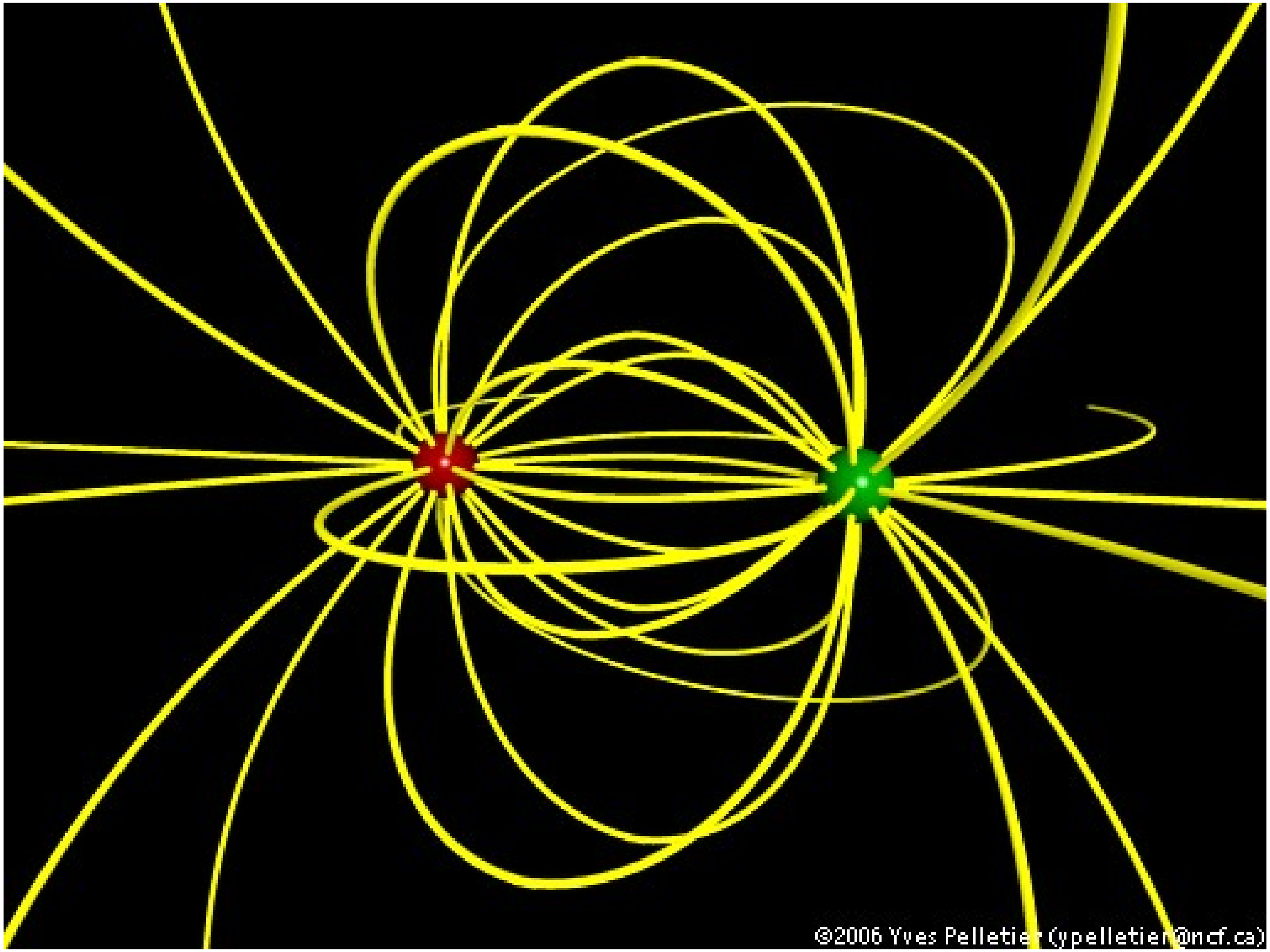
5.1 Electric force and field



5.1 Electric force and field

- Two types of electric charge
- Law of conservation of charge
- Coulomb’s law
- Electric field strength
- Electric field patterns

5.1 Nature of Science

Modelling: Electrical theory demonstrates the scientific thought involved in the development of a microscopic model (behaviour of charge carriers) from macroscopic observation. The historical development and refinement of these scientific ideas when the microscopic properties were unknown and unobservable is testament to the deep thinking shown by the scientists of the time

Some Basics

- There are only two types of charge – positive and negative.
- Matter that contains equal amounts of positive or negative charge, is said to be neutral.
- An electrical conductor is one that allows the flow of charge through it.
- The flow of charge through a conductor is always as a result of the flow of electrons.
- An electrical insulator is one that does not allow the flow of charge through it.

Properties of electric charge

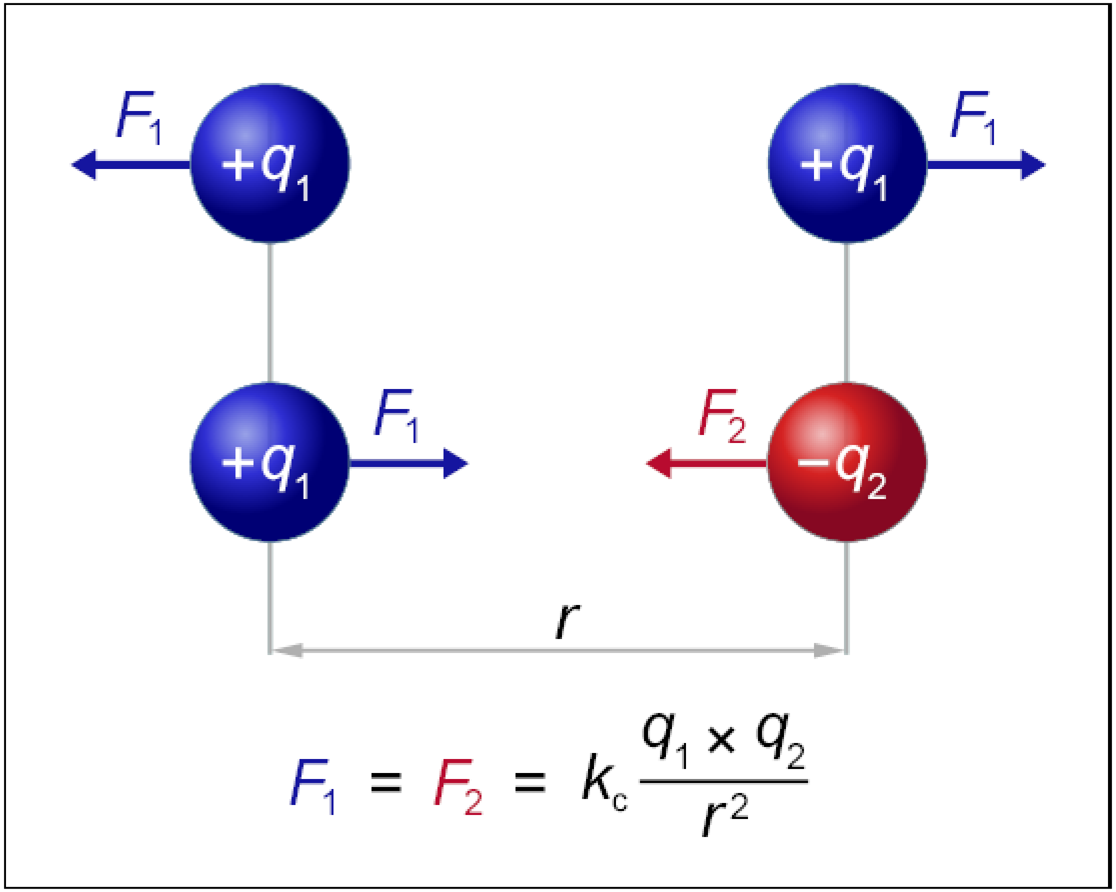
1. Electric charge is measured in units of Coulomb (C); and the electron carries the smallest unit of electric charge equals to 1.6×10^{-19} C.

2. Conservation of electric charge

   The total charge of an isolated system cannot change.

Coulomb's law for the electric force

Coulomb's law states that the electrostatic force between 2 point charges is directly proportional to the product of their charges & inversely proportional to the square of the distance between them.



Coulomb's law for the electric force

1. The electric force between two electric charges, q_1 and q_2, was investigated by Coulomb in 1784 and independently, by Canvendish.
2. This force is inversely proportional to the square of the separation, r, of the charges and is proportional to the product of the two charges.
3. It is attractive for opposite charges and repulsive for similar-sign charges.
4. In equation form, Coulomb's law states that the electric force between two *point charges* q_1 and q_2 , is given by

$$F = k\frac{q_1 q_2}{r^2}$$

4. The numerical value of the factor

$$k = \frac{1}{4\pi\varepsilon_0}$$

or k is equal to $8.99 \times 10^{9}\ Nm^{2}C^{-2}$.

Note: The very high value of k suggests that very large forces exist even between small charges. This indicates why solids exist.

The constant $\varepsilon_o = 8.85 \times 10^{-12}\ C^{2}N^{-1}m^{-2}$ (or Fm^{-1})

ε_o is called permittivity of free space

the index zero in ε_o signifies that we are considering the two charges to be in a vacuum. If the charges are in a medium, such as plastic or water, then we must use the value of ε appropriate to that medium in the formula above.

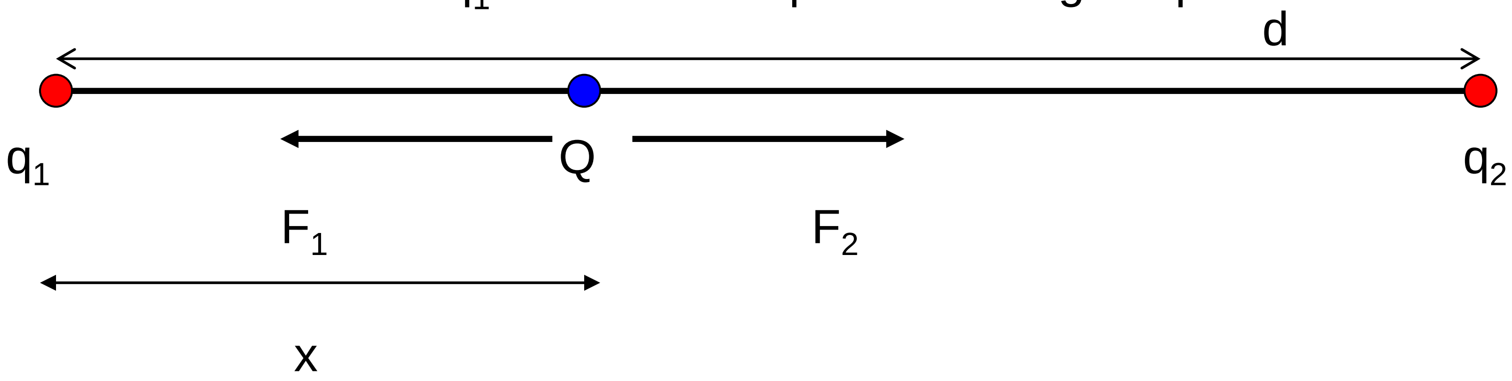
5. This law is very similar to Newton's law of gravitation. Both forces are proportional to the products of masses or charges and both are inversely proportional to the square of the separation. This means that many problems in electricity have the same solution as corresponding problems in gravitation.

