **Dipole-Dipole Forces** | • Stronger than Dispersion forces.<br>• Between slightly polar molecules.<br>• Force of attraction between the $\delta^+$ end of the one molecule and the $\delta^-$ end of another. | Esters<br>Alkyl Halides |
| | **London forces (Induced Dipole forces/Dispersion forces)** | • Very weak Van der Waals forces.<br>• Between non-polar molecules that form induced (temporary) dipoles and these temporary dipoles attract each other | Alkanes<br>Alkenes |

## RELATIONSHIP BETWEEN PHYSICAL PROPERTIES AND IMF

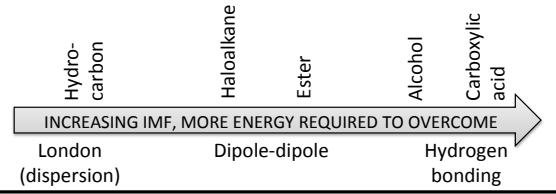
| PHYSICAL PROPERTY | RELATIONSHIP TO IMF |
|---|---|
| **Melting Point:**<br>**The temperature at which the solid and liquid phases of a substance are at equilibrium**. It is the temperature where solid particles will undergo a phase change (melt) and become a liquid. | Directly proportional |
| **Boiling Point:**<br>**The temperature at which vapour pressure of the substance equals atmospheric pressure.** It is the temperature where liquid boils and turns into a vapour (gas). | Directly proportional |

## COMPARING IMF

1. Identify the type of intermolecular force.
2. Discuss the difference between the two compounds (① → ④ ).
3. Discuss how this difference either ↑ or ↓ the strength of the intermolecular force.
4. Discuss how the physical property is affected (↑ or ↓ ).
5. Discuss energy required to overcome forces.

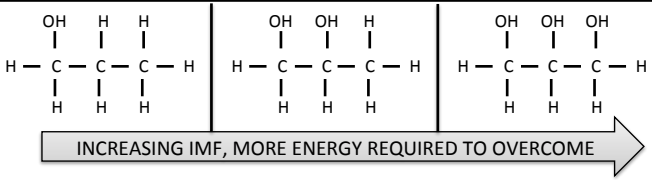
### ① TYPE OF FUNCTIONAL GROUP

The more polar the molecule, the stronger the IMF



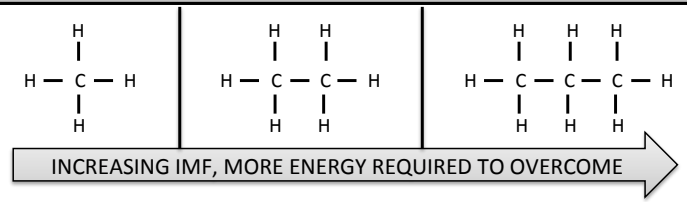

### ② NUMBER OF FUNCTIONAL GROUPS

An increase in functional groups increase the IMF



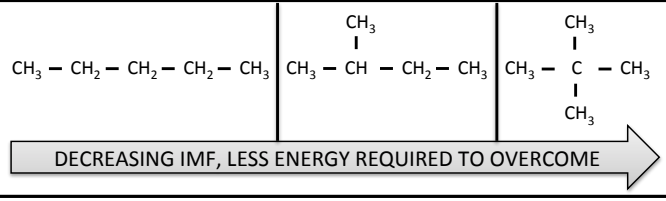

### ③ CHAIN LENGTH: ELECTRON DENSITY

The greater the number of carbon atoms in the chain, the greater the electron density. An increase in electron density increases the IMF




### ④ CHAIN LENGTH: BRANCHES

More branching results in a smaller contact surface area and lower the strength of the IMF



# ORGANIC REACTIONS

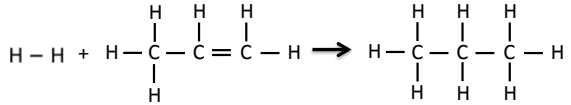


## ADDITION REACTIONS (UNSATURATED → SATURATED)

Addition reactions are reactions where atoms are added to an organic molecule. The double or triple bonds break open and the new atoms are added to the carbon atoms on either side of the double or triple bond.

We can add hydrogen ($H_2$), a halogen (Group 7 – e.g. $Cl_2$), a Hydrogen halide or water $H_2O$. In addition reactions alkenes or alkynes form an alkane chain as a product.

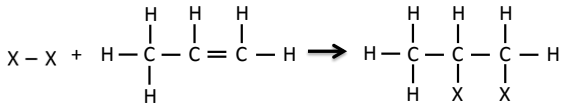
### 1) Hydrogenation – add $H_2$



hydrogen + alkene → alkane

**Reaction conditions:**
The alkene needs to be dissolved in an organic solvent and needs to have a catalyst present eg. Pt, Ni or Pd.
In a $H_2$ atmosphere.

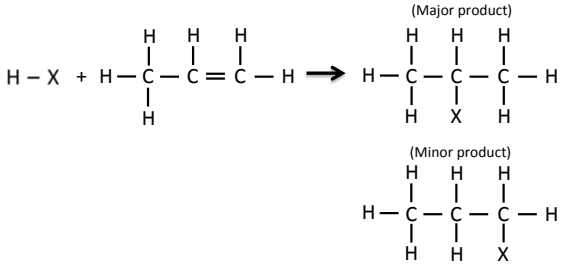
### 2) Halogenation – add $X_2$, (X = Halogen: $F_2$, $Cl_2$, $Br_2$, $I_2$)



halogen + alkene → haloalkane

**Reaction conditions:**
No water to be present if it is to take place.
(Refer to Saturation test)

### 3) Hydrohalogenation – add HX (X = Halogen: $F_2$, $Cl_2$, $Br_2$, $I_2$)

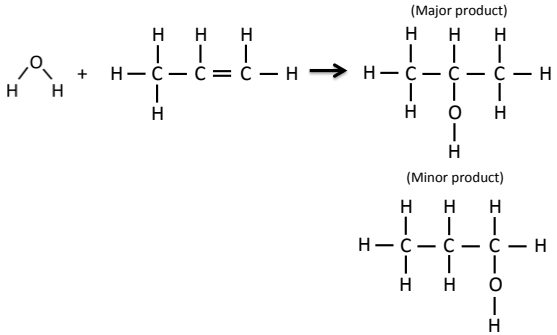


hydrogen halide + alkene → haloalkane

**Reaction conditions:**
No water to be present if it is to take place.

**Markovnikov's rule:** The H atom will bond to the carbon atom which has the greater number of H atoms bonded to it. (Form biggest H groups)

### 4) Hydration – add of $H_2O$



water ($H_2O$) + alkene → alcohol

**Reaction conditions:**
Suitable catalyst e.g. $H_2SO_4$ or $H_3PO_4$
Heat in the form of steam

**Markovnikov's rule:** The H atom will bond to the carbon atom which has the greater number of H atoms bonded to it. (Form biggest H groups)

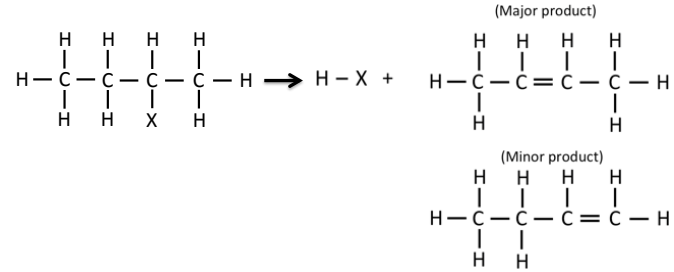
**Note:**
Either product will be accepted

## ELIMINATION REACTIONS (SATURATED → UNSATURATED)

An elimination reaction is a reaction where atoms or groups of atoms are removed from an organic molecule to form either a double or triple bonded compound.

This reaction is the **opposite reaction** to the addition reactions and is the removal of hydrogen ($H_2$), a halogen (Group 7 – e.g. $Cl_2$), a hydrogen halide or water $H_2O$. In elimination reactions, alkanes form either an alkene or alkyne chain as a product.

### 1) Dehydrohalogenation – remove HX (X = Halogen: $F_2$, $Cl_2$, $Br_2$, $I_2$)

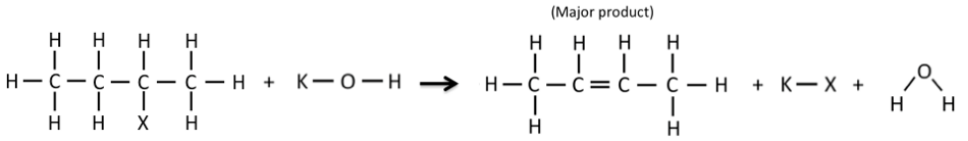


haloalkane → hydrogen halide + alkene

**Reaction conditions:**
Takes place in the presence of hot concentrated NaOH/KOH in ethanol as the solvent. (i.e. in the absence if water)

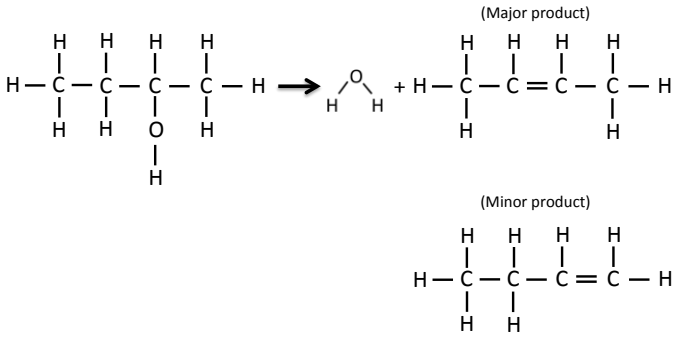
**Zaitzev's rule:** H atom is removed from the carbon atom with the least number of H atoms. (Keeps biggest H groups)

**OR**



haloalkane + base → alkene + ionic salt + water ($H_2O$)

### 2) Dehydration – remove $H_2O$ from any alcohol



alcohol → water ($H_2O$) + alkene

**Reaction conditions:**
Requires the heating of an alcohol with concentrated acid catalyst eg. $H_2SO_4$ or $H_3PO_4$. The acid should be in excess
(Acid catalyzed dehydration)

Sulfuric acid is known as a dehydrating agent.

**Zaitzev's rule:** H atom is removed from the carbon atom with the least number of H atoms. (Keeps biggest H groups)

**Note:**
Either product will be accepted

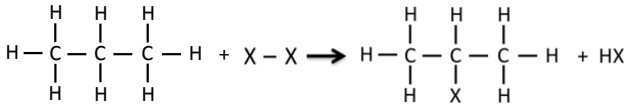
# ORGANIC REACTIONS



## SUBSTITUTION REACTIONS (SATURATED → SATURATED)

Substitution reactions is when an atom or group of atoms in an organic molecule are replaced or swopped/exchanged for another atom or group of atoms. Substitution reactions take place between compounds that are saturated alkanes, haloalkanes and alcohols.

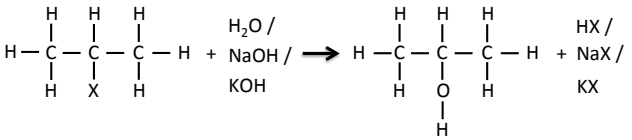
1) **Alkanes: Halogenation (free-radical halogenation) - Substitute $X_2$ (X = Halogen: $F_2$, $Cl_2$, $Br_2$, $I_2$)**



**Reaction conditions:**
Reaction takes place in the presence of UV light/heat

alkane + halogen → haloalkane + hydrogen halide

**2) Haloalkanes: Hydrolysis - Substitute $H_2O$**



**Reaction conditions:**
The haloalkane is dissolved in an ethanol solution and treated with hot aqueous dilute NaOH/KOH solution. OR Heat under reflux in a dilute alkali solution

haloalkane + $H_2O$/NaOH/KOH → alcohol + HX/NaX/KX

## COMBUSTION/OXIDATION REACTIONS

Hydrocarbons are the main source of fuel in the world at the moment. They are used in the production of electrical energy and as fuel for various engines. When hydrocarbons and alcohols react with oxygen they form water and carbon dioxide. These reactions are **exothermic** and produce large quantities of heat energy.

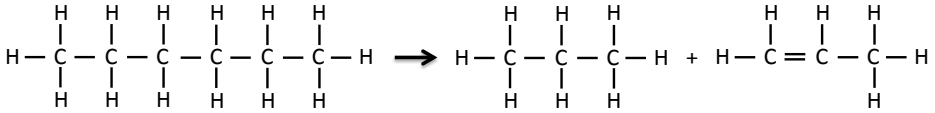
Complete combustion (excess oxygen): $C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$ + energy

Balancing: C → H → O

## ELIMINATION (Cracking)

Hydrocarbons can be made up of very long chains of hundreds of carbons. Crude oil is a mixture of many large hydrocarbons and each source of crude oil is different resulting in different types and amounts of hydrocarbons.

Shorter chain hydrocarbons are more useful to use as fuels as they burn more readily and are more flammable. Cracking is the breaking up of long hydrocarbon chains into smaller more useful hydrocarbons. An alkene and alkane will be the products as a result of cracking. Cracking is a type of elimination reaction.



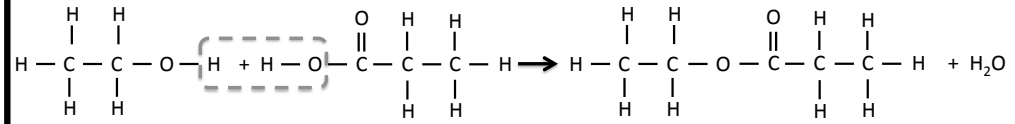
alkane → alkane + alkene

**Thermal cracking**
This method makes use of high pressures and high temperatures to crack the long hydrocarbon chains with no catalyst.

**Catalytic cracking**
This method uses a catalyst to crack long carbon chains at low pressure and low temperature. The heated crude oil is passed into a fractional distillation column and passed over a catalyst. The column is hottest at the bottom and coolest at the top. The crude oil separates according to boiling points and condenses as the gas rises up the column. The substances/chains with the longest chains will have higher boiling points and condense at the bottom and vice versa.