Worked Examples

1. Two negative charges, q_1 = -4μC and q_2 = -6 μC , are separated by a distance of 2.0 cm. Find the force exerted on each charge. [1 μC = 10^{-6} C]

$$F = \frac{8.99\times10^{9}\times4\times10^{-6}\times6\times10^{-6}}{(2\times10^{-2})^{2}} = 540\text{ N}$$

2. At what distance from q_1 would a third positive charge experience no net force?



To experience zero force, $F_1 = F_2$;

$$k\frac{q_1 Q}{x^2} = k\frac{q_2 Q}{(d-x)^2}$$

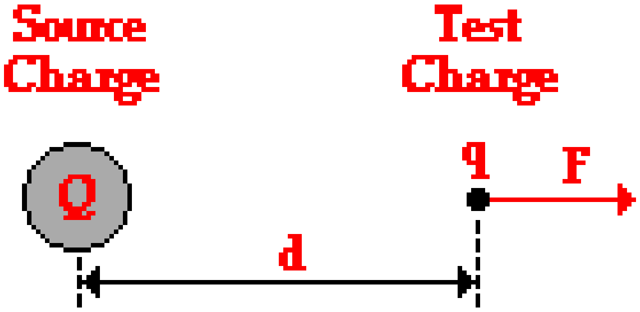
$4\,(d - x)^2 = 6\,x^2$

Solving for x = 0.90 cm and – 8.90 cm; hence the possible solution is 0.90 cm.

Electric field strength

Electric field strength is a vector quantity; it has both magnitude and direction. The magnitude of the electric field strength is defined in terms of how it is measured.   Let's suppose that an electric charge can be denoted by the symbol Q. This electric charge creates an electric field; since Q is the source of the electric field, we will refer to it as the source charge.

The strength of the source charge's electric field could be measured by any other charge placed somewhere in its surroundings. The charge that is used to measure the electric field strength is referred to as a test charge since it is used to test the field strength. The test charge has a quantity of charge denoted by the symbol q. When placed within the electric field, the test charge will experience an electric force - either attractive or repulsive. As is usually the case, this force will be denoted by the symbol F. The magnitude of the electric field is simply defined as the force per charge on the test charge.



Electric field strength

Definition: the *electric field strength* at a point is defined as the *force per unit charge* experienced by a small *positive test charge* q.

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

- Electric field strength is a *vector*. Its direction being the same as that of the force a *positive charge* would experience at the given point.
- The unit of electric field is *NC^{-1}*.
- The test charge needs to be small so that it does not disturb the charge or charges that are being considered.

Electric field strength around a point charge Q

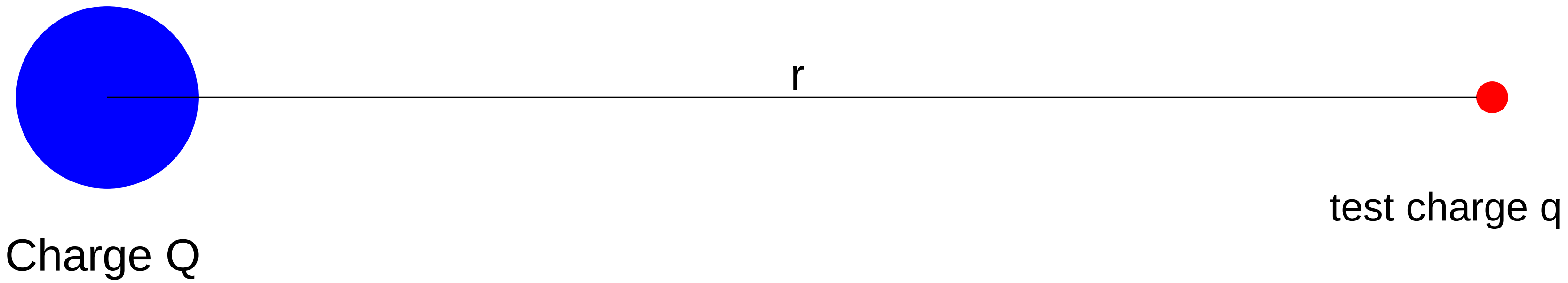
- The force experienced by a small test charge q placed at a distance r from a point charge Q is given by Coulomb's law as

$$F = k\frac{Qq}{r^2}$$

- Since E=F/q, the electric field strength from a single point charge Q at a distance r away is given by

$$E = k\frac{Q}{r^2}$$

Electric field strength of a charged sphere



At a distance r from the <u>centre</u> of a sphere on which a charge Q has been placed, the electric field is given by the same formula as before.

$$E = k\frac{Q}{r^2}$$

(a) On the surface of the charged sphere of radius R,

electric field strength $E = \frac{kQ}{R^2}$

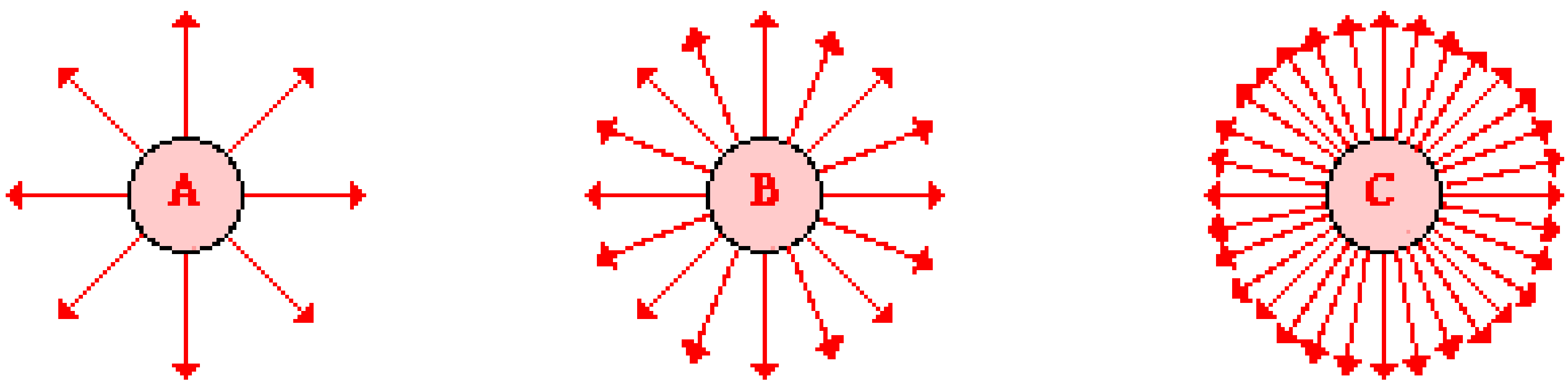
(b) Inside the sphere, electric field is <u>zero</u>.

Electric Field Patterns

At any point in an electric field

- The direction of field is represented by the direction of the field lines closest to that point.
- The magnitude of the field is represented by the number of field lines passing near that point.

Density of Lines in Patterns



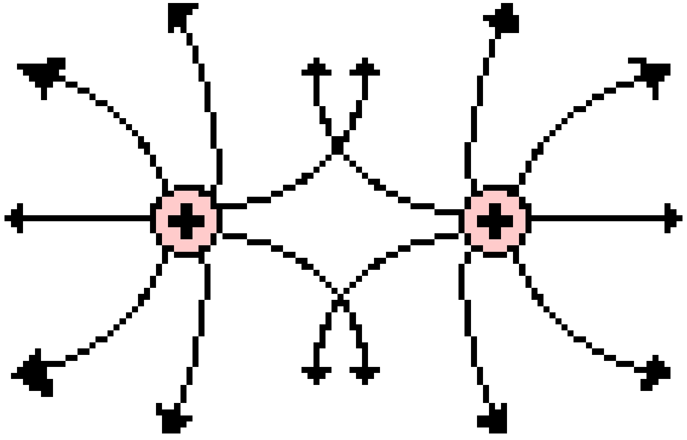
The density of electric field lines around these three objects reveals that the quantity of charge on C is greater than that on B which is greater than that on B.

Electric Field Patterns

Other drawing rules

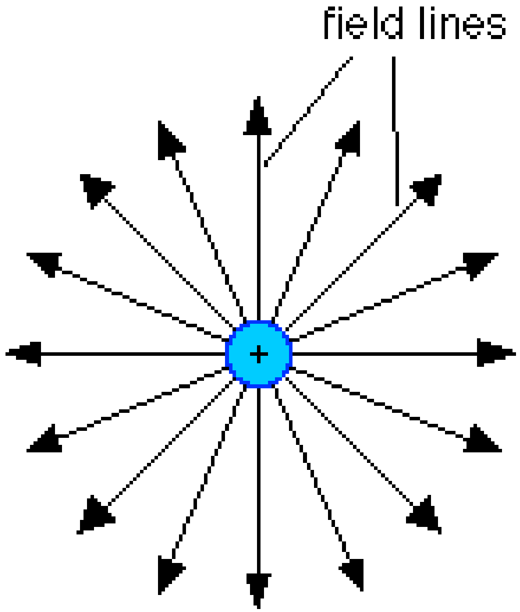
- The electric field is always directed perpendicular to the surface of an object.
- Electric field lines should never cross.

This is wrong.

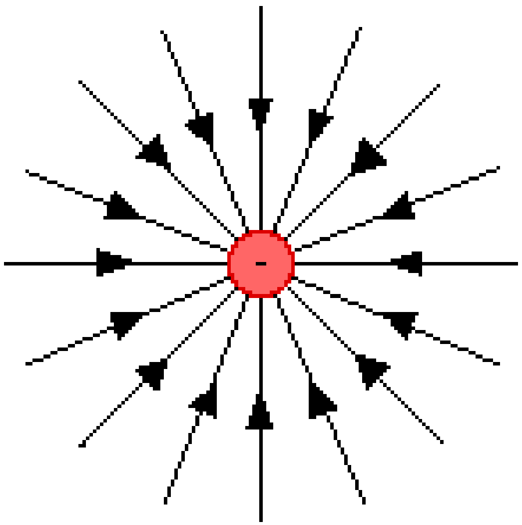


Electric Field Patterns

- Point charges have a radial field, i.e. branching out in all directions from a common center.



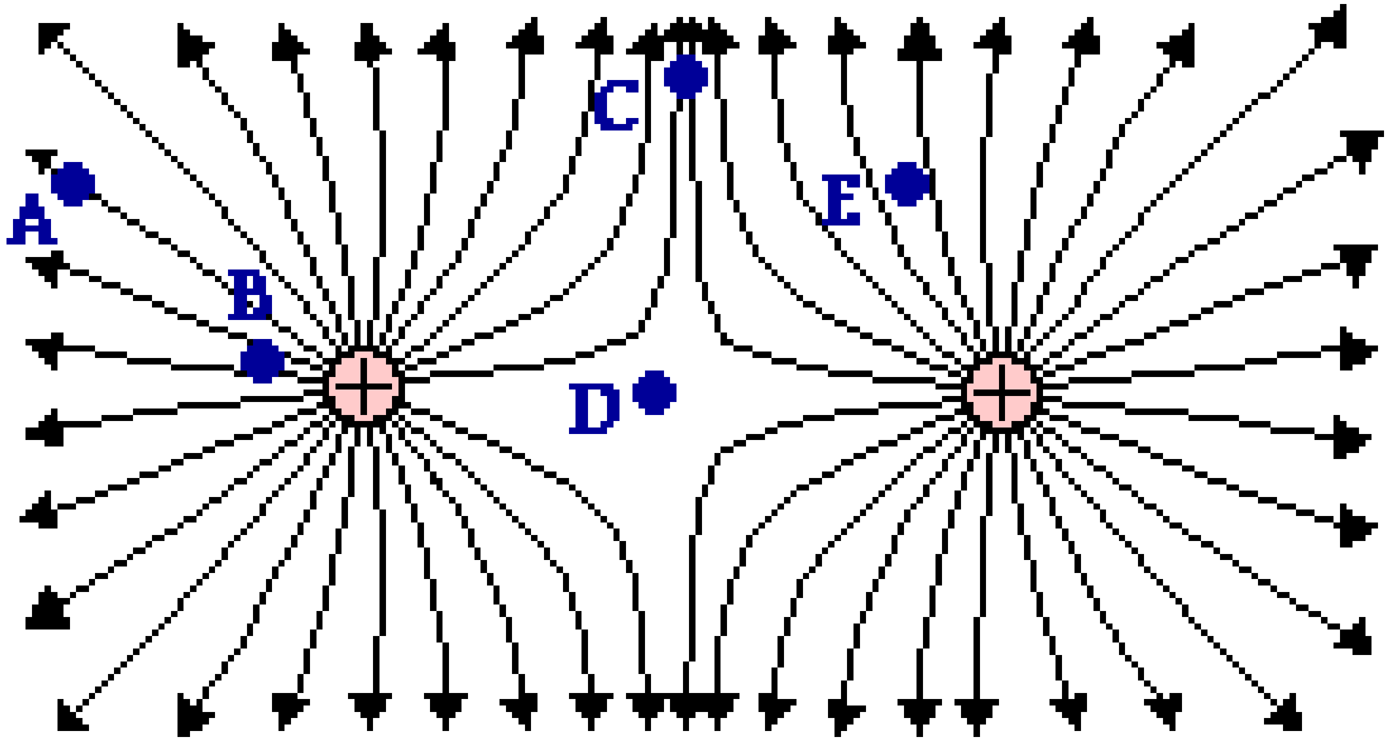
The electric field from an isolated positive charge



The electric field from an isolated negative charge

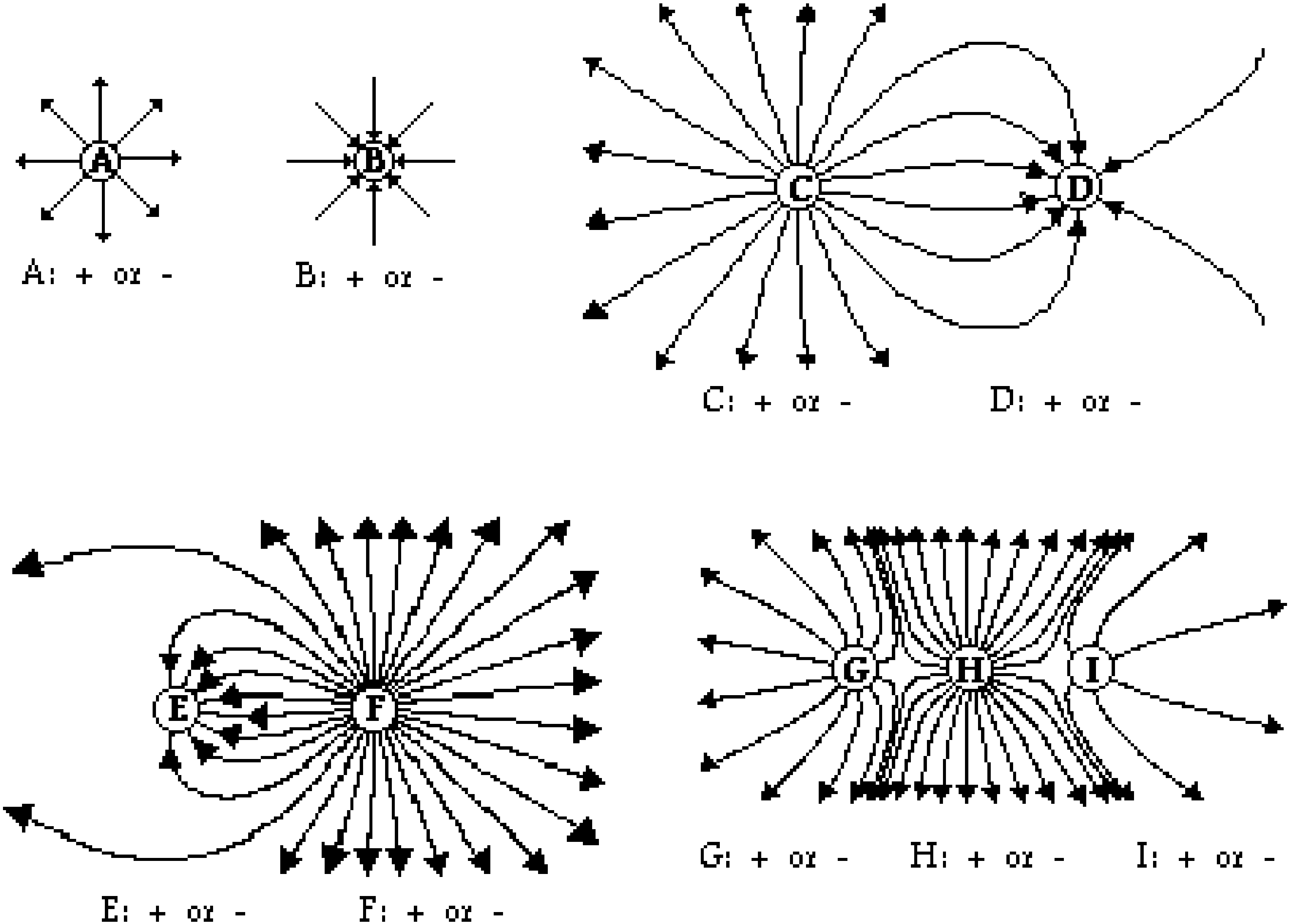
Electric Field Patterns

Consider the electric field lines drawn for a configuration of two charges. Several locations are labeled on the diagram.



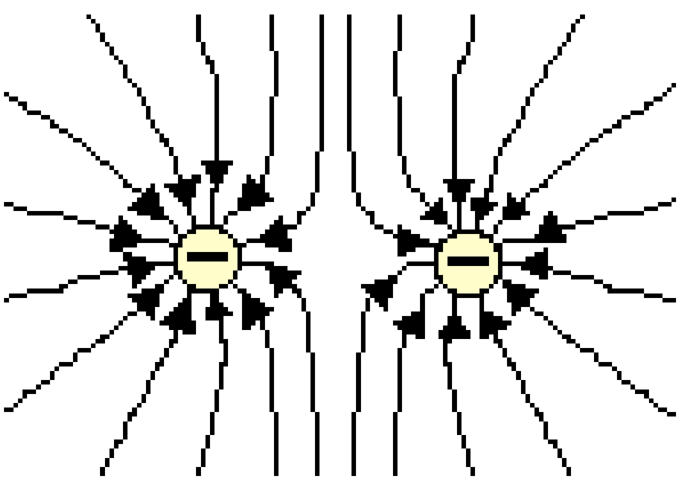
Question: Rank these locations in order of the electric field strength - from smallest to largest. (Ans: DAEBC)