## CONDENSATION (Esterification)

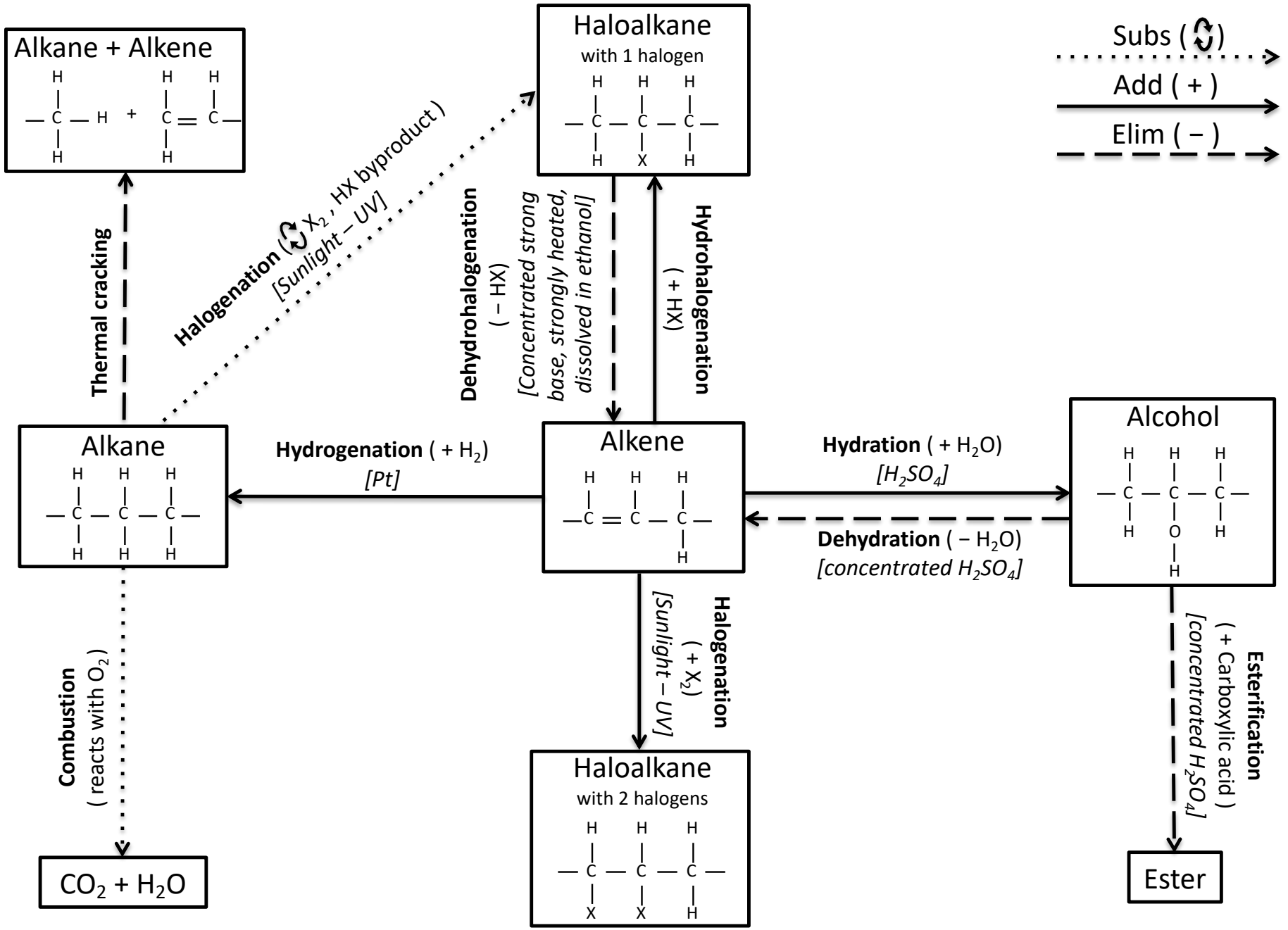
This is a reaction between an alcohol and a carboxylic acid in the **presence of a concentrated acid catalyst, $H_2SO_4$**. This reaction is a type of an elimination reaction and is also known as a condensation reaction as two organic molecules form one organic molecule and water is removed from the reactants and forms as a product in the reaction. Esters are responsible for the various smells which occur in nature and they are generally pleasant smells like banana and apple etc.



alcohol + carboxylic acid → ester + water

# SUMMARY OF ORGANIC REACTIONS





# QUANTITATIVE ASPECTS OF CHEMICAL CHANGE



## The Mole

Atoms, molecules and ions are too small to count, and there are so many particles in even the smallest sample of a substance.

The **mole** is the SI unit for amount of a substance. A mole of particles is an amount of 6,02 x $10^{23}$ particles. **6,02 x $10^{23}$ is known as Avogadro's number, $N_A$.**

$$n = \frac{N}{N_A}$$

$n$: number of mole (mol); $N$: number of particles; $N_A$: Avogadro's number (6,02 x $10^{23}$)

**EXAMPLE:**

Determine the amount of $H^+$ ions in 3 mol of $H_2SO_4$.

$N(H_2SO_4) = nN_A$

$= 3(6{,}02 \times 10^{23})$

$= 1{,}81 \times 10^{24}$ $H_2SO_4$ molecules

$H_2SO_4 : H^+$

$1 : 2$

$1{,}81 \times 10^{24} : 3{,}62 \times 10^{24}$

$\therefore N(H^+) = 3{,}62 \times 10^{24}$ ions

### Molar Mass

Particles are too small to weigh individually.

**Molar mass (M)** is defined as **the mass in grams of one mole of that substance** (atoms, molecules or formula units) and is measured in the unit g.mol$^{-1}$.

$$n = \frac{m}{M}$$

$n$: number of mole (mol); $m$: mass of substance (g); $M$: molar mass ($g \cdot mol^{-1}$)

**EXAMPLE:**

Determine the number of moles in 13 g of $CuSO_4$.

$M(CuSO_4) = 63{,}5 + 32 + 4(16)$

$= 159{,}5\ g \cdot mol^{-1}$

$n = \frac{m}{M}$

$= \frac{13}{159{,}5}$

$= 0{,}082$ mol

### Percentage Composition

**Percentage composition of element** $= \frac{\text{molar mass of element}}{\text{M of compound}} \times 100$

**Consider these iron ores: haematite and magnetite** – which contains more iron by mass?

| Ore | Haematite | Magnetite |
|---|---|---|
| **Formula** | $Fe_2O_3$ | $Fe_3O_4$ |
| **Relative molecular mass** | (2 x 56) + (3 x 16) =160 | (3 x 56) + (4 x 16) =232 |
| **% iron by mass** | [(2 x 56) /160] x 100 = 70% | [(3 x 56) / 232] x 100 = 72% |

$\therefore$ **magnetite contains more iron**

## Concentrations of solutions

**Solutions** are homogeneous (uniform) mixtures of solute and solvent.

The solvent and solute can be a gas, liquid, or solid. The most common **solvent** is liquid water. This is called an **aqueous solution**

| Solution | Solute | Solvent |
|---|---|---|
| salt water | salt | water |
| soda water | carbon dioxide | water |
| air | $O_2$, $CO_2$ and other gases | nitrogen gas (78%) |
| steel | carbon | iron |

**Concentration**

**The concentration of a solution is the number of moles of solute per unit volume of solution.**

$$c = \frac{n}{V}$$

$c$: concentration ($mol \cdot dm^{-3}$); $n$: number of moles (mol) of solute; $V$: volume ($dm^3$) of solution

can also be calculated with $c = \frac{m}{MV}$

Concentration is the number moles of solute per 1 $dm^3$ of solution i.e. mol·dm$^{-3}$. If a solution of **potassium permanganate $KMnO_4$** has a concentration of 2 mol.dm$^{-3}$ it means that for every 1 $dm^3$ of solution, there are 2 moles of $KMnO_4$ dissolved in the solvent.

**EXAMPLE:**

A solution contains 10 g of sodium hydroxide, NaOH, in 200 $cm^3$ of solution. Calculate the concentration of the solution.

$n(NaOH) = \frac{m}{M}$

$= \frac{10}{23 + 16 + 1}$

$= 0{,}25$ mol

$V = 200\ cm^3 = 0{,}2\ dm^3$

$c(NaOH) = \frac{n}{V}$

$= \frac{0{,}25}{0{,}2}$

$= 1{,}25\ mol \cdot dm^{-3}$

**EXAMPLE:**

Calculate the mass of solute in 600 $cm^3$ of 1,5 $mol \cdot dm^{-3}$ sodium chloride solution.

$V = 600\ cm^3 = 0{,}6\ dm^3$

$M(NaCl) = 23 + 35{,}5$

$= 58{,}5\ g \cdot mol^{-1}$

$n = cV$

$= 1{,}5 \times 0{,}6$

$= 0{,}9$ mol

$m = nM$

$= 0{,}9 \times 58{,}5$

$= 52{,}65$ g

## Molar Volumes of Gases

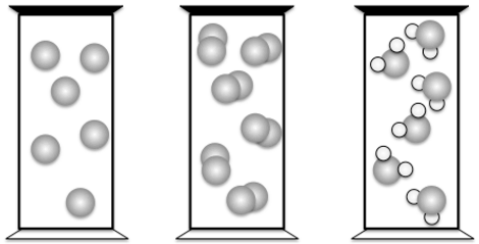
If different gases have the same volume under the same conditions of temperature and pressure, they will have the same number of molecules.

**The molar volume of a gas, $V_M$, is the volume occupied by one mole of the gas.**

**$V_M$ for all gases at STP is 22.4 $dm^3 \cdot mol^{-1}$.**

**Standard Temperature and Pressure (STP)** is 273 K (0°C) and 1,013×$10^5$ Pa (1 atm).

This also means that for reactions at constant temperature and pressure, gas volumes will react in the same ratio as the molar ratio.



$N_2 + 2O_2 \rightarrow 2NO_2$

1 mol + 2 mol → 2 mol

1 $dm^3$ + 2 $dm^3$ → 2 $dm^3$

$$n = \frac{V}{V_M}$$

$n$: number of moles (mol); $V$: volume of gaseous substance ($dm^3$); $V_M$: molar gas volume at STP (22,4 $dm^3 \cdot mol^{-1}$)

**EXAMPLE:**

A gas jar with a volume of 224 $cm^3$ is full of **chlorine gas**, at STP. How many **moles** of chlorine gas are there in the gas jar?

$n = \frac{V}{V_M}$

$= \frac{0{,}224}{22{,}4}$

$= 0{,}01\ mol$

# QUANTITATIVE ASPECTS OF CHEMICAL CHANGE



## Calculating Empirical Formula from Mass

1.Determine the mass of the elements.
2.Determine mol of each substance.
3.Simplify the atomic ratio.

**EXAMPLE:**
A sample of an **oxide of copper** contains 8 g of copper combined with 1 g of oxygen. Find the **empirical formula** of the compound.

| Steps | Copper | Oxygen |
|---|---|---|
| **Step 1:** Mass of element | 8 g | 1 g |
| **Step 2: Mol** (divide by mass of 1 mol) | n = m / M<br>= 8 / 63,5<br>= 0,126 mol | n = m / M<br>= 1 / 16<br>= 0,0625 mol |
| **Step 3: Atom ratio** (divide by smallest no in ratio) | 0,125/0,0625<br>≈2 | 0,0625/0,0625<br>=1 |

**Empirical formula: $Cu_2O$**

## Calculating Empirical Formula from Percentage Composition

The empirical formula of a compound can also be found from its percentage composition. We assume that 100 g of the compound is analysed, then each percentage gives the mass of the element in grams in 100 g of the compound.

An **oxide of sulphur** contains 40% sulphur and 60% oxygen by mass. Determine the **empirical formula** of this oxide of sulphur.

| Steps | Sulphur | Oxygen |
|---|---|---|
| **Step 1:** % of element | 40 | 60 |
| **Step 2:** Mass of element (g) | 40 | 60 |
| **Step 3:** Mol | n = m / M<br>= 40 / 32<br>= 1,25 mol | n = m / M<br>= 60 / 16<br>= 3,75 mol |
| **Step 4:** Divide by smallest mol ratio | 1,25 / 1,25<br>=1 | 3,75 /1,25<br>=3 |

**Empirical formula: $SO_3$**

## Empirical formula to Molecular Formula

The **empirical formula** is the simplest whole number ratio of atoms in a molecule. The **molecular formula** is actual ratio of the atoms in a molecule.

The molecular formula can be calculated from the empirical formula and the relative molecular mass.

**STEPS TO DETERMINE MOLECULAR FORMULA:**

**1.** Determine the empirical formula (if not given).
**2.** Determine the molar mass of the empirical formula.
**3.** Determine the ratio between molecular formula and empirical formula.
**4.** Multiply the ratio into the empirical formula

**EXAMPLE:**

An unknown organic compound has the empirical formula $CH_2$. The molar mass of the compound is $56 g \cdot mol^{-1}$. Determine the molecular formula of the compound.

**1. Empirical formula given:** $CH_2$

**2. Determine the molar mass of the empirical formula.**

$$\begin{aligned} M(CH_2) &= 12 + 1 + 1 \\ &= 14 g \cdot mol^{-1} \end{aligned}$$

**3. Determine the ratio between molecular and empirical.**

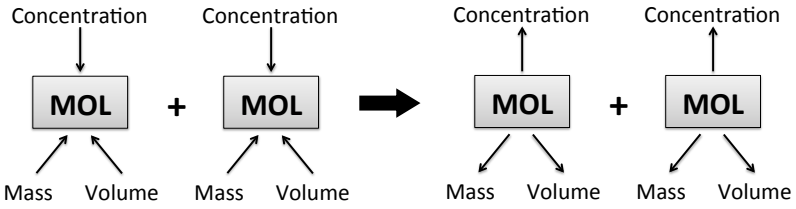
$$\begin{aligned} \text{ratio number} &= \frac{\text{molecular formula mass}}{\text{empirical formula mass}} \\ &= \frac{56}{14} \\ &= 4 \end{aligned}$$

**4. Multiply the ratio into the empirical formula**

$$CH_2 \times 4 = C_4H_8$$

## Approach to reaction stoichiometry

**1.** Write a balanced chemical equation.
**2.** Convert the 'given' amount into mole (use limiting reactant if applicable).
**3.** Determine the number of mole of the 'asked' substance using the mole ratio.
**4.** Determine the 'asked' amount from the number of mole.




## Limiting Reactants

In a reaction between two substances, one reactant is likely to be used up completely before the other. This limits the amount of product formed.

Consider the reaction between magnesium and dilute sulphuric acid. The balanced chemical equation is

$$Mg(s) + H_2SO_4(aq) \rightarrow MgSO_4(aq) + H_2(g)$$

This means that 1 mole of magnesium reacts with 1 mole of sulphuric acid. Both reactants will be completely used up by the time the reaction stops.

What happens if 1 mole of magnesium and 2 mole of sulphuric acid are available to react? There is now insufficient magnesium to react with all of the sulphuric acid. 1 mole of sulphuric acid is left after the reaction.

All of the magnesium is used up, We say the magnesium is the **limiting reactant**. Some sulphuric acid is left after the reaction. We say the sulphuric acid is in **excess**.

**The amount of limiting reactant will determine:**

- The amount of product formed.
- The amount of other (excess) reactants used.

## Determining limiting reactants

**1.** Calculate the number of moles of each reactant.
**2.** Determine the ratio between reactants.
**3.** Determine limiting reactant using the ratios.

**NOTE:**

If one reactant is in **excess, it means that there is more than enough of it.** If there are only 2 reactants and one is in excess, it means that the other is the limiting reactant.

# QUANTITATIVE ASPECTS OF CHEMICAL CHANGE



**EXAMPLE:**

A 8,4 g sample of nitrogen reacts with 1,5 g hydrogen. The balanced equation is:

$$N_2(g) + 3H_2(g) \rightarrow 2NH_3(g)$$

Determine (a) which reactant is the limiting reactant, and (b) the mass of ammonia that can be produced.

**(a)**

**1.**

$$n(N_2) = \frac{m}{M} = \frac{8,4}{28} = 0,3 \text{ mol}$$

$$n(H_2) = \frac{m}{M} = \frac{1,5}{2} = 0,75 \text{ mol}$$

**2.**

| $N_2$ | : | $H_2$ |
|---|---|---|
| 1 | : | 3 |
| 0,3 mol | : | 0,9 mol |
| 0,25 mol | : | 0,75 mol |

**3 .**

If all nitrogen is used, 0,9 mol hydrogen is needed, However, only 0,75 mol hydrogen is available. The hydrogen will run out first, therefore hydrogen is the limiting reactant.

**(b)**

Because the hydrogen is the limiting reactant, it will determine the mass of ammonia produced:

| $H_2$ | : | $NH_3$ |
|---|---|---|
| 3 | : | 2 |
| 0,75mol | : | 0,5mol |

$$m(NH_3) = nM = (0,5)(17) = 8,5g$$

## Percentage Purity

Sometimes chemicals are not pure and one needs to calculate the percentage purity. **Only the pure component of the substance will react**. For an impure sample of a substance:

$$\text{Percentage purity} = \frac{\text{Mass of pure substance}}{\text{Mass of impure substance}} \times 100$$

**STEPS TO DETERMINE THE PERCENTAGE PURITY**

**1.** Determine moles of products.
**2.** From the balanced formula, determine the ratio between reactants and products.
**3.** Using the ratio, determine the number of moles of reactants.
**4.** Determine the mass of pure reactant.
**5.** Calculate the percentage purity of the sample.

**EXAMPLE:**

An impure sample of calcium carbonate, $CaCO_3$, contains calcium sulphate, $CaSO_4$, as an impurity. When excess hydrochloric acid was added to 6g of the sample, 1200 $cm^3$ of gas was produced (measured at STP). Calculate the percentage purity of the calcium carbonate sample. The equation for the reaction is:

$$CaCO_3(s) + 2HCl(aq) \rightarrow CaCl_2(aq) + H_2O(l) + CO_2(g)$$

**1.** $n(CO_2) = \frac{V}{V_M} = \frac{1,2}{22,4} = 0,054\text{mol}$

**2.**

| $CaCO_3$ | : | $CO_2$ |
|---|---|---|
| 1 | : | 1 |

**3.**

| $CaCO_3$ | : | $CO_2$ |
|---|---|---|
| 1 | : | 1 |
| 0,054 | : | 0,054 |

$\therefore$ 0,054mol $CaCO_3$ reacted

**4.**

$$m(CaCO_3) = nM = (0,054)(40 + 12 + 16 + 16 + 16) = 5,4g$$

**5.**

$$\text{Percentage purity} = \frac{\text{Mass of pure substance}}{\text{Mass of impure substance}} \times 100$$

$$\text{Percentage purity} = \frac{5,4}{6,0} \times 100$$

$$\text{Percentage purity} = 90\,\%$$

## Percentage Yield

Yield is the measure of the extent of a reaction, generally measured by comparing the amount of product against the amount of product that is possible.

Some of the product may be lost due to evaporation into the surrounding air, or due to a little being left in solution. Some of the reactants may not react. We say that the reaction has not run to completion.

This results in the amount of the product produced being less than the maximum theoretical amount you would expect. We can express this by the percentage yield:

$$\text{Percentage yield} = \frac{\text{Actual yield}}{\text{Theoretical yield}} \times 100$$

Percentage yield is usually determined using mass, but can also be determined with mol and volume.

**STEPS TO DETERMINE THE PERCENTAGE YIELD**

**1.** Determine moles of reactants.
**2.** From the **balanced** formula, determine the ratio between reactants and products.
**3.** Using the ratio, determine the number of moles of products and convert to mass.
**4.** Determine the theoretical mass of product.
**5.** Calculate the percentage yield.

**EXAMPLE:**

128g of sulphur dioxide, $SO_2$, was reacted with oxygen to produce sulphur trioxide, $SO_3$. The equation for the reaction is:

$$2SO_2(g) + O_2(g) \rightarrow 2SO_3(g)$$

140g of $SO_3$ was produced in the reaction. Calculate the percentage yield of the reaction.

**1.** $n(SO_2) = \frac{m}{M} = \frac{128}{64} = 2\text{mol}$

**2.**

| $SO_2$ | : | $SO_3$ |
|---|---|---|
| 2 | : | 2 |
| 1 | : | 1 |

**3.**

| $SO_2$ | : | $SO_3$ |
|---|---|---|
| 1 | : | 1 |
| 2 | : | 2 |

$\therefore$ 2mol $SO_3$

**4.** $m(SO_3) = nM = (2)(32 + 16 + 16 + 16) = 160g$

**5.**

$$\text{Percentage yield} = \frac{\text{Mass of product produced}}{\text{Maximum theoretical mass of product}} \times 100$$

$$\text{Percentage yield} = \frac{140}{160} \times 100$$

$$\text{Percentage yield} = 87.5\,\%$$

# MOLECULAR STRUCTURE



## A) Covalent Bonding
### (Between non-metals)

**Covalent bonding is the sharing of at least one pair of electrons by two atoms.**

**Non-polar (pure) covalent**
**An equal sharing of electrons**
Eg. H – P bond: ΔEN = EN(P) – EN(H) = 0

**Weak polar covalent**
Eg. H – Br bond: ΔEN = EN(Br) – EN(H) = 0,7

**Polar covalent**
**An unequal sharing of electrons leading to a dipole forming**
Eg. H – O bond: ΔEN = EN(O) – EN(H) = 1,4

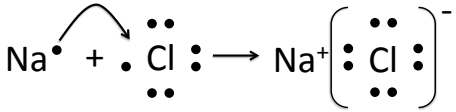
## B) Ionic Bonding
### (between metals and non-metals)

**Ionic bonding is a transfer of electrons and subsequent electrostatic attraction.**

1. Involves a complete transfer of electron(s).
2. Metal atom gives $e^-$ to non-metal.
3. Metal forms a positive cation.
4. Non-metal forms a negative anion.
5. Electrostatic attraction of ions leads to formation of giant crystal lattice.

Ionic Bonding takes place in two steps.
1. Transfer of $e^-$(s) to form ions
2. Electrostatic attraction

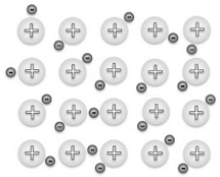
Electron transfer from sodium to chlorine




## C) Metallic Bonding
### (between metals)

**Metallic bonding is the bond between the positive metal kernels and the sea of delocalized electrons.**

The metal atoms release their valence electrons to surround them. There is a strong but flexible bond between the positive metal kernels and a sea of delocalised electrons.



## INTERMOLECULAR FORCES (IMF)

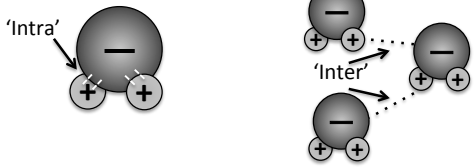
**Intermolecular forces are weak forces of attraction between molecules, ions, or between atoms of noble gases.**

### IMF vs Intramolecular bonds

Intermolecular forces are not the same as intramolecular bonds.

**Intramolecular bonds** occur between atoms within a molecule. These can be broken during chemical reactions.

**Intermolecular forces** exist between molecules or between atoms of noble gases. These can be overcome during physical processes (eg. phase changes)




## STRENGTH OF IMF

Hydrogen bonding > dipole-dipole > London dispersion forces

## TYPES OF INTERMOLECULAR FORCES

| **Hydrogen bonding** | **Van der Waals Forces** | |
|---|---|---|
| **Hydrogen bonding** | **Dipole-dipole** | **London dispersion forces** |
| A type of dipole-dipole attraction, but much STRONGER. Between small, highly electronegative atoms. **Elements N,O,F bonded to H.**<br><br>Eg. $H_2O$ | IMF that occur between **polar molecules** (same or not the same molecules).<br><br>Eg. $H_2S$; $CH_3Cl$. | IMF between **non-polar** molecules that form temporary dipoles.<br><br>Eg. $CO_2$ |

## IMF AND PHYSICAL PROPERTIES

| PHYSICAL PROPERTY | RELATIONSHIP TO IMF |
|---|---|
| * **Melting Point:** The temperature at which the solid and liquid phases of a substance are at equilibrium. It is the temperature where solid particles will undergo a phase change (melt) and become a liquid. | Directly proportional |
| * **Boiling Point:** The temperature at which vapour pressure of the substance equals atmospheric pressure. It is the temperature where liquid boils and turns into a vapour (gas). | Directly proportional |
| **Vapour Pressure:** This is the pressure that an enclosed vapour at equilibrium exerts on the surface of its liquid. | Inversely proportional |
| **Viscosity: this is the measure of a liquid's resistance to flow.** A liquid with high viscosity resists motion e.g. syrup and a liquid with low viscosity are runny e.g water. | Directly proportional |
| **Solubility:** Substances will only dissolve in substances that are like bonded. A non-polar substance will dissolve in a non-polar substance. A polar substance will dissolve only in polar substances. | Inversely proportional |
| **Density: Density is a measure of the mass per unit volume**. The solid phase of the substance is generally more dense than the gaseous and liquid phase. | Directly proportional |
| **Flammability: The ability to burn in air or ignite causing combustion**. Most organic compounds are flammable and burn in oxygen to form carbon dioxide and water. | Inversely proportional |
| **Odour:** Different functional groups attach differently to different receptors in our nose. Different organic substances give off odour quicker based on their intermolecular forces and distinct odours. | Inversely proportional |

* are examinable

# ENERGY AND CHEMICAL CHANGE



## ENERGY CHANGE

The energy change that takes place occurs because of bonds being broken and new bonds being formed.

**When bonds are broken, energy is absorbed** from the environment. (endothermic)

**When bonds are formed, energy is released** into the environment. (exothermic)

The net energy change will determine if the reaction is endothermic or exothermic.

### ACTIVATION ENERGY

In order to start a reaction, energy first needs to be absorbed to break the bonds. This energy is known as the **activation energy – the minimum energy required to start a chemical reaction OR the energy required to form the activated complex.**

Once the bonds have been broken, the atoms in the chemical system form an **activated complex – a high energy, unstable temporary transition state between the reactants and the products**.

## ENTHALPY AND ENTHALPY CHANGE

Enthalpy (H) is the total amount of stored chemical energy (potential energy) of the reactants and the products. During chemical reactions, energy can be exchanged between the chemical system and the environment, resulting in a change in enthalpy. This change in enthalpy, $\Delta H$, represents the heat of the reaction measured in $kJ \cdot mol^{-1}$.

**The heat of reaction ($\Delta H$) is the net change of chemical potential energy of the system.**

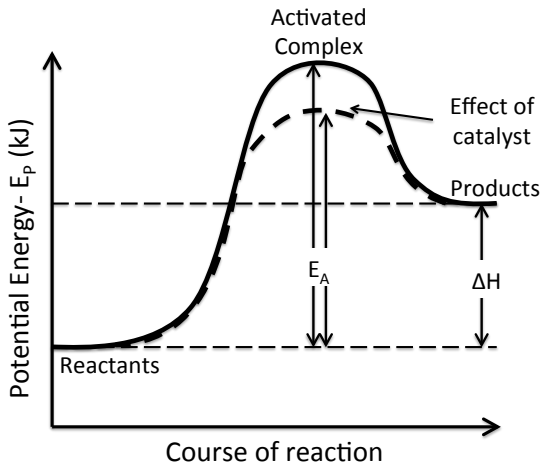
## CHEMICAL SYSTEM AND THE ENVIRONMENT

The chemical system is the reactant and product molecules.

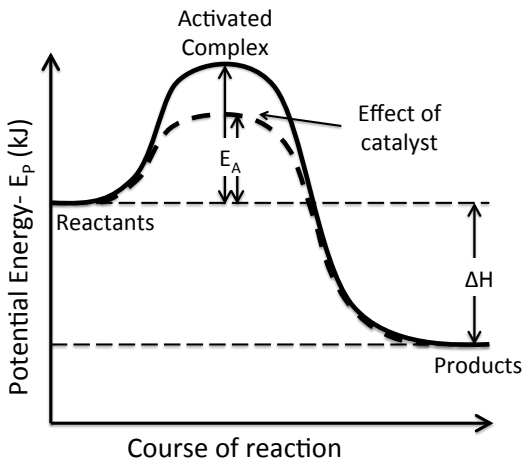
The environment is the surroundings of the chemical system, including the container in which the reaction takes place, or the water in which the molecules are dissolved.

| ENDOTHERMIC | EXOTHERMIC |
|---|---|
| **A reaction which transforms thermal energy into chemical potential energy** | **A reaction which transforms chemical potential energy into thermal energy** |
| More energy absorbed than released | More energy released than absorbed |
| Net energy change is energy absorbed from the environment | Net energy change is energy released into the environment |
| The chemical system's energy increases ($\Delta H>0$) | The chemical system's energy decreases ($\Delta H<0$) |
| The environment's energy decreases | The environment's energy increases |
| Temperature of the environment decreases (test tube gets colder) | Temperature of the environment increases (test tube gets hotter) |

**POTENTIAL ENERGY PROFILE GRAPH OF AN ENDOTHERMIC REACTION**




**POTENTIAL ENERGY PROFILE GRAPH OF AN EXOTHERMIC REACTION**




## CATALYST

In order for a reaction to occur, enough energy has to be provided (activation energy) for particles to collide effectively.

The amount of required energy can be decreased by using a catalyst. A catalyst is a chemical substances that lowers the activation energy required without undergoing chemical change. By lowering the activation energy, the rate of the reaction can also be increased.