Electric Field Patterns

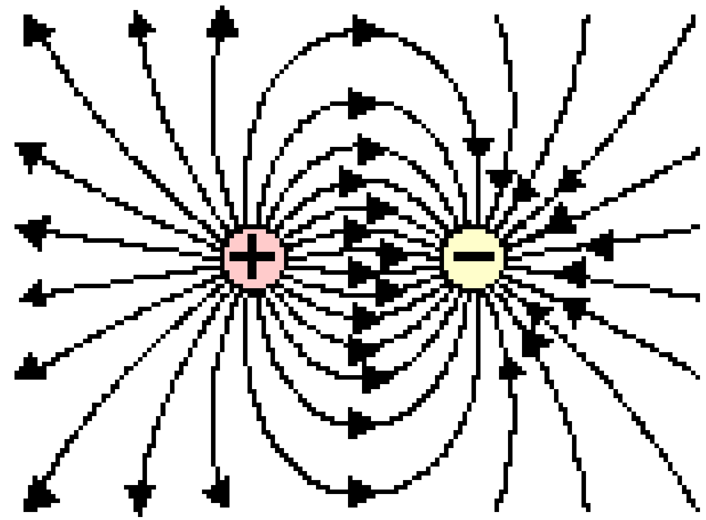


Electric Field Patterns

Other Charge Configurations



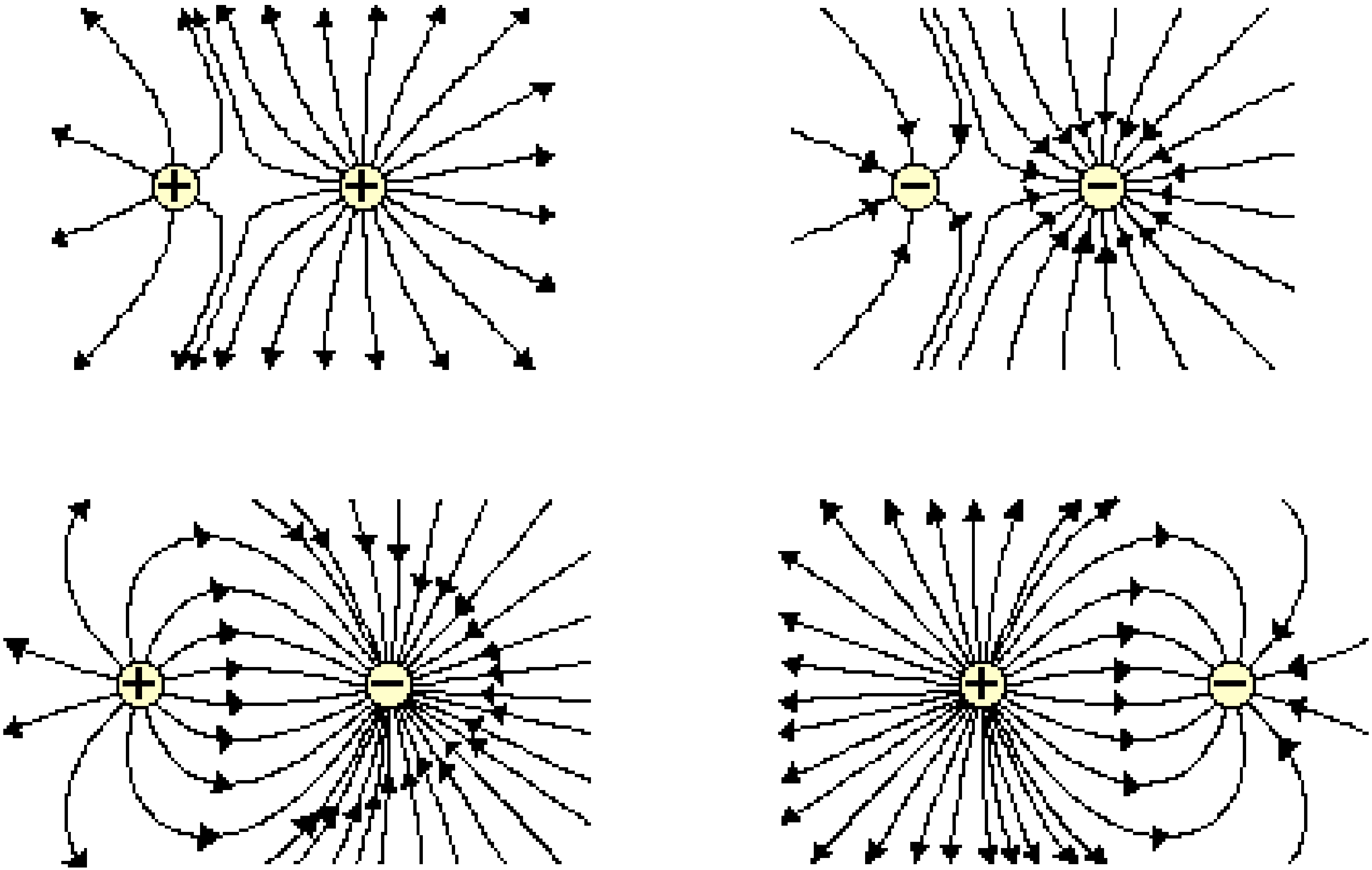
Two Negatively Charged Objects



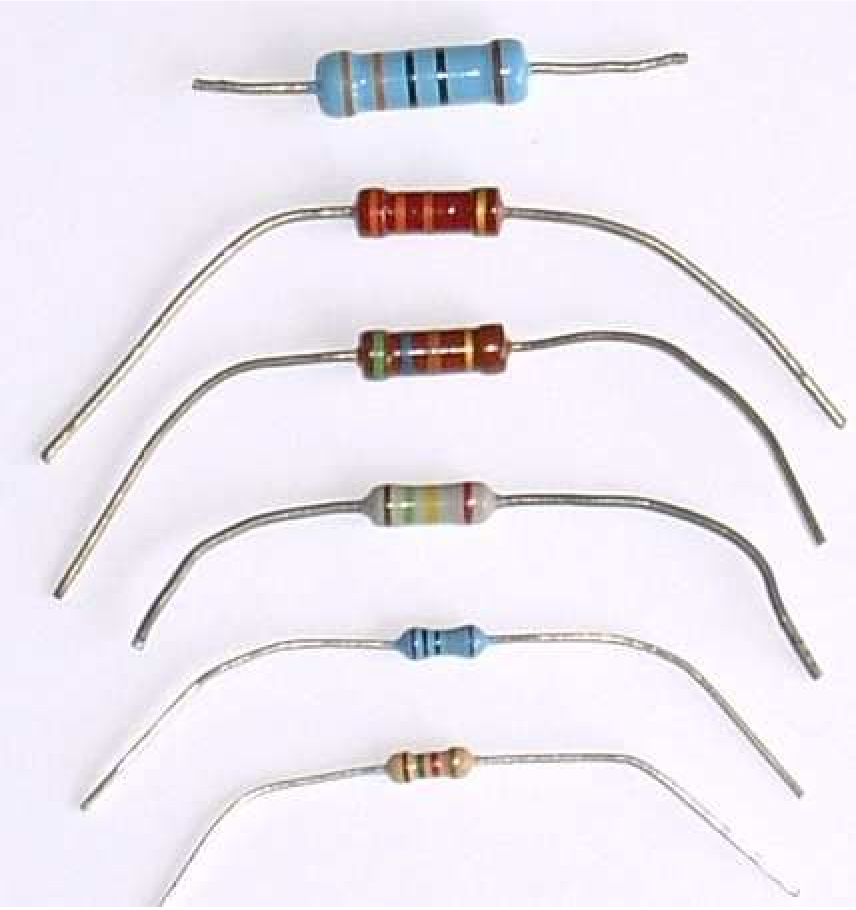
A Positively and a Negatively Charged Object

Electric Field Patterns

Electric Field Line Patterns for Objects with Unequal Amounts of Charge



5.2 Heating effect of current



Parts adaped from Giancoli and from Tim Kirk, Eric Wee

5.2 Nature of Science

Peer review: Although Ohm and Barlow published their findings on the nature of electric current around the same time, little credence was given to Ohm. Barlow’s incorrect law was not initially criticized or investigated further. This is a reflection of the nature of academia of the time with physics in Germany being largely non-mathematical and Barlow held in high respect in England. It indicates the need for the publication and peer review of research findings in recognized scientific journals

Electric potential difference

Definition: Electric Potential Difference

The electric potential difference is defined as the energy/work done per unit charge to move a small positive test charge between 2 points.

This definition comes from the formula given on the right which defines work done in terms of charge and potential difference. This formula comes from topic 9.3.

$$W = q\Delta V$$

$$W = qV$$

It is standard practice in electricity to use the symbol V instead of ΔV to denote potential difference. So the symbol V is used throughout topic 5 to stand for potential difference.

In other words, potential difference is equal to the energy difference per unit charge moved.

The basic unit for potential difference is the $J\ C^{-1}$

Electric potential difference

The basic unit for potential difference is the Joule/coulomb, i.e. J C^{-1}.

A new unit called the **Volt**, V, is defined to be equal to J C^{-1}, therefore

1 V = 1 J C^{-1}

The term "**Voltage**" and potential difference have the same meaning. Potential difference is probably a better name to use as it reminds us that it is measuring the difference between two points.

Note: Be careful to note that the symbol V has several meanings – potential at a point, potential difference/voltage or the unit Volt.

Electronvolt

1. The energy scale that characterizes the atomic world is one of about 10^{-18} J. This is a tremendously small amount of energy by macroscopic standards; the joule is not an appropriate energy unit.

2. A more convenient unit is the electronvolt, eV.

3. One electronvolt is defined as the work done when a charge equals to one electron charge is taken across a potential difference of one volt.

4. Thus 1 eV = 1.6×10^{-19} C x 1V = 1.6×10^{-19} J

5. If a charge of two electron charges is taken across a potential difference of 2 V, the work done will then be 4 eV.

Electric current

Definition: Electric Current

Electric current is defined as the rate of flow of electric charge.

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

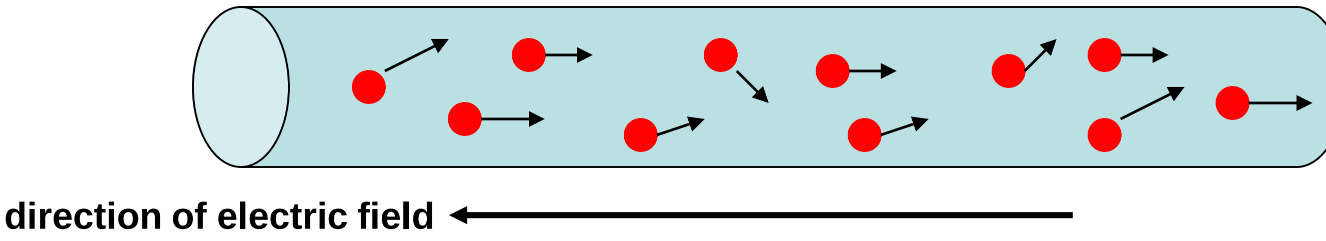
- The unit of electric current is the *ampere* and 1 A = 1 Cs^{-1}.
- The ampere is experimentally defined in terms of the force per unit length between parallel current-carrying conductors. It can be shown that the force per unit length between two infinitely long current-carrying wires is equal to the following:

$$\frac{F}{l} = \frac{\mu I_1 I_2}{2\pi r}$$

(don't need to memorize this equation)

Therefore if the the current is 1 A on both wires and the distance r between them is 1 m, then we can predict that the force per unit length will be 2 x 10^{-7} N.

Electric current

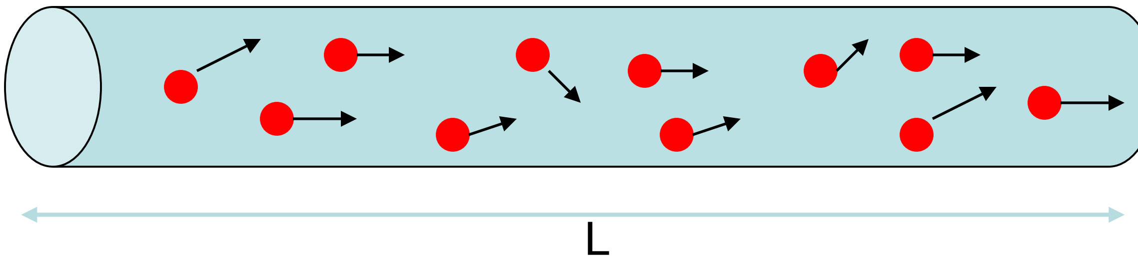


- In a conductor the ‘free’ electrons (conduction electrons) move randomly (just like the random motion of gas molecules) at high speeds. This random motion increases with an increase in temperature. In the presence of an electric field (when a potential difference is applied across the conductor), the electrons are forced to accelerate in the same direction (opposite to the direction of electric field). This drift motion of the free electrons constitutes an electric current.

- However electrons constantly collide with the lattice ions. This results in an increase in temperature of the material. Therefore resistance increases. This means that work needs to be done.

- Drift Velocity :Therefore, when current flows, the metal heats up. The speed of the electrons due to the current is called their drift velocity. Typical value of drift velocity v is about 6×10^{-4} m s^{-1}. Is this very fast?

Electric current



Let's take a look at a section of a conductor length L, cross section area A.

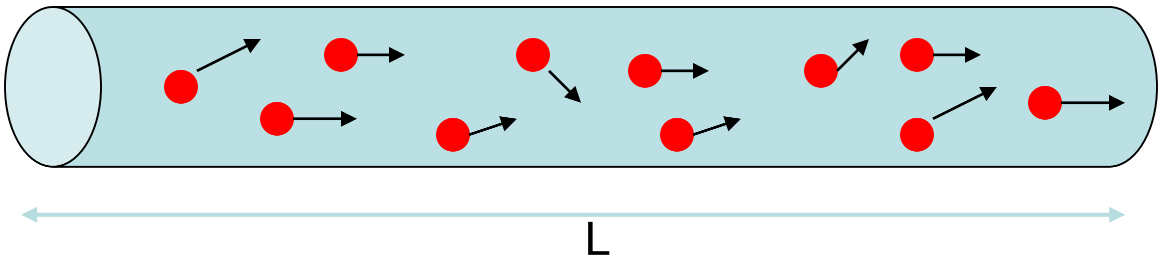
If the conductor has n mobile charges (electrons) per unit volume, then the number of charge carriers in the section would be equal to N.

N = volume of section x number of charge carriers per volume
= ALn

Therefore the total charge of all the mobile charges in this section would be Q where

Q = ALnq

Electric current



If the charges are moving to the right and it takes time t for them to all move through the extreme right end of the section, then the rate of flow of charges I would be

I = ALnq/t

Since L/t = length travelled by the charges per unit time, it is equal to v, the drift speed of the electrons along the conductor

Thus the current, I is related to the drift speed by

$$I = nAvq$$

Electrical resistance

Definition: Resistance

Resistance is defined as the ratio of potential difference to the current.