**A catalyst is a chemical substance that increases the rate of the reaction but remains unchanged at the end of the reaction**

## IMPORTANT REACTIONS

### ENDOTHERMIC

Photosynthesis

$6CO_2 + 6H_2O \xrightarrow{light} C_6H_{12}O_6 + 6O_2$ ; $\Delta H>0$

### EXOTHERMIC

Cellular respiration

$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$ ; $\Delta H<0$

Combustion

$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$ ; $\Delta H<0$

$C_2H_5OH + 3O_2 \rightarrow 2CO_2 + 3H_2O$ ; $\Delta H<0$

# RATES OF REACTIONS



## RATES OF REACTIONS

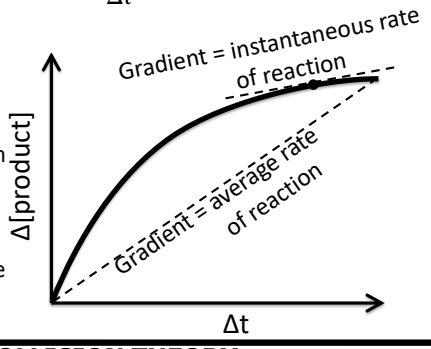
**The change in concentration per unit time of either a reactant or product.**

$$\text{Rate} = \frac{\Delta \text{ amount of product}}{\Delta t}$$

$$\text{Rate} = \frac{\Delta \text{ amount of reactant}}{\Delta t}$$

Rate may be given in terms of change in mass per unit time ($g \cdot s^{-1}$) **OR** change in volume per unit time ($dm^3 \cdot s^{-1}$) **OR** change in number of moles per unit time ($mol \cdot s^{-1}$).

The gradient of a rate graph indicates the rate of the reaction at that point in time.



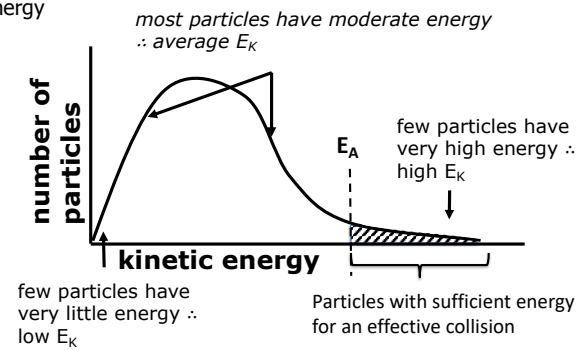

## COLLISION THEORY

The conditions for successful collisions are:

1. **Particles must collide with correct orientation**
   The structure of the molecules and their relative orientations to each other is important for effective collisions. Some catalysts function by improving molecular orientation.
2. **Particles must collide with sufficient energy (kinetic energy ≥ activation energy)**
   The molecules have to collide with sufficient amount of energy for bonds to break and the reaction to occur (activation energy).

### MAXWELL-BOLTZMAN DISTRIBUTION CURVE

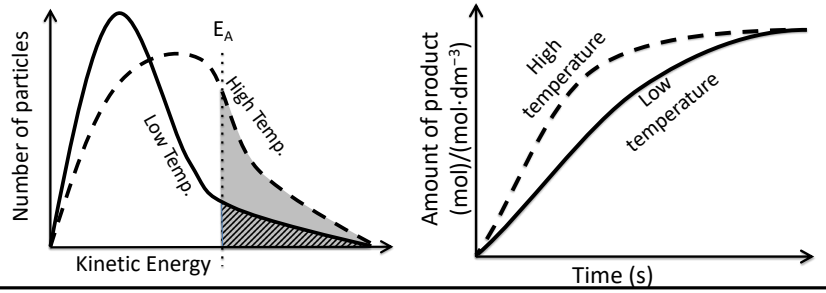
The Maxwell-Boltzman distribution curve shows the distribution of the kinetic energy of molecules. The area under the graph to the right of the $E_A$ line represents the particles with sufficient kinetic energy




## FACTORS INFLUENCING REACTION RATE

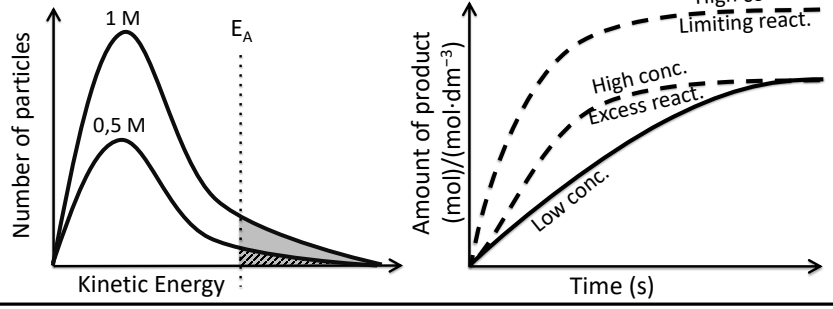
### Temperature

Increasing temperature increases rate of reaction. When the temperature is increased, the kinetic energy of the particles are increased. More particles have sufficient energy to overcome the activation energy, and **more effective collisions** can take place per unit time.



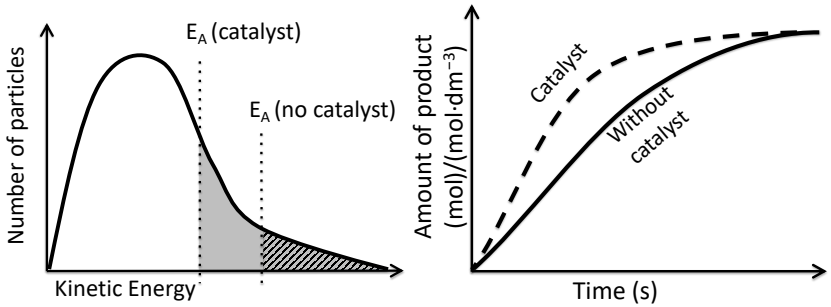

### Concentration (gases and solutions only)

Increasing concentration increases rate of reaction. The greater the concentration, the more particles occur per unit volume. More particles have sufficient energy to overcome the activation energy, and **more effective collisions** can take place per unit time. If the concentration of a limiting reactant is increased, more product can be formed.




### Catalyst

The presence of a catalyst decreases the activation energy ($E_A$). More particles have sufficient kinetic energy to overcome the lowered activation energy, and **more effective collisions** can take place per unit time.




### Nature of reactants

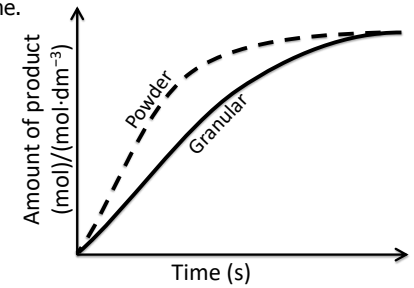
The physical and chemical properties of certain molecules make them more likely to react.

For example:

- $O_2$ has many effective orientations
- F's electronegativity makes it more reactive
- Tertiary alcohols have limited effective collision orientations due to molecule structure
- Simple ($Ca^{2+}$) and complex ($C_2O_4^-$) ions.

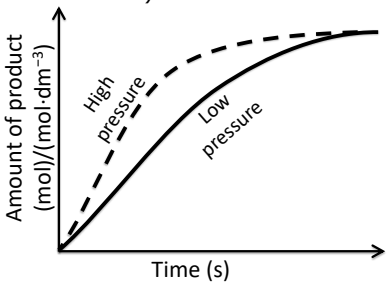
### State of division / surface area (solids only)

Increased state of division (powder instead of chunks) increases rate of reaction. Increasing the surface area exposed to collisions increases that number of particles that will undergo collisions, and **more effective collisions** can take place per unit time.




### Pressure (gases only)

Increased pressure (by decreasing volume) increases the concentration of the gas thus increasing the rate of reaction.
(See 'Concentration')




## WAYS TO MEASURE RATE

1. Change in mass
2. Volume of gas produced
3. Change in colour
4. Turbidity (precipitation)
5. Change in pH

All calculated per unit time

# CHEMICAL EQUILIBRIUM



An **open system** is one in which both energy and matter can be exchanged between the system and its surroundings - it interacts continuously with its environment.
A **closed system** is one in which energy can enter or leave the system freely, but no reactant or products can leave or enter the system.

A reaction is a **reversible reaction** when products can be converted back to reactants. Reversible reactions are represented with double arrows.

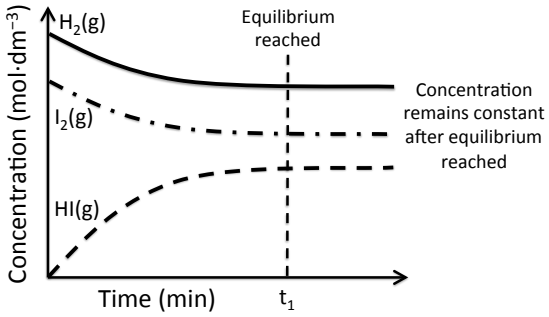
**For example:**
Hydrogen reacts with iodine to form hydrogen iodide:
$H_2(g) + I_2(g) \rightarrow 2HI(g)$

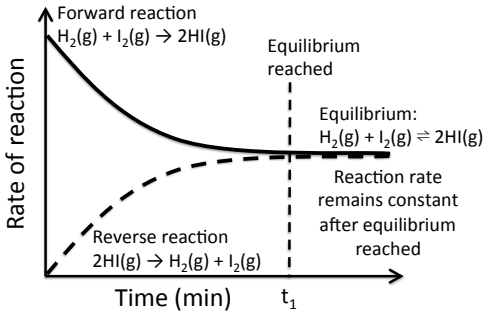
Hydrogen iodide can decompose to form hydrogen and iodine:
$2HI(g) \rightarrow H_2(g) + I_2(g)$

Therefore the reversible reaction can be written as:

Forward reaction →
$H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$
← Reverse reaction

**Dynamic chemical equilibrium** refers to a reversible reaction in which the forward reaction and the reverse reaction are taking place at the same rate. The concentrations of the reactants and products are constant. Chemical equilibrium can only be achieved in a closed system.




## LE CHATELIER'S PRINCIPLE

**When an external stress (change in pressure, temperature or concentration) is applied to a system in dynamic chemical equilibrium, the equilibrium point will change in such a way as to counteract the stress.**

### Factors which affect equilibrium position

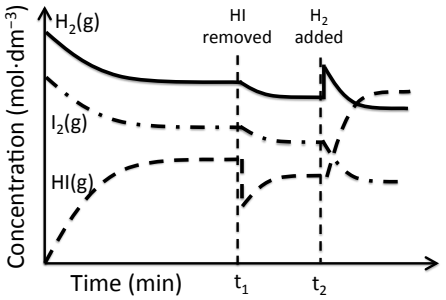
1. Concentration

Equilibrium will shift to decrease any increase in concentration of either reactants or products.
- Adding reactant: forward reaction favoured
- Adding product: reverse reaction favoured

Equilibrium will shift to increase any decrease in concentration of either reactants or products.
- Removing reactant: reverse reaction favoured
- Removing product: forward reaction favoured

The concentration can be changed by adding/ removing reactants/products that are in solution (aq) or a gas (g). Changing the mass of pure solids (s) or volume of liquids (l) will not disrupt the equilibrium or change the rate of the reactions.

$H_2(g) + I_2(g) \rightleftharpoons 2HI(g)$




**Removing HI ($t_1$):**

When HI is removed, the system re-establishes equilibrium by favouring the reaction that will produce more HI. Because the forward reaction is favoured, some of the reactants are used.

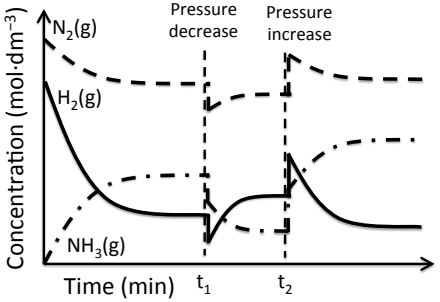
**Adding $H_2$ ($t_2$):**

When adding $H_2$, the system re-establishes equilibrium by favouring the reaction that uses $H_2$. Because the forward reaction is favoured, the reactants are used and more products form.

2. Pressure (gases only)

A change in pressure can be identified on a graph by an instantaneous change in concentration of all gasses due to a change in volume.)
Equilibrium will shift to decrease any increase in pressure by favouring the reaction direction that produces less molecules.
Equilibrium will shift to increase any decrease in pressure by favouring the reaction that produces more molecules.
To determine which reaction is favoured, compare the total number of mol of gaseous reactants to the total number of mol of gaseous products.

$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$




**Pressure decrease ($t_1$):**
When the pressure is decreased, the system re-establishes equilibrium by favouring the reaction that will produce more moles of gas. The reverse reaction is favoured, reacting 2 mol gas and forming 4 mol gas.

**Pressure increase ($t_2$):**
When the pressure is increased, the system re-establishes equilibrium by favouring the reaction that will produce less moles of gas. The forward reaction of favoured, reacting 4 mol of gas and forming 2 moles of gas.

3. Temperature

If the temperature is increased, the endothermic reaction will be favoured.

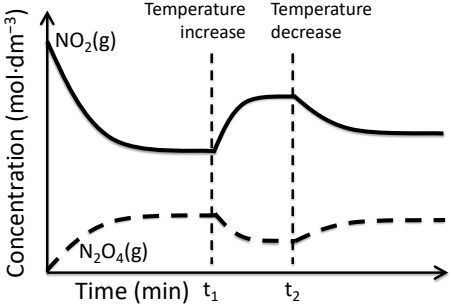
If the temperature decreases, the exothermic reaction is favoured.

The heat of the reaction, ΔH, is always used to indicate the forward reaction.

**NOTE: An increase in temperature increases the rate of both the forward and the reverse reaction, but shifts the equilibrium position.**

**NOTE: Temperature change is the only change that affects $K_c$.**

$2NO_2(g) \rightleftharpoons N_2O_4(g)$; $\Delta H = -57$ kJ
brown colourless




**Temperature increase ($t_1$):**

When the temperature is increased, the system re-establishes equilibrium by favouring the reaction that will decrease the temperature (i.e. the endothermic reaction). The reverse reaction will be favoured because the forward reaction is exothermic. The gas mixture becomes darker brown.

**Temperature decrease ($t_2$):**

When the temperature is decreased, the system re-establishes equilibrium by favouring the reaction that will increase the temperature (i.e. the exothermic reaction). The forward reaction will be favoured. The gas mixture becomes lighter brown.

# CHEMICAL EQUILIBRIUM



## COMMON ION EFFECT

When ionic substances are in solution, they form ions:

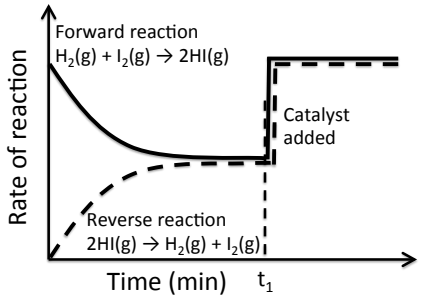
$$NaCl(s) \rightleftharpoons Na^+(aq) + Cl^-(aq)$$
*white* *colourless*

If HCl is added to this solution, the concentration of $Cl^-$ ions will increase because $Cl^-$ is a **common ion.** The system will attempt to re-establish equilibrium by favouring the reverse reaction, forming a white sodium chloride precipitate.

The disturbance of a system at equilibrium that occurs when the concentration of a common ion is increased, is known as the **common ion effect**.

## CATALYST AND EQUILIBRIUM

When a catalyst is added, the rate of the forward, as well as the reverse reaction, is increased. The use of a catalyst does not affect the equilibrium position or the $K_c$ value at all.




## DESCRIBING EQUILIBRIUM SHIFT ACCORDING TO LE CHATELIER

1. Identify the **disturbance**
   Adding/removing reactants or products, pressure change, temperature change.
2. State **Le Chatelier**'s principle
3. System **response**
   Use up/create more products or reactants, make more/less gas molecules, increase/decrease temperature.
4. State **favoured reaction**
5. Discuss **results**
   Equilibrium shift, change in colour/concentration/ pressure/temperature.

## EQUILIBRIUM CONSTANT ($K_C$)

General equation: $aA + bB \rightleftharpoons cC$

Where A,B,C are chemical substances (**ONLY aq and g, NOT s or l !**) and a,b,c are molar ratio numbers

$$K_c = \frac{[C]^c}{[A]^a[B]^b}$$

**Note:** The factors of the numerator and denominator must be MULTIPLIED respectively (NOT added)

$K_c$ value is a ratio and therefore has no units.

If $K_c > 1$ then equilibrium lies to the right – there are more products than reactants.
If $K_c < 1$ then equilibrium lies to the left – there are more reactants than products.

$K_c$ values are constant at specific temperatures. If the temperature of the system changes then the $K_c$ value will change.

| Temperature | $K_c$ of Exothermic | $K_c$ of Endothermic |
|---|---|---|
| Increase | Decrease | Increase |
| Decrease | Increase | Decrease |

**EXAMPLE:**

Consider the following equilibrium system:

$$CoCl_4^{2-}(aq) + H_2O(l) \rightleftharpoons Co(H_2O)_6^{2+}(aq) + 4Cl^-(aq) \qquad \Delta H < 0$$
*blue* *pink*

For each change made to the system state and explain the colour change seen.

**a) Water added**
Adding water decreases the concentration of all the ions. According to Le Chatelier's principle, the equilibrium will shift in such as way so as to produce more ions. Thus the forward reaction will be favoured, forming more product and the solution turns pink.

**b) $AgNO_3$ added**
Adding $AgNO_3$ creates an insoluble precipitate of AgCl. This decreases the $Cl^-$ ion concentration. According to Le Chatelier's principle the equilibrium will shift in such a way so as to produce more $Cl^-$ ions. The forward reaction will be favoured, more product is made and the solution turns pink.

**c) Temperature is increased**
The temperature of the system is increased. According to Le Chatelier's principle, the equilibrium will shift in such a way to reduce the temperature. The reverse endothermic reaction is favoured. This decreases the temperature and produces more reactant and the solution turns blue.

## EQUILIBRIUM CONSTANT TABLE

The equilibrium constant table assists in calculating the concentration of reactants and products when the reaction has reached equilibrium.

**EXAMPLE:**

3 moles of $NO_2$ are placed in a 1,5 $dm^3$ container and the following equilibrium is established:

$2NO_2(g) \rightleftharpoons N_2O_4(g)$

If no volume is given, assume volume = 1 $dm^3$

At equilibrium it was found that 0,3 mol of $NO_2$ was present in the container. Calculate the value of the equilibrium constant for this reaction.

| | $NO_2$ | $N_2O_4$ |
|---|---|---|
| **R**atio | 2 | 1 |
| **I**nitial (mol) | 3 | 0 |
| **C**hange (mol) | -2,7 | +1,35 |
| **E**quilibrium (mol) | 0,3 | 1,35 |
| **E**q. concentration in ($mol \cdot dm^{-3}$) | 0,3/1,5 = 0,2 | 1,35/1,5 =0,9 |

$$K_c = \frac{[N_2O_4]}{[NO_2]^2} = \frac{(0,9)}{(0,2)^2} = 22,5$$

## EXAMPLES OF APPLICATIONS OF CHEMICAL EQUILIBRIUM

**(The Haber Process): $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$ $\Delta H<0$**

**Temperature:** The forward reaction is exothermic, thus a decrease in temperature will favour the forward exothermic reaction. However, a decrease in temperature will also decrease the rate of the reaction. Therefore, a compromise between rate and yield is found at a temperature of around 450 °C to 550 °C.

**Pressure:** As there are fewer reactant gas particles than product gas particles, an increase in pressure will therefore favour the production of products. Thus this reaction is done under a high pressure of 200 atm.

**Catalyst:** Iron or Iron Oxide

**(The Contact Process): $2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$ $\Delta H < 0$**

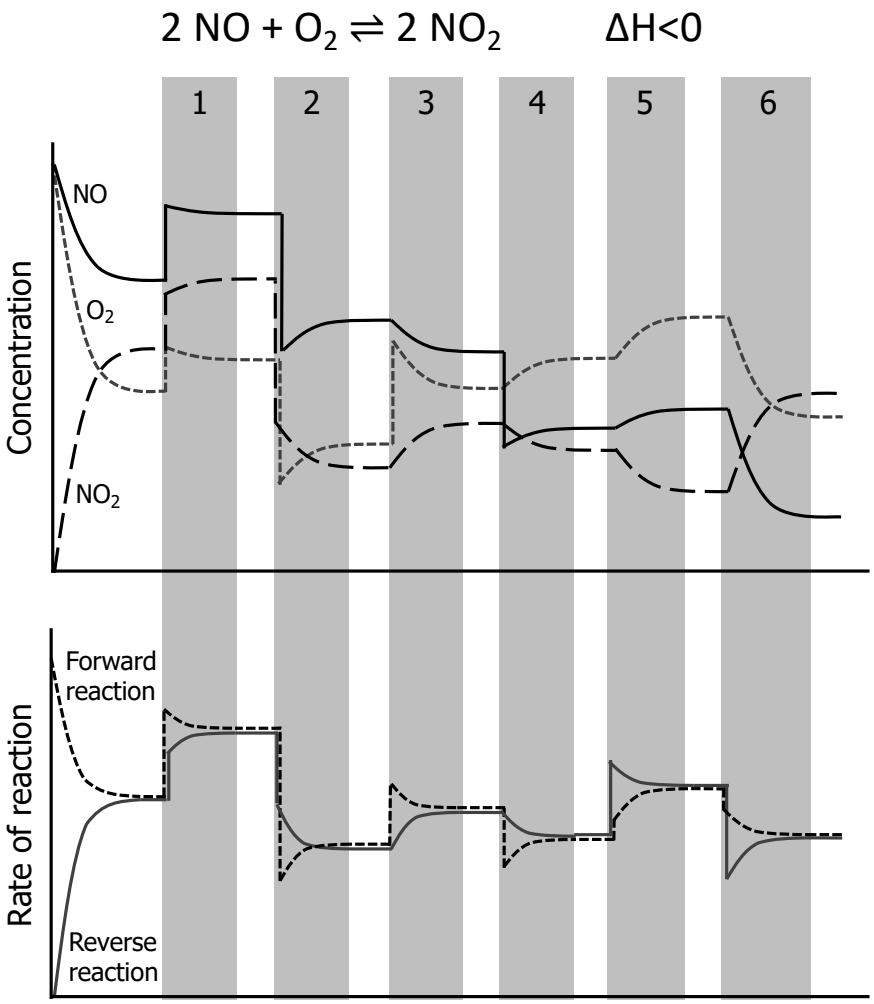
**Temperature:** The forward reaction is exothermic, thus a decrease in temperature will favour the forward exothermic reaction. However, a decrease in temperature will also decrease the rate of the reaction. Therefore, a compromise between rate and yield is found at a temperature of around 450 °C

**Pressure:** There are more reactant gas particles than product gas particles, therefore an increase in pressure will favour the production of product. However, in practice a very high yield is obtained at atmospheric pressure.

**Catalyst:** Vanadium pentoxide ($V_2O_5$)

# Chemical Equilibrium – Rate and Concentration






**1: Increase in pressure**

**Le Chatelier:** The forward reaction is favoured, less gas particles are formed and the pressure decreases.

**Concentration:**
①Concentration of all gasses increases sharply.
②The forward reaction is favoured.
③[$NO_2$] gradually increases, [NO], [$O_2$] gradually decreases.

**Rate:** Concentration of all gasses increases, therefore the rate of both the forward and the reverse reaction increases.
According to Le Chatelier the forward reaction will be favoured, therefore the forward reaction experiences a greater increase in rate.

**2: Decrease in pressure**

**Le Chatelier:** The reverse reaction is favoured, more gas particles are formed and the pressure increases.

**Concentration:**
①Concentration of all gasses decreases sharply.
②The reverse reaction is favoured.
③[$NO_2$] gradually decreases, [NO], [$O_2$] gradually increases.

**Rate:** Concentration of all gasses decreases, therefore the rate of both the forward and the reverse reaction decreases.
According to Le Chatelier the reverse reaction is favoured, therefore the reverse reaction experiences a smaller decrease in rate.

**3: $O_2$ is added**

**Le Chatelier:** The forward reaction is favoured to decrease the [$O_2$].

**Concentration:**
①Concentration of $O_2$ decreases sharply.
②The forward reaction is favoured.
③[$NO_2$] increases gradually, [NO], [$O_2$] decreases gradually.

**Rate:** An increase in concentration of a reactant leads to an increase in the rate of the and forward reaction.

**4: NO is removed**

**Le Chatelier:** The reverse reaction is favoured to increase the [NO].

**Concentration:**
①Concentration of NO decreases sharply.
②The reverse reaction is favoured.
③[$NO_2$] decreases gradually, [NO], [$O_2$] increases gradually.

**Rate:** A decrease in concentration of a reactant leads to an decrease in the rate of the forward and reverse reaction.

**5: Increase in temperature**

**Le Chatelier:** The reverse (endothermic)reaction is favoured to decrease the temperature.

**Concentration:**
①The reverse reaction is favoured.
②[$NO_2$] decreases gradually, [NO], [$O_2$] increases gradually.

**Rate:** An increase in temperature increases the rate of both the forward and the reverse reactions.

**6: Decrease in temperature**

**Le Chatelier:** The forward (exothermic) reaction is favoured to increase the temperature.

**Concentration:**
①The forward reaction is favoured.
②[$NO_2$] increases gradually, [NO], [$O_2$] decreases gradually.

**Rate:** A decrease in temperature decreases the rate of both the forward and the reverse reactions.

# ACIDS AND BASES



## ACID/BASE DEFINITIONS

**Lowry-Brønsted**
An acid is a proton ($H^+$) donor.
A base is a proton ($H^+$) acceptor.

## ACID PROTICITY

Some acids are able to donate more than one proton. The number of protons that an acid can donate is referred to as the acid proticity.

| 1 proton- monoprotic | 2 protons- diprotic | 3 protons- triprotic |
|---|---|---|
| $HCl \rightarrow Cl^- + H^+$ | $H_2SO_4 \rightarrow HSO_4^- + H^+$ | $H_3PO_4 \rightleftharpoons H_2PO_4^- + H^+$ |
| | $HSO_4^- \rightarrow SO_4^{2-} + H^+$ | $H_2PO_4^- \rightleftharpoons HPO_4^{2-} + H^+$ |
| | | $HPO_4^{2-} \rightleftharpoons PO_4^{3-} + H^+$ |

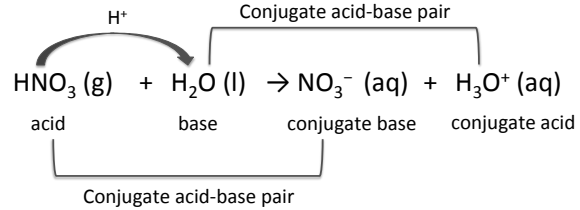
## CONJUGATE ACID-BASE PAIRS

An acid forms a conjugate base when it donates a proton.
**acid ⇌ conjugate base + $H^+$**

A base forms a conjugate acid when it accepts a proton.
**base + $H^+$ ⇌ conjugate acid**

Conjugate acid-base pairs are compounds that differ by the presence of one proton, or $H^+$.

**EXAMPLE:**
Identify the conjugate acid-base pair in the following example:




## AMPHOLYTE/ AMPHOTERIC SUBSTANCES

**Ampholyte- A substance that can act as either an acid or a base.**

Amphoteric/amphiprotic substances can therefore either donate or accept protons. Common ampholytes include $H_2O$, $HCO_3^-$ and $HSO_4^-$.

$HSO_4^-$ as an ampholyte:

Acid: $HSO_4^- + H_2O \rightarrow SO_4^{2-} + H_3O^+$

Base: $HSO_4^- + H_2O \rightleftharpoons H_2SO_4 + OH^-$

## CONCENTRATED VS DILUTE ACIDS AND BASES

Concentration is the number of moles of solute per unit volume of solution. ( $c = \frac{n}{V}$ of $c = \frac{m}{MV}$)

A concentrated acid/base is an acid with a large amount of solute (the acid) dissolved in a small volume of solvent (water).

A dilute acid is an acid with a small amount of solute (the acid) dissolved in a large volume of solvent (water).

Concentrated strong acid - 1mol.dm$^{-3}$ of HCl

Concentrated weak acid - 1mol.dm$^{-3}$ of $CH_3COOH$

Dilute strong acid - 0,01mol.dm$^{-3}$ of HCl

Dilute weak acid - 0,01mol.dm$^{-3}$ of $CH_3COOH$

**(Similar for bases)**

## STRONG VS WEAK ACIDS AND BASES

The strength of an acid/base refers to the ability of the substance to ionise or dissociate.

### ACIDS

A strong acid ionises completely in water to form a high concentration $H_3O^+$ ions
$HCl\ (g) + H_2O\ (\ell) \rightarrow H_3O^+\ (aq) + Cl^-\ (aq)$

(strong acid → weak conjugate base)

A weak acid ionises partially in water to form a high concentration $H_3O^+$ ions
$2H_2CO_3\ (\ell) + 2H_2O\ (\ell) \rightleftharpoons 2H_3O^+\ (aq) + CO_3^{2-}\ (aq)$

(weak acid → strong conjugate base)

### BASES

A strong base will **dissociate** completely in water.
$NaOH\ (s) \xrightarrow{H_2O} Na^+\ (aq) + OH^-\ (aq)$
(strong base → weak conjugate acid)

A weak base will **dissociate** only partially in water.
$CaCO_3\ (s) \xrightarrow{H_2O} Mg^{2+}\ (aq) + 2OH^-\ (aq)$
(weak base → strong conjugate acid)

$NH_3$ is an exception, it ionises.
$NH_3\ (g) + H_2O\ (\ell) \rightleftharpoons OH^-\ (aq) + NH_4^+\ (aq)$

## INFLUENCE OF ACID/BASE STRENGTH

Reaction rate
Reaction rates increase as the strength of the acid/base increases.