The *electrical resistance* of a conductor is defined as the *potential difference* across its ends divided by the *current* flowing through it.

- Mathematically,

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

- The unit of electrical resistance is the *ohm* (Ω) and $1\Omega = 1\ VA^{-1}$.
- Note that the equation R=V/I is a general definition of resistance. It is NOT a statement of Ohm's law.

Ohm's Law

Definition: Ohm's Law

The current through a conductor is directly proportional to the potential difference across it provided the temperature (& other physical conditions) remains constant.

- In 1826, Georg Ohm discovered that, when the *temperature* of a *metallic conductor* is kept constant, the *current* through the conductor is *directly proportional* to the *potential difference* across it.

  i.e. $I \alpha V$

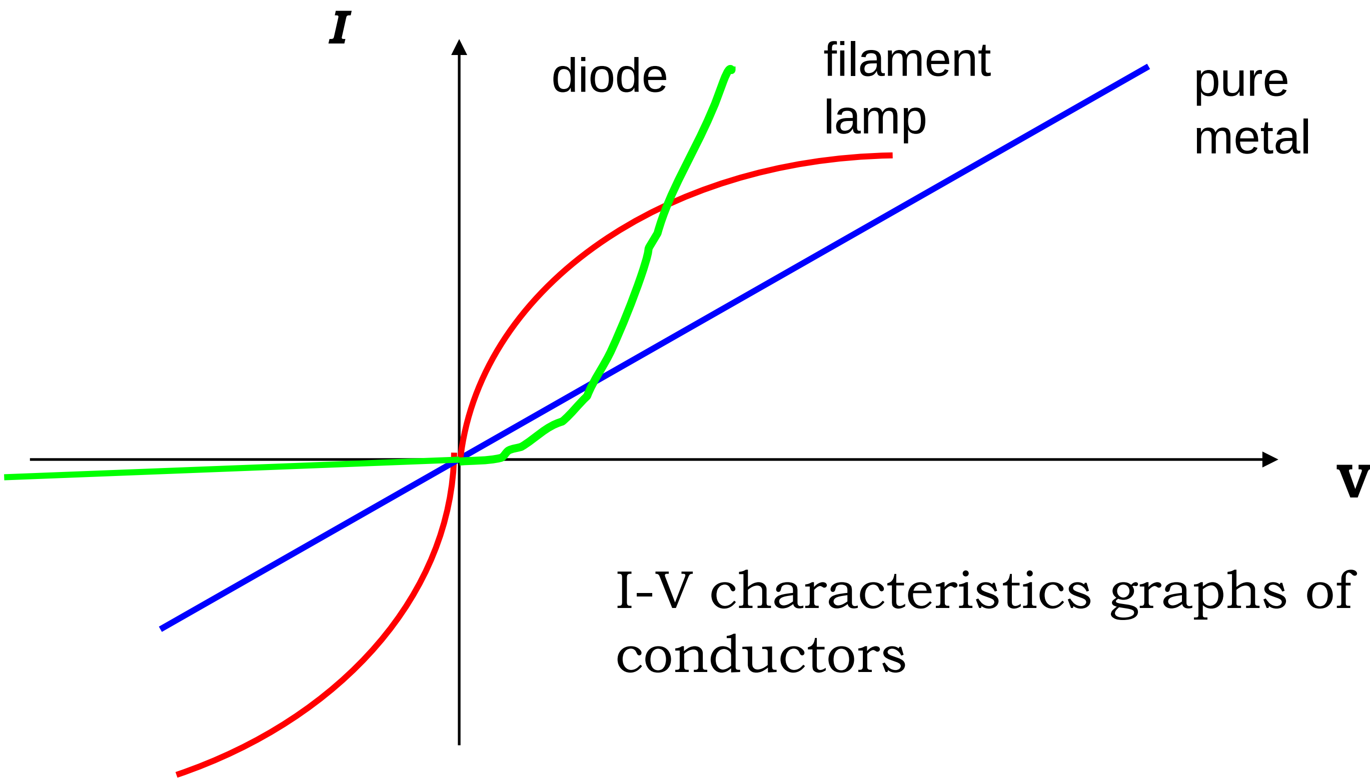
  This statement is known as *Ohm's Law*. Materials that obey Ohm's Law thus have a *constant resistance* at *constant temperature*.

  For example a light bulb has a constant resistance when the current is small. As current increases, temperature also increases and so does the resistance.

Ohmic and non-ohmic behaviour

- A device is said to be **ohmic** if the current and potential difference are proportional. E.g. a metal wire at constant temperature. A device with constant resistance (i.e. an ohmic device) is called a **resistor**.

- A device where current and potential difference are not proportional are said to be **non-ohmic**. E.g. a filament lamp or a diode.



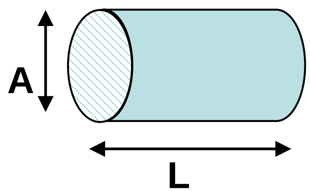
I-V characteristics graphs of some conductors

Resistivity

- Three factors affect the resistance of a *wire* kept at a *constant temperature*. They are the nature of the material, the length of the wire and the cross-sectional area of the wire.

- For a wire, the electrical resistance is *proportional* to its *length L* and *inversely proportional* to its cross-sectional area A.

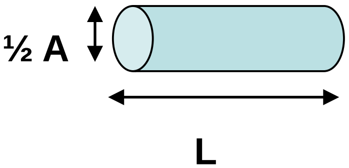
i.e. $R \alpha \frac{L}{A}$



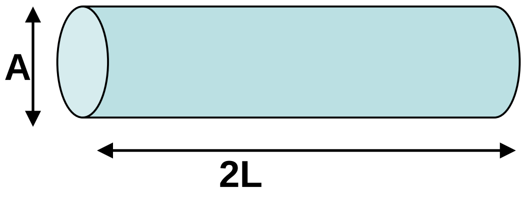
$$R = \rho \frac{L}{A}$$

- The resistivity, ρ, of a material is defined in terms of A and L. The units of resistivity is Ωm.

- If we halved the cross-sectional area A, the current is halved for the same potential difference; hence resistance is doubled.



- If we doubled the length L, the potential difference across its ends will double while current stays the same. Hence resistance doubles.



Resistivity

Example:

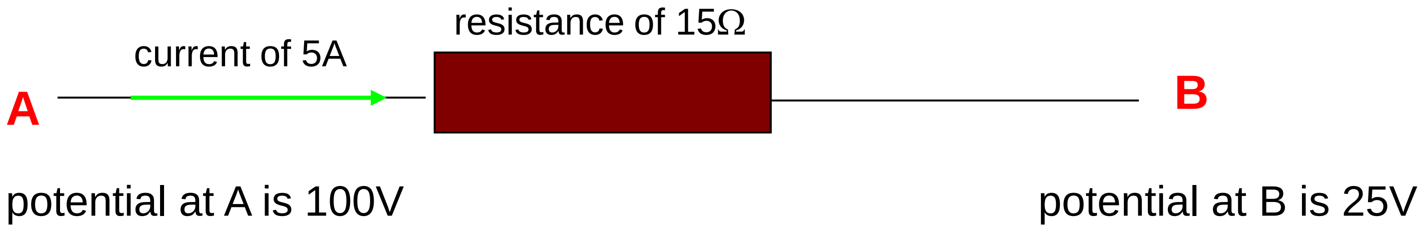
The resistivity of copper is 3.3 x 10^{-7} Ωm. Calculate the resistance of a 100m length of wire of cross-sectional area 1.0 mm^2.

$$R = \frac{\rho l}{A} = 3.3 \times 10^{-7} \times \frac{100}{10^{-6}} = 33\Omega$$

Potential difference across a resistor

- The defining equation for resistance can be rewritten as V = IR; which says that if a current flows through a resistor, then there must be a potential difference across the ends of the resistor.

  A resistor is thus said to *drop the potential*.



Potential difference (or potential drop) across resistor = IR = 75V

Electric Power

Derivation of power dissipation formulae

- Whenever an electric charge Δq moves through a resistor in time Δt such that there exists a potential difference V across the resistor, work is being done. This work done is W = VΔq.
- Power dissipated in a time Δt is defined as

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

Substituting W =VΔq, we get

$$P = \frac{V\Delta q}{\Delta t}$$

Since $I = \frac{\Delta q}{\Delta t}$, therefore

$$P = VI$$

$$P = VI$$

Electric Power

4. This power manifests itself in thermal energy and/or work performed by an electrical device.
5. In a device obeying Ohm's Law, we can use $R = \frac{V}{I}$ to rewrite the formula for power in equivalent ways:

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

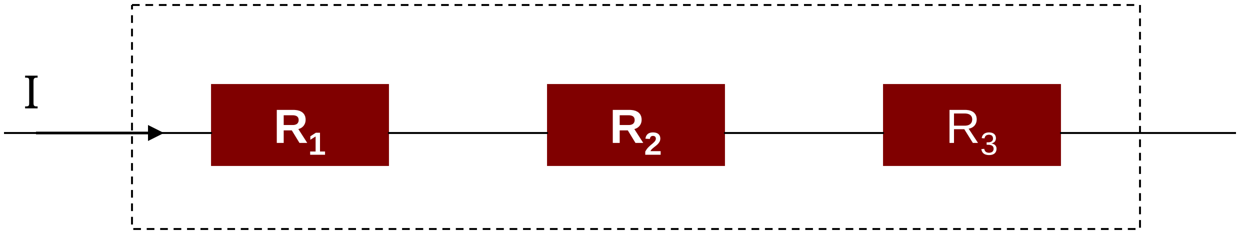
$$P = I^2 R$$

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

Simple electric circuits

(A)Series circuits

$$R = R_1 + R_2 + R_3 + \ldots$$



Three resistors in series

The resistors have the *same current* through them.

The potential difference across the resistors is

$V_1 = IR_1$, $V_2 = IR_2$, $V_3 = IR_3$

The sum of the potential difference is thus

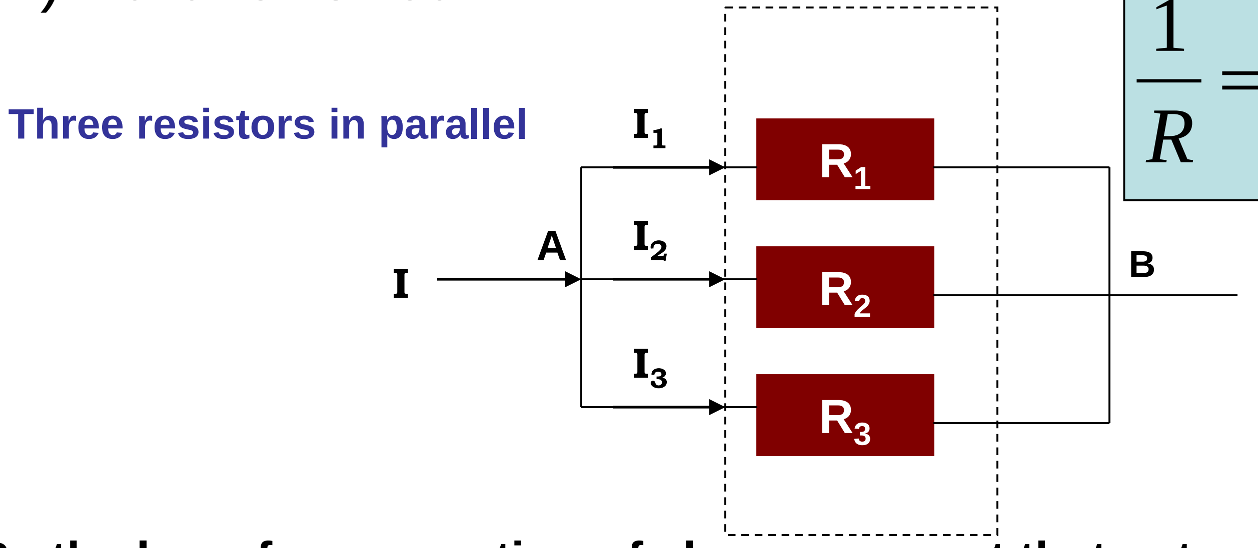
$V = IR_1 + IR_2 + IR_3 = I(R_1 + R_2 + R_3) = I\ \mathbf{R_{total}}$

If we replace the three resistors by a *single* resistor of value

$R_1+R_2+R_3$, the same current and p.d. exist between.