Stronger acid = higher concentration of ions = greater rate of reaction.

Conductivity
Conductivity increases as the strength of the acid/base increases.

Stronger acid = higher concentration of $H^+$ = greater conductivity.

| COMMON ACIDS | | COMMON BASES | |
|---|---|---|---|
| Hydrochloric acid (HCℓ) | STRONG | Sodium Hydroxide (NaOH) | STRONG |
| Nitric acid ($HNO_3$) | | Potassium hydroxide (KOH) | |
| Sulfuric acid ($H_2SO_4$) | | Sodium hydrogen carbonate ($NaHCO_3$) | WEAK |
| Oxalic acid ($(COOH)_2$) | WEAK | | |
| Hydrofluoric acid (HF) | | | |
| Sulfurous acid ($H_2SO_3$) | | Calcium carbonate ($CaCO_3$) | |
| Carbonic acid ($H_2CO_3$) | | | |
| Acetic acid / ethanoic acid ($CH_3COOH$) | | Sodium carbonate ($Na_2CO_3$) | |
| Phosphoric acid ($H_3PO_4$) | | Ammonia ($NH_3$) | |

## THE pH SCALE

The pH of a solution is a number that represents the acidity or alkalinity of a solution.

The greater the concentration of $H^+$ ions in solution, the more acidic the solution and the lower the pH. The lower the concentration of $H^+$ in solution, the more alkali the solution and the higher the pH.

The pH scale is a range from 0 to 14, and is a measure of the [H3O+] at 25 °C (in water).



# ACIDS AND BASES



## ACID REACTIONS

**Acid reactions are reactions during which protons ($H^+$) are transferred.**

**1. acid + metal → salt + $H_2$**
$2HNO_3(aq) + 2Na(s) \rightarrow 2NaNO_3(aq) + H_2(g)$
(Note the change in oxidation number)

**2. acid + metal hydroxide (base) → salt + $H_2O$**
$H_2SO_4(aq) + Mg(OH)_2(aq) \rightarrow MgSO_4(aq) + 2H_2O(l)$

**3. acid + metal oxide → salt + $H_2O$**
$2HCl\ (aq) + MgO(s) \rightarrow MgCl_2(aq) + H_2O(l)$

**4. acid + metal carbonate → salt + $H_2O$ + $CO_2$**
$2HCl\ (aq) + CaCO_3(s) \rightarrow CaCl_2(aq) + H_2O(l) + CO_2(g)$

**5. acid +metal hydrogen carbonate→ salt + $CO_2$ + $H_2O$**
$HCl + NaHCO_3 \rightarrow NaCl + CO_2 + H_2O$

**Reaction 1 is a redox reaction**
**Reactions 2–5 are protolytic reactions**

## HYDROLYSIS OF SALTS

Hydrolysis is the reaction of an ion with water. During hydrolysis, the salt will form an acidic, alkali or neutral solution. The pH of the salt solution is determined by the relative strength of the acid and base that is used to form the salt.

| ACID | BASE | SALT |
|---|---|---|
| Strong | Weak | Acidic |
| Strong | Strong | Neutral |
| Weak | Strong | Alkali |

A weak acid and a weak base do not form ions readily.

**How to determine the pH of a salt**

**$NH_4Cl$**

$NH_4Cl \rightarrow NH_4^+ + Cl^-$
$NH_4^+ + H_2O \rightleftarrows$ **$NH_3$** $+ H_3O^+$
$Cl^- + H_2O \rightleftarrows$ **HCl** $+ OH^-$

- **$NH_3$** is a weak base
- Equilibrium lies to the right
- High concentration $H_3O^+$

- **HCl** is a strong acid
- Equilibrium lies to the left
- Low concentration $OH^-$

High $[H_3O^+]$, low $[OH^-]$,
$\therefore NH_4Cl(aq)$ is acidic (pH<7)

**$Na_2CO_3$**

$Na_2CO_3 \rightarrow 2Na^+ + CO_3^{2-}$
$Na^+ + H_2O \leftrightarrows$ **NaOH** $+ H^+$
$CO_3^{2-} + 2H_2O \rightleftarrows$ **$H_2CO_3$** $+ 2OH^-$

- **NaOH** is a strong base
- Equilibrium lies to the left
- Low concentratioin $H^+/H_3O^+$

- **$H_2CO_3$** is a weak acid
- Equilibrium lies to the right
- High concentration $OH^-$

Low $[H_3O^+]$, high $[OH^-]$,
$\therefore Na_2CO_3(aq)$ is alkali (pH>7)

## INDICATORS

An indicator is a compound that changes colour according to the pH of the substance. During titrations, the indicator needs to be selected according to the pH of the salt solution that will be produced (see hydrolysis).

| INDICATOR | COLOUR IN ACID | COLOUR IN BASE | COLOUR AT EQUIVALENCE POINT | PH RANGE OF EQUIVALENCE |
|---|---|---|---|---|
| Litmus | Red | Blue | | 4,5 - 8,3 |
| Methyl orange | Red | Yellow | Orange | 3,1 - 4,4 |
| Bromothymol blue | Yellow | Blue | Green | 6,0 - 7,6 |
| Phenolphthalein | Colourless | Pink | Pale Pink | 8,3 - 10,0 |

Neutral: pH 7

Neutralisation is when the equivalence point is reached. Equivalence point is NOT when the solution is at pH 7, but when the molar amount of acid and base is the same according to the molar ratio. The pH at neutralisation is dependent on the salt that is formed. (see hydrolysis).

## TITRATIONS

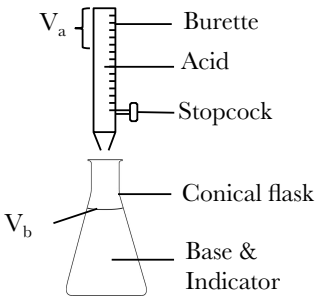
A titration is a practical laboratory method to determine the concentration of an acid or base. The concentration of an acid or base can be determined by accurate neutralisation using a **standard solution- a solution of known concentration**. Neutralisation occurs at the equivalence point, when the molar amount of acid and base is the same according to the molar ratio.

$$\frac{n_a}{n_b} = \frac{c_a V_a}{c_b V_b}$$

n- number of mole of substance (mol) / mol ratio from the balanced equation
c- concentration of acid/base ($mol.dm^{-3}$)
V- volume of solution ($dm^3$)

1 mL = 1 $cm^3$
1 L = 1 $dm^3$
1000 mL = 1 L
1000 $cm^3$ = 1 $dm^3$

**Titration setup**




1. Pipette known solution into conical flask (usually base).
2. Add appropriate indicator to flask.
3. Add unkown concentration solution to the burette (usually acid).
4. Add solution from burette to conical flask at a dropwise rate (remember to swirl).
5. Stop burette when indicator shows neutralisation/equivalence point has been reached.

**EXAMPLE:**

During a titration, 25 $cm^3$ of dilute $H_2SO_4$ neutralises 40 $cm^3$ of NaOH solution. If the concentration of the $H_2SO_4$ solution is 0,25 $mol.dm^{-3}$, calculate the concentration of the NaOH.

$$H_2SO_4 + 2NaOH \rightarrow Na_2SO_4 + 2H_2O$$

$n_a = 1$ $\quad$ $n_b = 2$
$c_a = 0{,}25\ mol \cdot dm^{-3}$ $\quad$ $c_b = ?$
$V_a = 25\ cm^3 = 0{,}025\ dm^3$ $\quad$ $V_b = 40\ cm^3 = 0{,}04\ dm^3$

**By titration equations**

$$\frac{n_a}{n_b} = \frac{c_a V_a}{c_b V_b}$$
$$\frac{1}{2} = \frac{(0{,}25)(0{,}025)}{c_b(0{,}04)}$$
$$c_b = 0{,}31\ mol \cdot dm^{-3}$$

**By first principles:**

Acid:
$n = cV$
$= (0{,}25)(0{,}025)$
$= 6{,}25 \times 10^{-3}\ mol$

Base:
$c = \frac{n}{V}$
$= \frac{6{,}25 \times 10^{-3} \times 2}{0{,}04}$
$= 0{,}31\ mol \cdot dm^{-3}$

# Acids and Bases



## AUTO-IONISATION OF WATER AND $K_W$

Water reacts with water to form hydronium and hydroxide ions in the following reaction:

$H_2O\ (\ell) + H_2O\ (\ell) \rightleftharpoons H_3O^+\ (aq) + OH^-\ (aq)$

The concentration of $H_3O^+$ (aq) and $OH^-$ (aq) are equal, and the equilibrium constant for the ionisation of water ($K_w$) is $1{,}00 \times 10^{-14}$ (at a temperature of 25 °C or 298 K), therefore:

$$[H_3O^+]\,[OH^-] = 1{,}00 \times 10^{-14}$$

$$[H_3O^+] = 1{,}00 \times 10^{-7}\ mol{\cdot}dm^{-3}$$

$$[OH^-] = 1{,}00 \times 10^{-7}\ mol{\cdot}dm^{-3}$$

When the concentration of $H_3O^+$ (aq) and $OH^-$ (aq) are equal, the solution is neutral and has a pH of 7.

**EXAMPLE:**

Calculate the concentration of $H_3O^+$ in a $Ba(OH)_2$ solution with a concentration of 0,35 $mol{\cdot}dm^{-3}$.

**Step 1:**
**Write down the dissociation reaction**

$$Ba(OH)_2\ (s) \xrightarrow{H_2O} Ba^+(aq) + 2OH^-(aq)$$

**Step 2:**
**Determine the mole ratio of base to $OH^-$ ions**

$$1\ mol\ Ba(OH)_2 : 2\ mol\ OH^-$$

**Step 3:**
**Determine the $[OH^-]$**

$$[OH^-] = 2[Ba(OH)_2]$$
$$= 2(0{,}35)$$
$$= 0{,}7\ mol \cdot dm^{-3}$$

**Step 4:**
**Determine the $[H_3O^+]$**

$$[H_3O^+][OH^-] = 1{,}00 \times 10^{-14}$$
$$[H_3O^+](0{,}7) = 1{,}00 \times 10^{-14}$$
$$[H_3O^+] = 1{,}43 \times 10^{-14}\ mol \cdot dm^{-3}$$

## $K_A$ AND $K_B$ VALUES

When weak acids or bases are dissolved in water, only partial ionisation/dissociation occurs. There is a mixture of the original reactant as well as the ionic products that are formed. The extent of ionisation can be treated in the same way as the extent to which an equilibrium reaction takes place. The acid dissociation constant ($K_a$) and base dissociation constant ($K_b$) values are like the equilibrium constant ($K_c$), but specifically describe the extent of ionisation/ dissociation, and therefore the strength of the acid/base.

**Calculating $K_a$**

General equation: $HA + H_2O \rightleftharpoons A^- + H_3O^+$

$$K_a = \frac{[A^-][H_3O^+]}{[HA]}$$

Example: $CH_3COOH + H_2O \rightleftharpoons CH_3COO^- + H_3O^+$

$$K_a = \frac{[CH_3COO^-][H_3O^+]}{[CH_3COOH]}$$

**Calculating $K_b$**

General equation: $B + H_2O \rightleftharpoons BH^+ + OH^-$

$$K_b = \frac{[BH^+][OH^-]}{[B]}$$

Example: $NH_3 + H_2O \rightleftharpoons NH_4^+ + OH^-$

$$K_b = \frac{[NH_4^+][OH^-]}{[NH_3]}$$

**EXAMPLE:**

0,1 mol HF is dissolved in 1 $dm^3$ water. Determine the $K_a$ of HF if the equilibrium concentration of $H^+$ is found to be $7{,}94 \times 10^{-3}$ . HF dissociates according to the following chemical equation:

$HF\ (aq) \rightleftharpoons H^+\ (aq) + F^-\ (aq)$

| | HF | $H^+$ | $F^-$ |
|---|---|---|---|
| **R**atio | 1 | 1 | 1 |
| **I**nitial (mol) | 0,1 | 0 | 0 |
| **C**hange (mol) | $-7{,}94 \times 10^{-3}$ | $+7{,}94 \times 10^{-3}$ | $+7{,}94 \times 10^{-3}$ |
| **E**quilibrium (mol) | 0,09206 | $7{,}94 \times 10^{-3}$ | $7{,}94 \times 10^{-3}$ |
| **E**q. concentration in ($mol{\cdot}dm^{-3}$) | 0,09206 | $7{,}94 \times 10^{-3}$ | $7{,}94 \times 10^{-3}$ |

$$K_a = \frac{[H^+][F^-]}{[HF]}$$
$$= \frac{(7{,}94 \times 10^{-3})(7{,}94 \times 10^{-3})}{0{,}09206}$$
$$= 6{,}85 \times 10^{-4}$$

$K_a/K_b > 1$; Strong acid/base
$K_a/K_b < 1$; Weak acid/base

## STRONG ACIDS

Strong acids ionise completely in water, meaning that all the acid molecules donate their protons ($H^+$). The concentration of the $H^+$ ions can be determined from the initial concentration of the acid, taking the proticity of the acid into account. For example:

| | | | | | |
|---|---|---|---|---|---|
| Monoprotic: | $HCl\ (g)$ | → | $H^+\ (aq)$ | + | $Cl^-\ (aq)$ |
| | 1 mol | : | 1 mol | : | 1 mol |
| | $0{,}3\ mol{\cdot}dm^{-3}$ | : | $0{,}3\ mol{\cdot}dm^{-3}$ | : | $0{,}3\ mol{\cdot}dm^{-3}$ |
| Diprotic: | $H_2SO_4\ (g)$ | → | $2\ H^+\ (aq)$ | + | $SO_4^{2-}\ (aq)$ |
| | 1 mol | : | 2 mol | : | 1 mol |
| | $0{,}3\ mol{\cdot}dm^{-3}$ | : | $0{,}6\ mol{\cdot}dm^{-3}$ | : | $0{,}3\ mol{\cdot}dm^{-3}$ |

Because all of he reactants are ionised, the $K_a$ value for strong acids is greater than 1. The greater the $K_a$, the stronger the acid.

## STRONG BASES

Similarly, the $K_b$ value of strong bases will be greater than 1. The greater the $K_b$ value, the stronger the base. In strong bases that contain hydroxide ions, the concentration of hydroxide ions can be determined according to the molar ratio.

| | | | | | |
|---|---|---|---|---|---|
| Monobasic: | $NaOH\ (aq)$ | → | $Na^+\ (aq)$ | + | $OH^-\ (aq)$ |
| | 1 mol | : | 1 mol | : | 1 mol |
| | $0{,}3\ mol{\cdot}dm^{-3}$ | : | $0{,}3\ mol{\cdot}dm^{-3}$ | : | $0{,}3\ mol{\cdot}dm^{-3}$ |
| Dibasic: | $Mg(OH)_2\ (aq)$ | → | $Mg^{2+}\ (aq)$ | + | $2\ OH^-\ (aq)$ |
| | 1 mol | : | 1 mol | : | 2 mol |
| | $0{,}3\ mol{\cdot}dm^{-3}$ | : | $0{,}3\ mol{\cdot}dm^{-3}$ | : | $0{,}6\ mol{\cdot}dm^{-3}$ |

## INDICATOR COLOUR ACCORDING TO LE CHATELIER

**Indicators are defined as weak acids in equilibrium with their conjugate base.**

Eg. Bromothymol blue: $HIn\ (aq) + H_2O\ (l) \rightleftharpoons H_3O^+\ (aq) + In^-\ (aq)$

weak acid (yellow) — conj. base (blue)

The colour of an indicator in its acid form is different from the conjugate base form. Le Chatelier's principle can be used to predict the colour change that takes place.

**Acidic solution:** Excess $H_3O^+$ present due to acid, system reacts by favouring the reverse reaction, forming more HIn and turning the solution yellow.

**Alkali solution:** $OH^-$ ions from the base react with $H_3O^+$ ions to form water, system responds by favouring forward reactions forming more $In^-$ ions and turning the solution blue.

# ELECTROCHEMISTRY–REDOX



## REDOX REACTION

A redox reaction is a reaction in which there is a transfer of electrons between elements/compounds.

**Oxidation is the loss of electrons** (oxidation number increases)

**Reduction is the gain of electrons** (oxidation number decreases)

**The oxidising agent is the substance which accepts electrons.** (It is the substance which is reduced and causes oxidation.)

**The reducing agent is the substance that donates electrons**. (It is the substance which is oxidised and causes reduction.)

**The anode is the electrode where oxidation takes place.**

**The cathode is the electrode where reduction takes place.**

**OIL:** Oxidation is loss
**RIG:** Reduction is gain

**LEO:** Loss of electrons is oxidation
**GER:** Gain of electrons is reduction

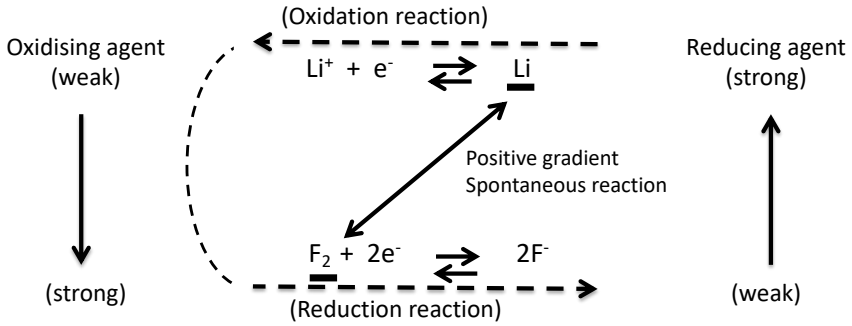
**REDCAT:** Reduction at cathode
**ANOX:** Oxidation at anode

## TABLE OF STANDARD REDUCTION POTENTIALS (REDOX TABLE)

The oxidation and reduction half reactions can also be found using the Table of Standard Reduction Potentials. (We will use Table 4B).

The reactions shown on the table are all written as reduction half reactions, with the reversible reaction arrow (⇌) shown. This means that each reaction is reversible. When a reaction is written from the table the arrow must only be one way (i.e. →).

The reduction half reaction is written from the table from left to right and the oxidation half reaction is written from right to left.




Once the half-reactions are identified it is possible to write a balanced reaction, without the spectator ions. A spectator ion is an ion in a redox reaction that does not take part in electron transfer. Remember that the number of electrons lost or gained by each substance must be the same.

If the line drawn between the two reactants has a positive gradient, the reaction is spontaneous.

If the line between the reactants are negative, the reaction is non-spontaneous.

**STEPS TO WRITING BALANCED REDOX REACTIONS USING REDOX TABLE**

1. IDENTIFY THE REACTANTS
2. UNDERLINE REACTANTS ON THE REDOX TABLE
3. DRAW ARROWS IN DIRECTION OF REACTION
4. WRITE THE OXIDATION AND REDUCTION HALF-REACTIONS
5. BALANCE ELECTRONS IF NECESSARY
6. WRITE OVERALL REACTION (LEAVE OUT SPECTATORS)

**EXAMPLE:**

Zinc metal reacts with an acid, $H^+(aq)$ to produce hydrogen gas. Using the oxidation and reduction half reactions write a balanced equation for this reaction.

**STEP 1: IDENTIFY THE REACTANTS**

Zn(s) and $H^+(aq)$

**STEP 2: UNDERLINE REACTANTS ON THE REDOX TABLE**

**STEP 3: DRAW ARROWS IN DIRECTION OF REACTION**

**STEP 4: WRITE THE OXIDATION AND REDUCTION HALF-REACTIONS**

Ox half-reaction: $Zn \rightarrow Zn^{2+} + 2e^-$

Red half-reaction: $2H^+ + 2e^- \rightarrow H_2$

**STEP 5: BALANCE ELECTRONS IF NECESSARY**

**STEP 6: WRITE OVERALL REACTION (LEAVE OUT SPECTATORS)**

Overall: $Zn + 2H^+ \rightarrow Zn^{2+} + H_2$

**EXAMPLE:**

Magnesium ribbon is burnt in a gas jar containing chlorine gas. Using half reactions write a balanced chemical equation for this reaction.

Ox half-reaction: $Mg \rightarrow Mg^{2+} + 2e^-$
Red half-reaction: $Cl_2 + 2e^- \rightarrow 2Cl^-$
Overall reaction: $Mg + Cl_2 \rightarrow Mg^{2+} + 2Cl^-$

**EXAMPLE:**

Using half reactions, complete and balance the following reaction: $Pb + Ag^+$

Ox half reaction: $Pb \rightarrow Pb^{2+} + 2e^-$
Red half reaction: $Ag^+ + e^- \rightarrow Ag$

Ox half reaction: $Pb \rightarrow Pb^{2+} + 2e^-$
(x2 red half reaction): $2Ag^+ + 2e^- \rightarrow 2Ag$
Overall reaction: $Pb + 2Ag^+ \rightarrow Pb^{2+} + Ag$

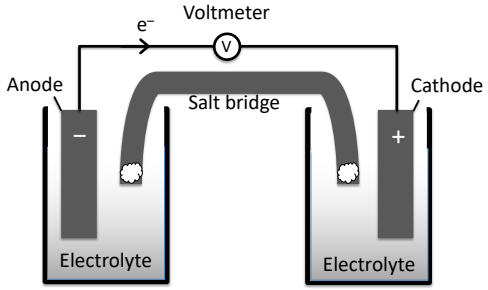
# ELECTROCHEMISTRY– GALVANIC/VOLTAIC CELL



A galvanic cell reaction is always a spontaneous, exothermic reaction during which **chemical energy is converted to electrical energy**. A electric cell/ battery is an example of a galvanic cell.

## STRUCTURE

Two half-cells (usually in separate containers):
Anode – where oxidation takes place – negative electrode
Cathode – where reduction takes place – positive electrode
The anode and cathode connected together through an external circuit, which allows for current to flow from the anode to the cathode




**SALT BRIDGE**

The salt bridge connects the two half-cells. It is filled with a saturated ionic solution of either KCl, NaCl, $KNO_3$ or $Na_2SO_4$. A concentrated solution is used to reduce the internal resistance. The ends of the tubes are closed with a porous material such as cotton wool or glass wool.

**Functions of the salt bridge:**

Completes the circuit (which allows current to flow)
Maintains the electrical neutrality of the electrolyte solutions.

## EQUILIBRIUM IN A CELL

When the circuit is complete the current will begin to flow. The current and potential difference of the cell is related to the rate of the reaction and extent to which the reaction in the cell has reached equilibrium.
As the chemical reaction proceeds, the rate of the forward reaction will decrease, so the rate of transfer of electrons will also decrease which results in the $E^{\theta}$cell value decreasing.
The cell potential will continue to decrease gradually until equilibrium is reached at which point the cell potential will be zero and the battery is "flat".
Le Chatelier's principle can be applied to increase the EMF, with conditions that favour the forward reaction.

## EMF OF THE CELL

The emf of the cell is calculated using one of the following equations:

$$E^{\theta}_{cell} = E^{\theta}_{cathode} - E^{\theta}_{anode}$$

$$E^{\theta}_{cell} = E^{\theta}_{reduction} - E^{\theta}_{oxidation}$$

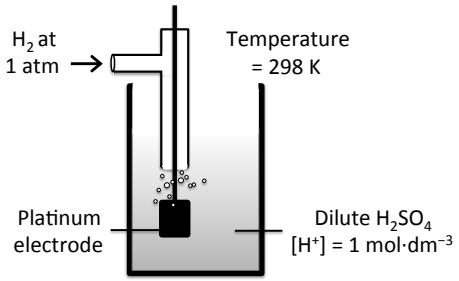
$$E^{\theta}_{cell} = E^{\theta}_{oxidising\ agent} - E^{\theta}_{reducing\ agent}$$

A positive $\varepsilon^{\theta}$ value indicates a spontaneous reaction

The emf of the half-cells are determined using the standard hydrogen half-cell

### Standard hydrogen half-cell

The hydrogen half-cell is allocated a reference potential of 0,00 V. All other half-cells will have a potential which is either higher or lower than this reference. This difference is the reading on the voltmeter placed in the circuit.




$H_2$ is bubbled through the electrolyte over the inert platinum electrode.
Reduction potentials are measured under standard conditions:

temperature 25 °C; 298 K
concentration of the solutions 1 mol·dm$^{-3}$
pressure 1 atm; 101,3 kPa (only relevant for gases)

The cell-notation for the hydrogen half-cell is:

Pt | $H_2$ (g) / $H^+$ (aq) (1 mol·dm$^{-3}$)

**The hydrogen half-cell is always written first.**

**EXAMPLE**

Consider the cell notation of the following electrochemical cell:

Pt | $H_2$(g)/$H_2SO_4$(aq) (0,5 mol·dm$^{-3}$)// $CuSO_4$(aq) (1 mol·dm$^{-3}$)/Cu(s)

The experimentally determined cell potential is 0,34 V at 25 °C.

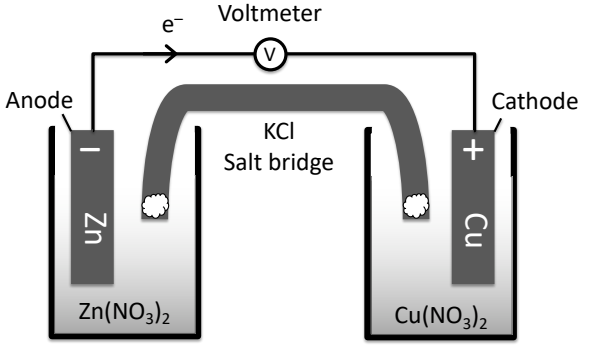
If a value of 0,00 V is given to the hydrogen half-cell, it means that the value of the copper half-cell must be 0,34 V.

$$E^{\theta}cell = E^{\theta}cathode - E^{\theta}anode$$

$$0{,}34 = E^{\theta}(Cu) - 0{,}00$$

$$E^{\theta}(Cu) = +0{,}34\ V$$

## ZINC-COPPER CELL




**The zinc half-cell (–):**

- Zinc electrode
- Zinc salt solution (e.g. zinc nitrate)
- Zn is a stronger RA than Cu, ∴ Zn oxidises
- Oxidation reaction occurs: $Zn \rightarrow Zn^{2+} + 2e^-$
- Anode
- Electrode decreases in mass

**The copper half-cell (+):**

- Consists of a copper electrode
- Copper salt solution (e.g. copper (II) nitrate)
- $Cu^{2+}$ is a stronger OA than $Zn^{2+}$, ∴$Cu^{2+}$ reduces
- Reduction reaction occurs: $Cu^{2+} + 2e^- \rightarrow Cu$
- Cathode
- Electrode increases in mass

Ox: $Zn\ (s) \rightarrow Zn^{2+}\ (aq) + 2e^-$
Red: $Cu^{2+}\ (aq) + 2e^- \rightarrow Cu\ (s)$
Nett cell: $Zn\ (s) + Cu^{2+}(aq) \rightarrow Zn^{2+}\ (aq) + Cu\ (s)$

**For the zinc-copper cell:**

The anode reaction is: $Zn\ (s) \rightarrow Zn^{2+}\ (aq) + 2e^-$; $E^{\theta} = -0{,}76$ V
The cathode reaction is: $Cu^{2+}\ (aq) + 2e^- \rightarrow Cu\ (s)$; $E^{\theta} = +0{,}34$ V

$$E^{\theta}cell = E^{\theta}cathode - E^{\theta}anode$$

$$= 0{,}34 - (-0{,}76)$$

$$= +1{,}1\ V \text{ (spontaneous)}$$

## CELL NOTATION

**Anode** ↓ | **Salt bridge** ↓ | **Cathode** ↓

Zn(s) / $Zn^{2+}$(aq) (1 mol·dm$^{-3}$) // $Cu^{2+}$(aq) (1 mol·dm$^{-3}$) / Cu(s) at 25°C

↓ **Zn(s) → $Zn^{2+}$(aq) + 2e$^-$** ↓ **$Cu^{2+}$(aq) + 2e$^-$ → Cu(s)**

When the half-reactions do not include conductors (metals), unreactive electrodes are used, e.g. carbon or platinum.