$\mathbf{R_{total} = R_1 + R_2 + R_3 + \ldots\ldots = \Sigma R_i}$ where *i takes values of 1, 2,3, …*

(B) Parallel Circuit



$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$$

By the law of conservation of charge, current that enters a junction must be the same as the current that leaves the junction.

Hence at the junction A, we must have $I = I_1 + I_2 + I_3$

Furthermore we note that the left ends of the three resistors are at the same potential (the potential at A) and the right ends are all at the potential of B. Let V be the common potential difference.

Thus $I_1 = V/R_1$, $I_2 = V/R_2$, $I_3 = V/R_3$

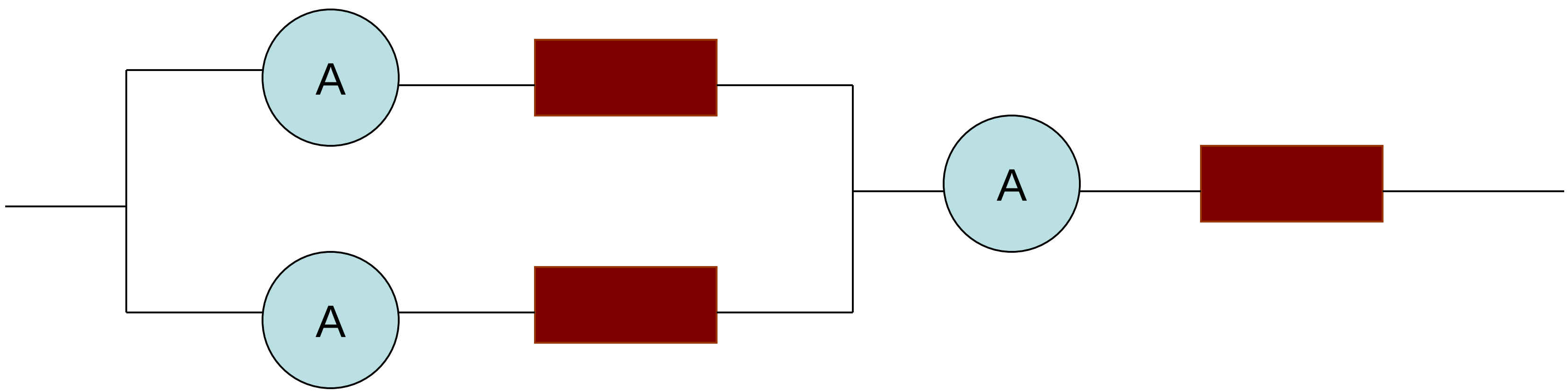
and so $I = V\,(1/R_1 + 1/R_2 + 1/R_3) = V/R_{total}$

If we replace the three resistors in the box with a *single* resistor, then its value would be

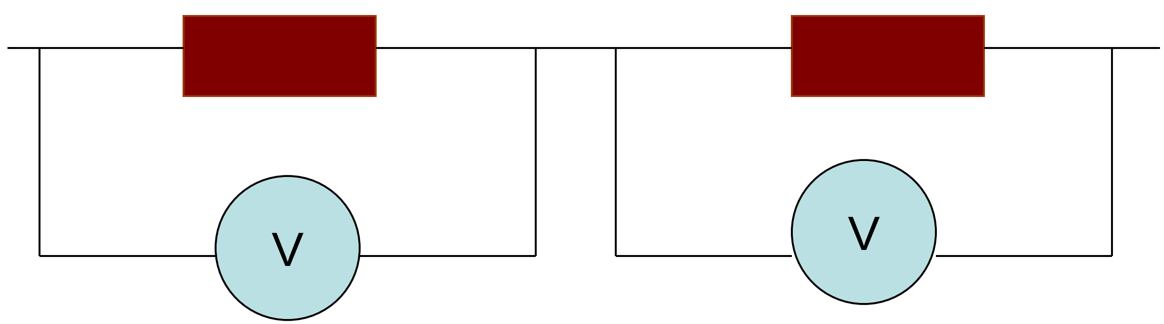
$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

Ammeters & Voltmeters

1. The current through a resistor is measured by an ammeter, which is connected in series to the resistor.

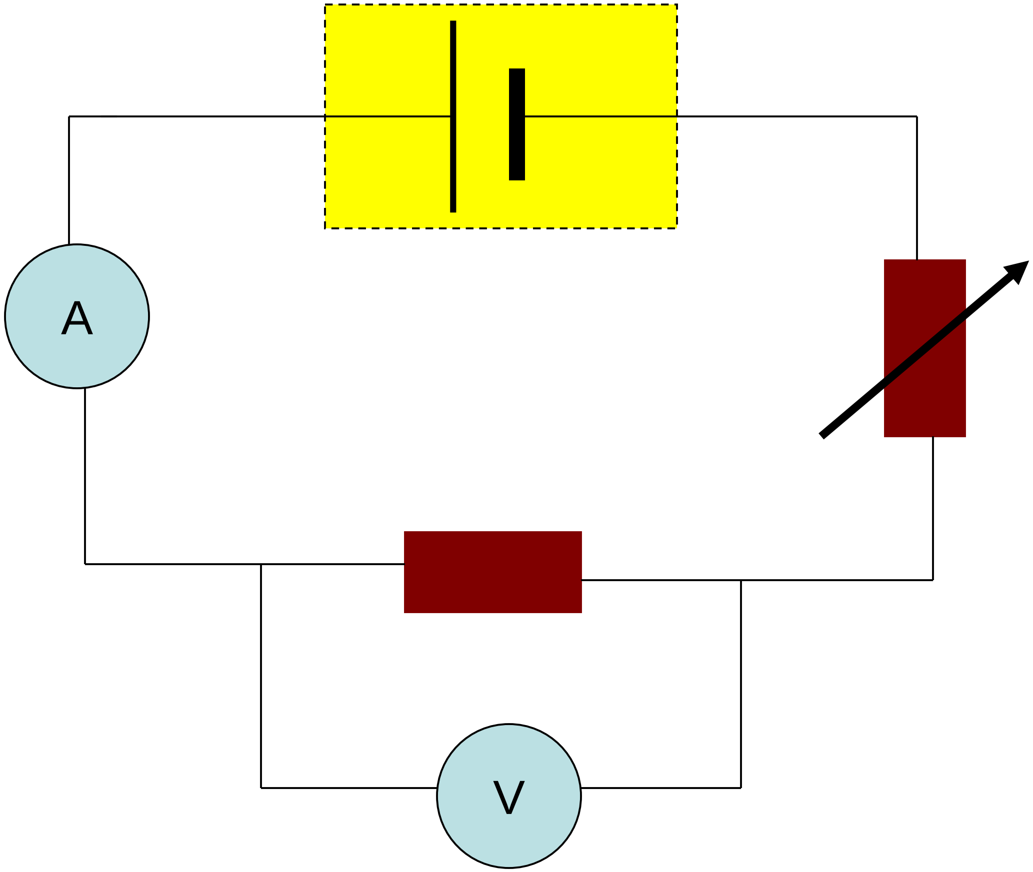


2. The ammeter itself has a small resistance. However an *ideal ammeter has zero resistance*.



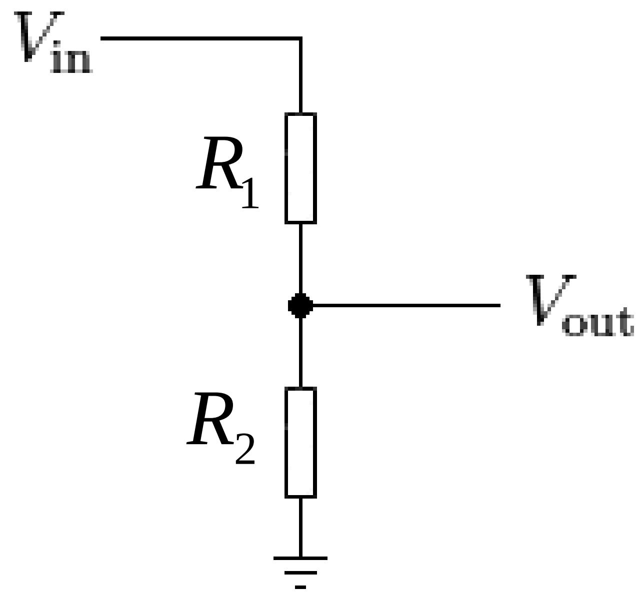
3. The potential difference across the ends of a resistor is measured by a voltmeter, which is connected in *parallel* to the resistor.

4. An ***ideal** voltmeter* has *infinite resistance* (in practice about 50 kΩ) which means that it takes no current when it is connected to a resistor.



Note: Real ammeters and voltmeters have their own resistance. A common mistake is to assume the current or potential difference remains constant after adding a voltmeter or ammeter to the circuit.

The Potential Divider Circuit



The potential divider is so called because two resistors 'divide up' the potential difference of a battery or source.

You can calculate the 'share' taken by one resistor using the ratio of resistances.