**Pt(s)/**$H_2$(g)(1 atm)**/**$H^+$(aq)(1 mol·dm$^{-3}$)**//**$Br_2$(g)(1 atm)**/**$Br^-$(aq)(1 mol·dm$^{-3}$)**/Pt(s)**

Ca(s)**/**$Ca^{2+}$(aq)(1 mol·dm$^{-3}$ )**//**$Fe^{3+}$(aq)(1 mol·dm$^{-3}$)**,** $Fe^{2+}$(aq)(1 mol·dm$^{-3}$)**/C(s)**

# ELECTROCHEMISTRY- ELECTROLYTIC CELLS

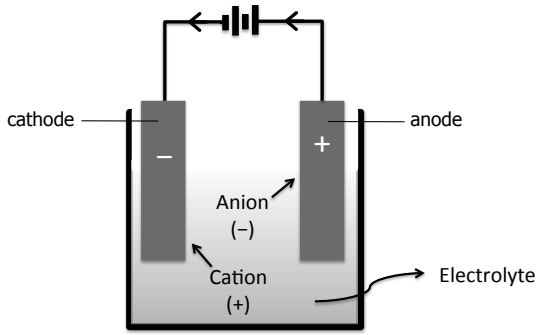


An electrolytic cell reaction is always a non-spontaneous, endothermic reaction which requires a battery. **The electrical energy is converted to chemical energy.**

## STRUCTURE

Two electrodes (in the same container):
Anode – where oxidation takes place – positive electrode
Cathode – where reduction takes place – negative electrode

The anode and cathode are connected to an external circuit, which is connected to a DC power source.



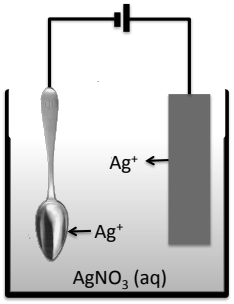

## ELECTROPLATING

Electroplating is the process of depositing a layer of one metal onto another metal.

**EXAMPLE:** Silver plating of a metal spoon

The anode is silver, it will be oxidised to $Ag^+$ ions. The mass of the silver electrode decreases.

The cathode is the object (spoon) to be plated. The $Ag^+$ ions from the electrolyte will be reduced to form silver metal, which plates the spoon. The mass of the cathode (spoon) increases.




The anode and electrolyte always contains the plating metal.

Oxidation (anode): $Ag\ (s) \rightarrow Ag^+\ (aq) + e^-$
Reduction (cathode): $Ag^+\ (s) + e^- \rightarrow Ag\ (s)$
Nett cell: $Ag^+\ (aq) + Ag\ (s) \rightarrow Ag^+\ (aq) + Ag\ (s)$

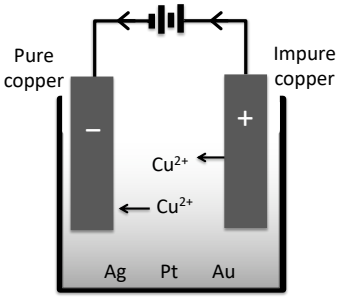
$\therefore [Ag^+]$ stays constant

## ELECTROREFINING OF COPPER

When copper is purified, the process is similar to electroplating. Impure (blister) copper is used as the anode and the cathode is pure copper.

At the anode the copper is oxidised to produce $Cu^{2+}$ ions in the electrolyte. The mass of the impure copper anode decreases.

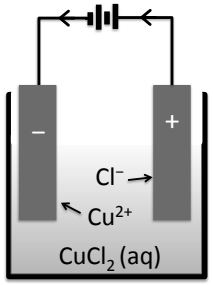
At the cathode the $Cu^{2+}$ ions in the electrolyte is reduced to form a pure copper layer on the cathode. The mass of the cathode increases.




The less reactive elements and compounds found in the impure copper anode are precipitated to the bottom of the reaction vessel. The more reactive metals (stronger reducing agents) are also oxidised. The ions of these metals remain in the solution. $Cu^{2+}$ is a stronger oxidising agent, thus it is preferentially reduced at the cathode. $Cu^{2+}$ stays constant.

Oxidation (anode): $Cu\ (s) \rightarrow Cu^{2+}\ (aq) + 2e^-$
Reduction (cathode): $Cu^{2+}\ (aq) + 2e^- \rightarrow Cu\ (s)$
Nett cell: $Cu^{2+}\ (aq) + Cu\ (s) \rightarrow Cu^{2+}\ (aq) + Cu\ (s)$
impure pure

## ELECTROLYSIS OF COPPER (II) CHLORIDE




Oxidation (anode): $2Cl^-\ (aq) \rightarrow Cl_2\ (g) + 2e^-$
Reduction (cathode): $Cu^{2+}\ (aq) + 2e^- \rightarrow Cu\ (s)$
Nett cell: $2Cl^-\ (aq) + Cu^{2+}\ (aq) \rightarrow Cl_2\ (g) + Cu\ (s)$

Chlorine gas is produced at the anode, while copper metal is produced at the cathode.

## EXTRACTION OF ALUMINIUM (HALL-HEROLT PROCESS)

Aluminium is found in the mineral known as bauxite which contains primarily aluminium oxide ($Al_2O_3$) in an impure form.

Bauxite is not found in South Africa so is imported from Australia for refining.

**Step 1: Converting impure $Al_2O_3$ to pure $Al_2O_3$**

Bauxite treated with NaOH – impure $Al_2O_3$ becomes $Al(OH)_3$

$Al(OH)_3$ is heated (T > 1000 °C)

$Al(OH)_3$ becomes pure $Al_2O_3$ – alumina

**Step 2: Melting $Al_2O_3$**

Alumina is dissolved in cryolite (sodium aluminium hexafluoride – $Na_3AlF_6$).

Melting point reduced from over 2000 °C to 1000 °C.

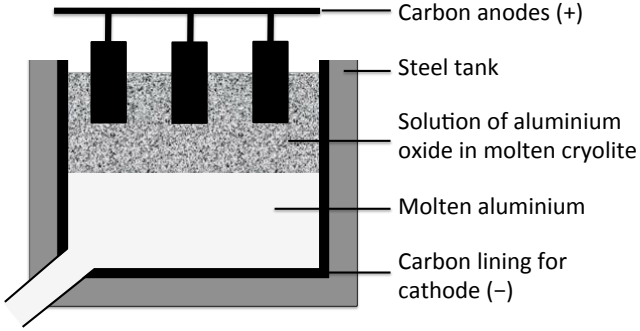
Reduces energy requirements, costs and less environmental impact.

**Step 3: Molten Alumina – cryolite mixture placed in reaction vessel**

Anodes (+) are carbon rods in mixture

Cathode (-) is the carbon lining of the tank

At cathode $Al^{3+}$ ions are reduced to Al metal




Oxidation (Anode): $2O^{2-}\ (aq) \rightarrow O_2(g) + 4e^-$ $\times 3$
Reduction (Cathode): $Al^{3+}\ (aq) + 3e^- \rightarrow Al\ (l)$ $\times 4$
Nett cell: $2Al_2O_3\ (aq) \rightarrow 4Al\ (l) + 3O_2\ (g)$

Due to the high temperature of the reaction, the oxygen produced reacts with the carbon electrodes to produce carbon dioxide gas. The carbon electrodes (anodes) therefore need to be replaced regularly.

Aluminium extraction uses a large amount of electrical energy, therefore the cost of aluminium extraction is very high.

# ELECTROCHEMISTRY- ELECTROLYTIC CELLS



## ELECTROLYSIS OF SOLUTIONS

In the electrolysis of NaCl, the $Na^+$ ions are not reduced as might be expected. To identify which ions are oxidised/reduced apply the following rules (based on relative strength of OA/RA):

**OXIDATION (ANODE):**
Either the anion or $H_2O$ will be oxidised.

If a HALOGEN ION ($Cl^-$, $Br^-$, $I^-$, not $F^-$) is present, the HALOGEN ION is oxidised.
If no halogen ion is present, or the concentration is very low, water is oxidised according to:
$2H_2O\ (l) \rightarrow O_2\ (g) + 4H^+\ (aq) + 4e^-$

**REDUCTION (CATHODE):**
Either the cation or $H_2O$ will be reduced.

If a GROUP I OR GROUP II METAL CATION is present, WATER will be reduced according to:

$2H_2O\ (l) + 2e^- \rightarrow H_2\ (g) + 2OH^-\ (aq)$

Water is reduced because it is a stronger oxidising agent than other group I and II elements. If any other cation is present, the cation will

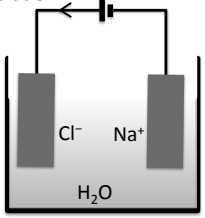
## ELECTROLYSIS OF NaCl (CHLOR-ALKALI INDUSTRY)

Brine (concentrated NaCl solution) is placed in an electrolytic cell to produce chlorine gas, hydrogen gas and sodium hydroxide solution.

Overall reaction: $2NaC\ell(aq) + 2H_2O(\ell) \rightarrow C\ell_2(g) + 2NaOH(aq) + H_2(g)$

At the anode, $C\ell^-$ ions are oxidised to form $C\ell_2$ (g). $Cl_2$ gas bubbles form on the electrode.

At the cathode, water is reduced to form $H_2$ (g) and $OH^-$ (aq). $H_2$ (g) bubbles form on the electrode.




Oxidation (anode): $2Cl^-\ (aq) \rightarrow Cl_2\ (g) + 2e^-$
Reduction (cathode): $2H_2O\ (\ell) + 2e^- \rightarrow H_2\ (g) + 2OH^-\ (aq)$

Nett cell: $2C\ell^-\ (aq) + 2H_2O\ (\ell) \rightarrow Cl_2\ (g) + H_2\ (g) + OH^-\ (aq)$

Overall reaction:
$2NaC\ell\ (aq) + 2H_2O\ (\ell) \rightarrow Cl_2\ (g) + 2NaOH\ (aq) + H_2\ (g)$

In theory, this is a easy process. However, $H_2$ and $C\ell_2$ recombine explosively. As a result, the electrolysis is conducted in specialised electrolytic cells to control the reaction process and allow reactions to occur under controlled conditions.

## MEMBRANE CELL

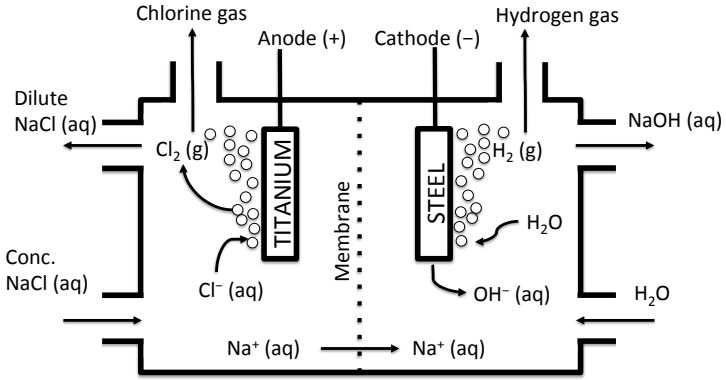
An ion-exchange membrane is used to separate the sodium and chloride ions of the sodium chloride. The selectively permeable ion-exchange membrane is a fluoro-polymer which allows only $Na^+$ ions to pass through it. The cell consists of two half cells separated by the membrane. The electrolytic cell has the lowest environmental impact. It is also the most cost effective to run, as the internal resistance is far lower than that of the diaphragm and mercury cells.

The cathode is filled with pure water

**At cathode - Reduction:**
$2H_2O\ (l) + 2e^- \rightarrow H_2\ (g) + 2OH^-$

The anode is filled with the brine solution

**At anode - Oxidation:**
$2Cl^-\ (aq) \rightarrow Cl_2\ (g) + 2e^-$

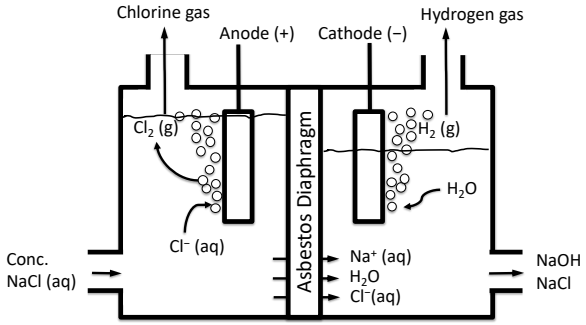



Nett cell: $2Cl^-\ (aq) + 2H_2O\ (l) \rightarrow Cl_2\ (g) + H_2\ (g) + 2OH^-\ (aq)$

Overall reaction: $2NaCl\ (aq) + 2H_2O\ (l) \rightarrow Cl_2\ (g) + 2NaOH\ (aq) + H_2\ (g)$

## DIAPHRAGM CELL

The cell consists of two half cells separated by an asbestos diaphragm. The diaphragm allows only $Na^+$ ions, $Cl^-$ ions and water to pass through.




**At anode - Oxidation:**
$2Cl^-\ (aq) \rightarrow C\ell_2\ (g) + 2e^-$

**At cathode - Reduction:**
$2H_2O\ (\ell) + 2e^- \rightarrow H_2\ (g) + 2OH^-\ (aq)$

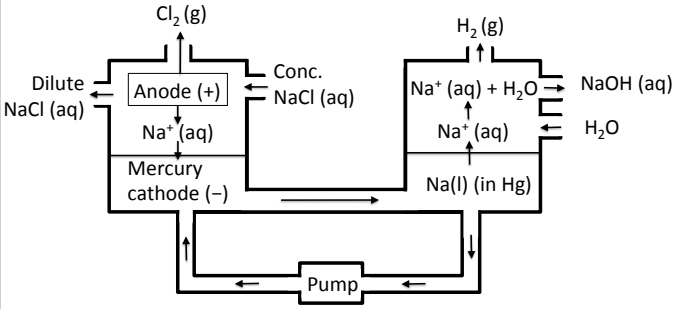
Overall reaction:
$2NaC\ell\ (aq) + 2H_2O\ (\ell) \rightarrow C\ell_2\ (g) + 2NaOH\ (aq) + H_2\ (g)$

The diaphragm has forms a low concentration NaOH compared to other cells. The different levels of electrolyte in anode vs cathode compartments reduce the flow of OH– from cathode to anode, in turn preventing the formation of $C\ell O$– ions.

The asbestos used for the diaphragm is a health hazard, hence the use of diaphragm cells have been discontinued.

## MERCURY CELL

The mercury cell uses a mercury cathode to reduce and transport Na (ℓ) as an amalgam and react with water to form NaOH and $H_2$ as products of a decomposition reaction. This process forms the highest % purity of NaOH due to being collected in separate containers, but with trace amounts of toxic mercury. Mercury cells have been discontinued due to high running cost and mercury toxicity.




**At cathode - Reduction:**

$Na^+\ (aq)$ reduces to form an amalgam
$Na^+\ (aq) + Hg\ (\ell) + e^- \rightarrow Na\ (\ell)(in\ Hg)$

**At anode - Oxidation:**
$2C\ell^-\ (aq) \rightarrow C\ell_2\ (g) + 2e^-$

Decomposition reaction:
$2Na\ (\ell) + H_2O\ (\ell) \rightarrow 2NaOH\ (aq) + H_2\ (g)$

Overall reaction:
$2NaC\ell\ (aq) + 2H_2O\ (\ell) \rightarrow C\ell_2\ (g) + 2NaOH\ (aq) + H_2\ (g)$