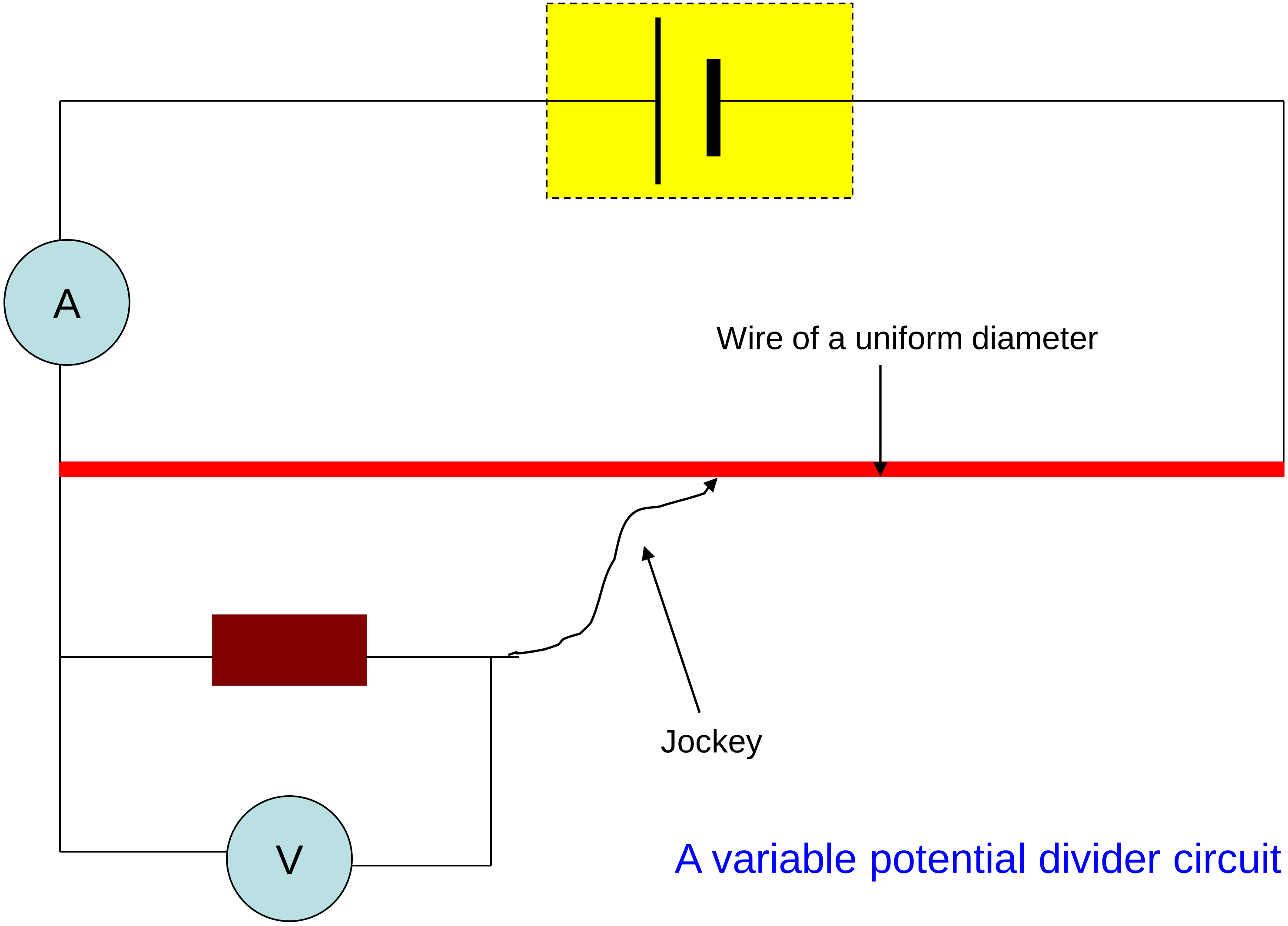
In the case shown, V_{out} measures the p.d. across R_2.

Note that V_{in} is actually the potential difference across both R_1 and R_2 in combination.

$$V_{out} = V_{in}\left(\frac{R_2}{R_1 + R_2}\right)$$

Note: Many circuit problems may be solved by regarding the circuit as a potential divider.

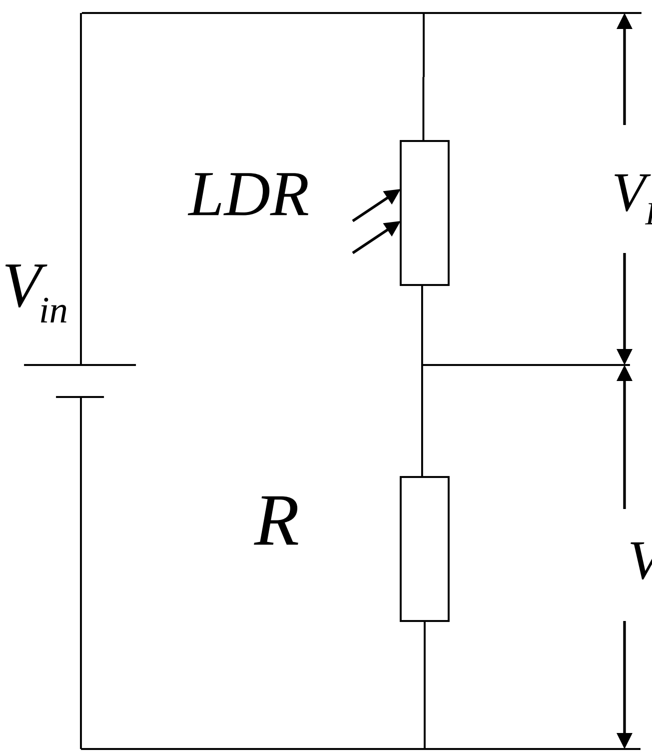
A Variable Potential Divider Circuit (Potentiometer)



A variable potential divider circuit

Sensors used in a potential divider circuit

<u>Light dependent resistor (LDR):</u> An LDR is a device whose resistance depends on the amount of light shining on its surface. An increase in light intensity will result in a decrease in the resistance of the LDR (and vice versa).



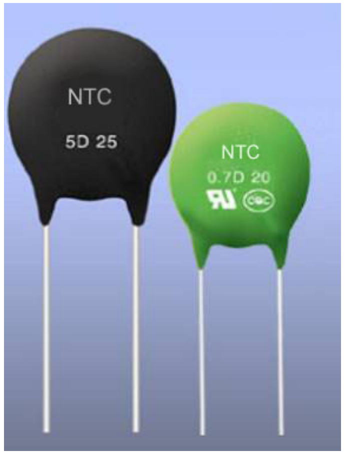
$$V_{LDR} = V_{in}\left(\frac{R_{LDR}}{R_{LDR}+R}\right)$$

$$V_R = V_{in}\left(\frac{R}{R_{LDR}+R}\right)$$

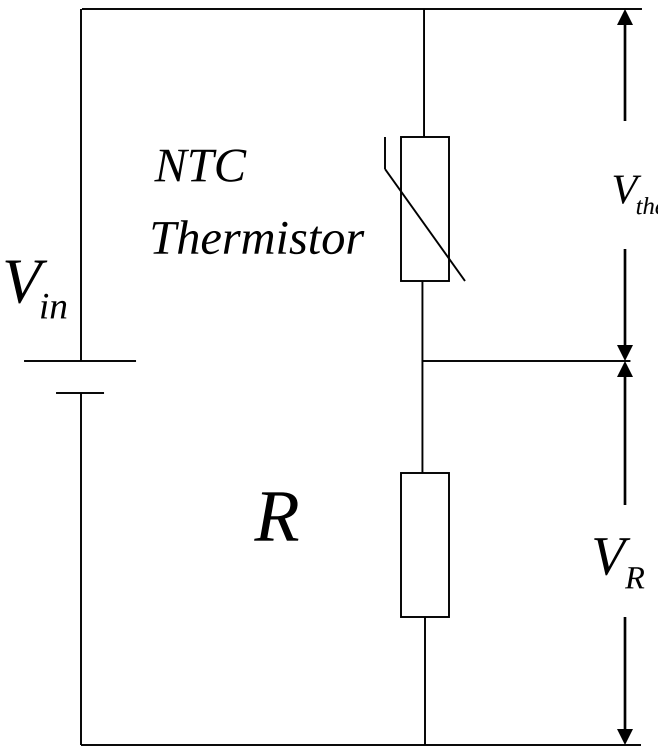
An increase in light intensity on the LDR will result in a decrease in R_{LDR}, therefore V_{LDR} will decrease and V_R will increase.

A decrease in light intensity will result in an increase in R_{LDR}, therefore V_{LDR} will increase and V_R will decrease.

Sensors used in a potential divider circuit



Thermistor: This is a device whose resistance depends on the temperature. Most thermistors are semi-conducting devices that have a negative temperature coefficient (NTC). The resistance of a NTC thermistor decreases with increasing temperature.



$$V_{thermistor} = V_{in}\left(\frac{R_{thermistor}}{R_{thermistor} + R}\right)$$

$$V_R = V_{in}\left(\frac{R}{R_{thermistor} + R}\right)$$

An increase in temperature will result in a decrease in $R_{thermistor}$, therefore $V_{thermistor}$ will decrease and V_R will increase.

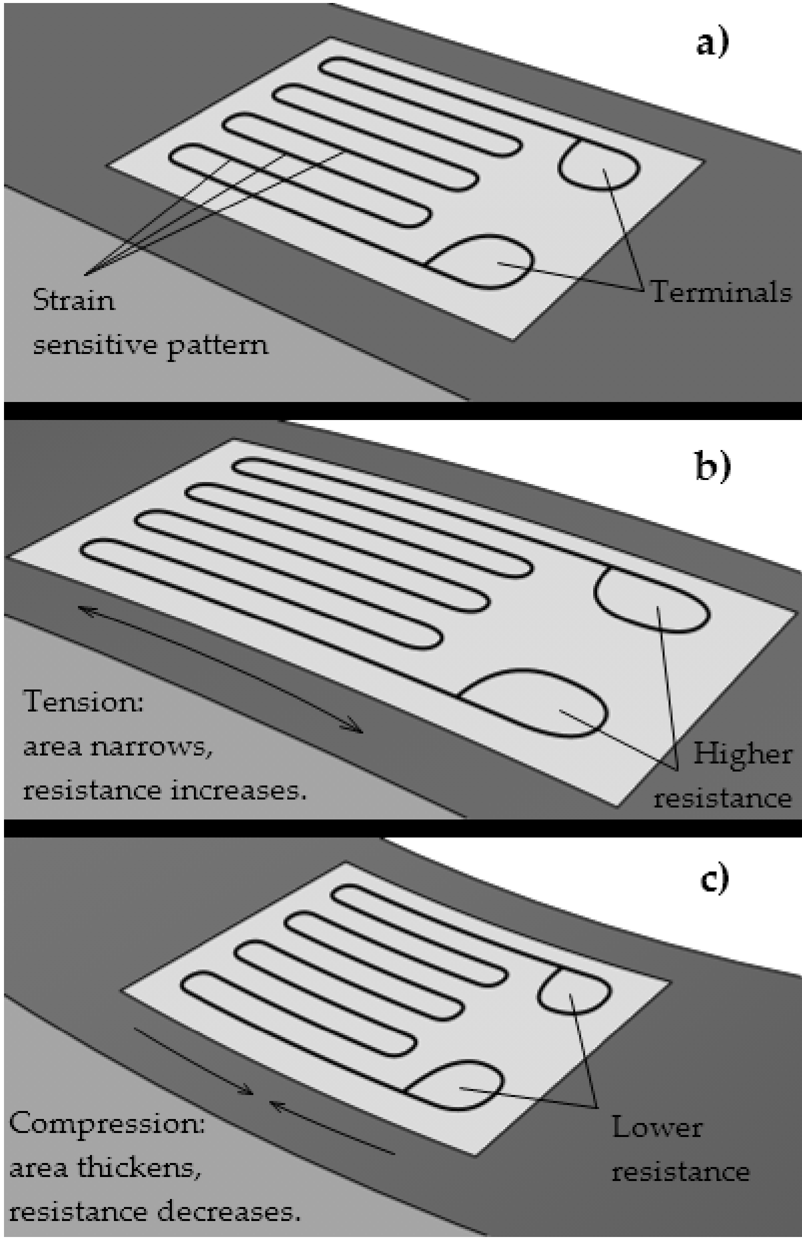
A decrease in temperature will result in an increase in $R_{thermistor}$, therefore $V_{thermistor}$ will increase and V_R will decrease.

Sensors used in a potential divider circuit

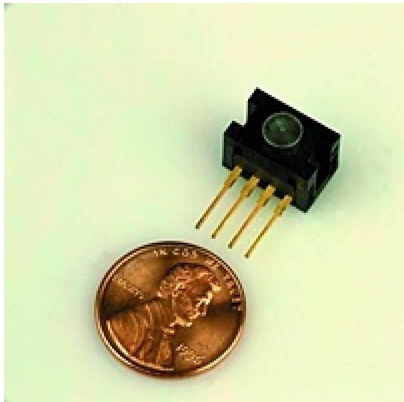
<u>**Strain Gauge:**</u> This is a device whose resistance will change depending on the change in length due to a small extension or compression of the device.

A typical **foil strain gauge** arranges a long, thin conductive strip in a zig-zag pattern of parallel lines such that a small amount of stress in the direction of the orientation of the parallel lines results in a multiplicatively larger strain over the effective length of the conductor—and hence a multiplicatively larger change in resistance—than would be observed with a single straight-line conductive wire.

An extension will result in a reduction of the cross sectional area of the wire and therefore increase its resistance (and vice versa).



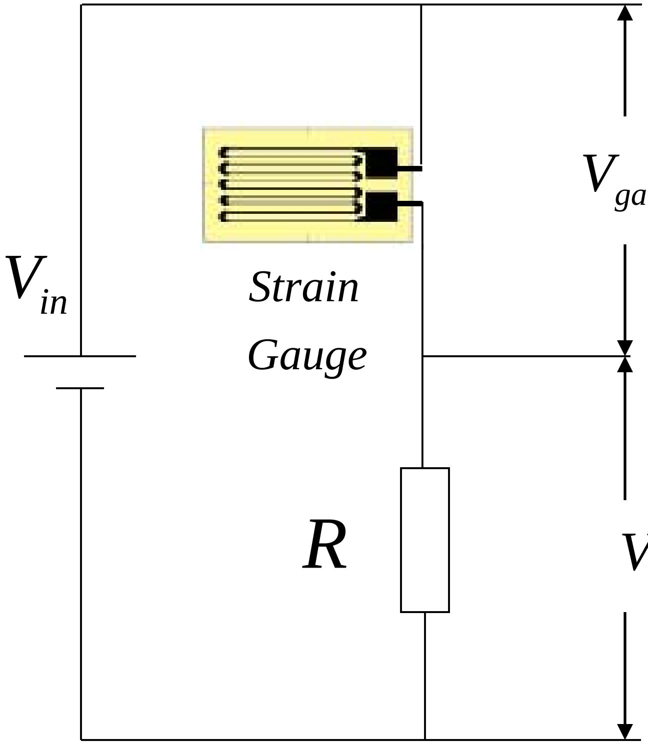
Sensors used in a potential divider circuit



For measurements of small strain, semiconductor strain gauges, so called **piezoresistors**, are normally used.

Note that all strain gauges are temperature dependend.

The strain gauge can be used in a potential divider circuit as shown below:

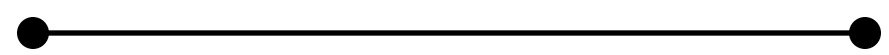
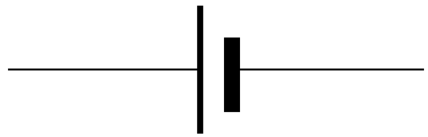
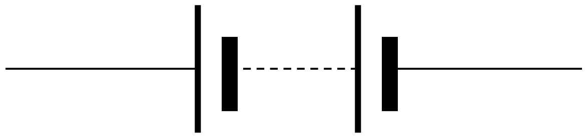
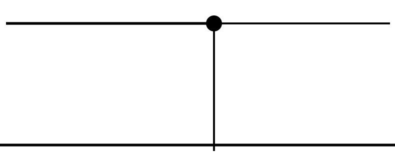
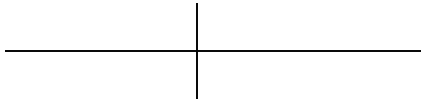


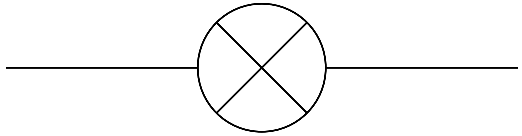
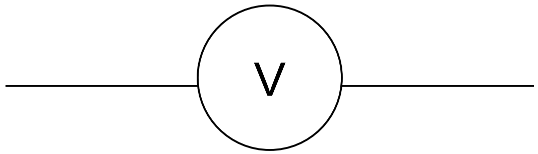
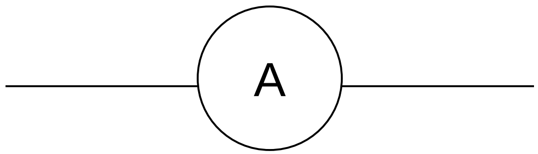
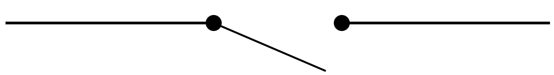
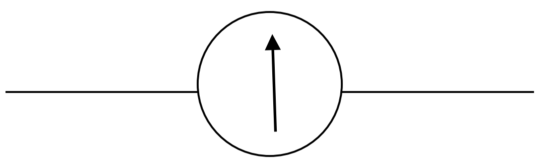
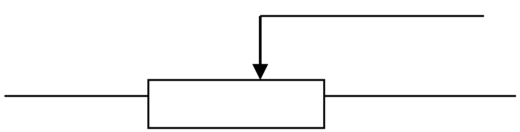
$$V_{gauge} = V_{in}\left(\frac{R_{gauge}}{R_{gauge}+R}\right)$$

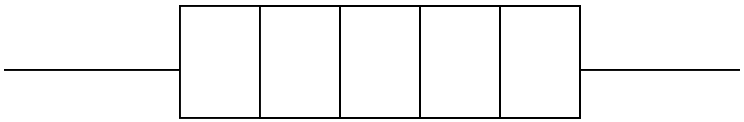
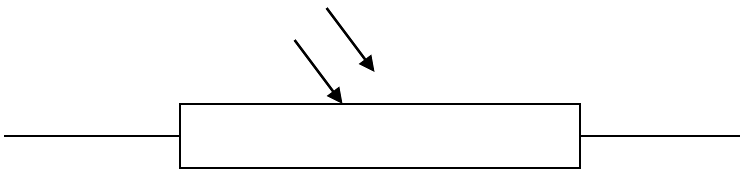
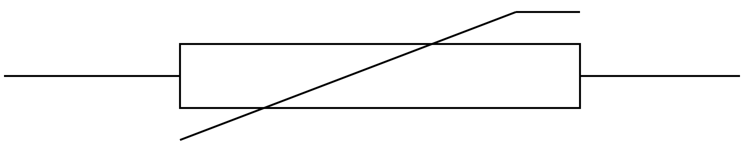
$$V_R = V_{in}\left(\frac{R}{R_{gauge}+R}\right)$$

A increase in length of the gauge will result in an increase in R_{gauge}, therefore V_{gauge} will increase and V_R will decrease.

A decrease in length of the gauge will result in a decrease in R_{gauge}, therefore V_{gauge} will decrease and V_R will increase.

Symbols	Component Name
	Connection lead
	cell
	Battery of cells
	resistor
	Power supply
	Junction of conductors
	Crossing conductors (no connection)

Symbols	Component Name
	Filament lamp
	Voltmeter
	Ammeter
	Switch
	a.c. supply
	Galvanometer
	Potentiometer

Symbols	Component Name
	Heating element
	Light-dependent Resistor (LDR)
	Thermistor

Worked Examples

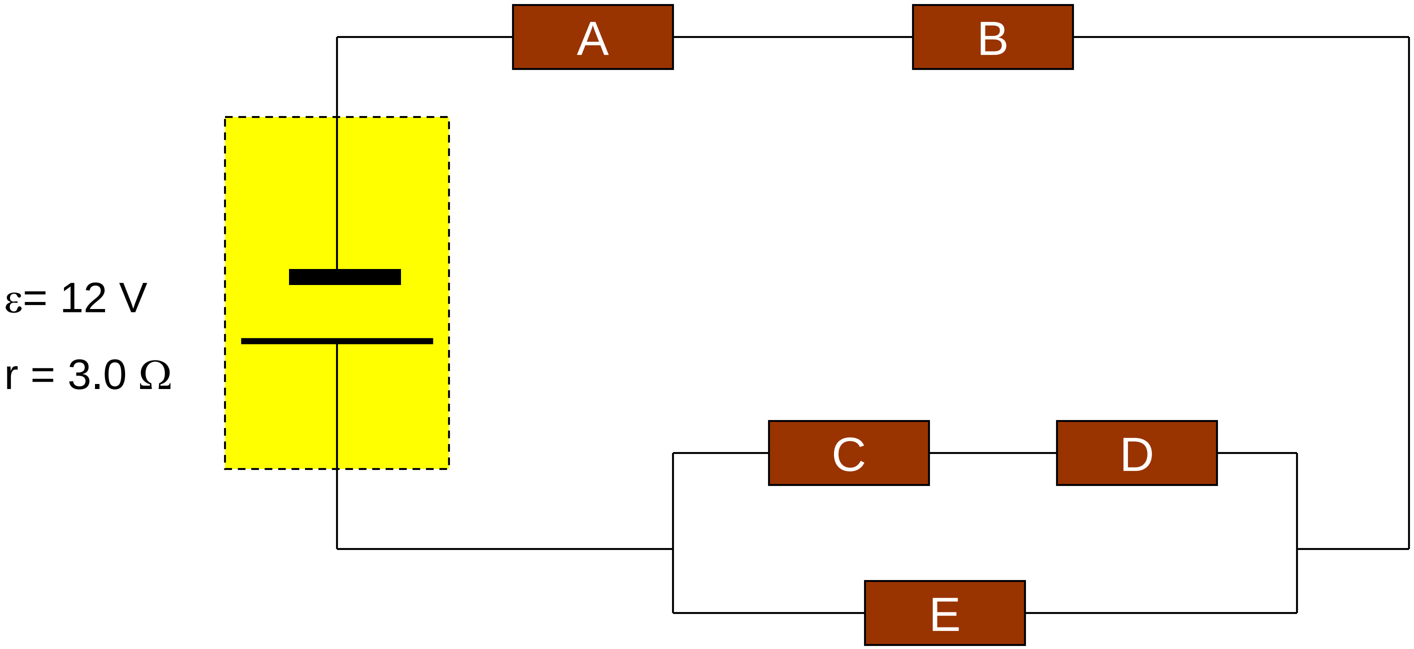
1. A toaster is rated at 1200 W and a mixer as 500 W, both at 220 V.

   (a) If both appliances are connected to a 220 V source, what current does each appliance draw? (5.45 A & 2.27 A)

   (b) How much energy do these appliances use if both work for one hour?(1.7 kWh or 6.1×10^6 J)

2. Calculate the current in each of the resistors in the circuit shown. What is the total energy dissipated in one hour? A = 60.0 Ω, B = 57.0 Ω, C = 40.0 Ω,

   D = 20.0 Ω, E = 60.0 Ω (0.08 A, 0.08 A, 0.04 A, 0.04 A, 0.04 A, 3460J)

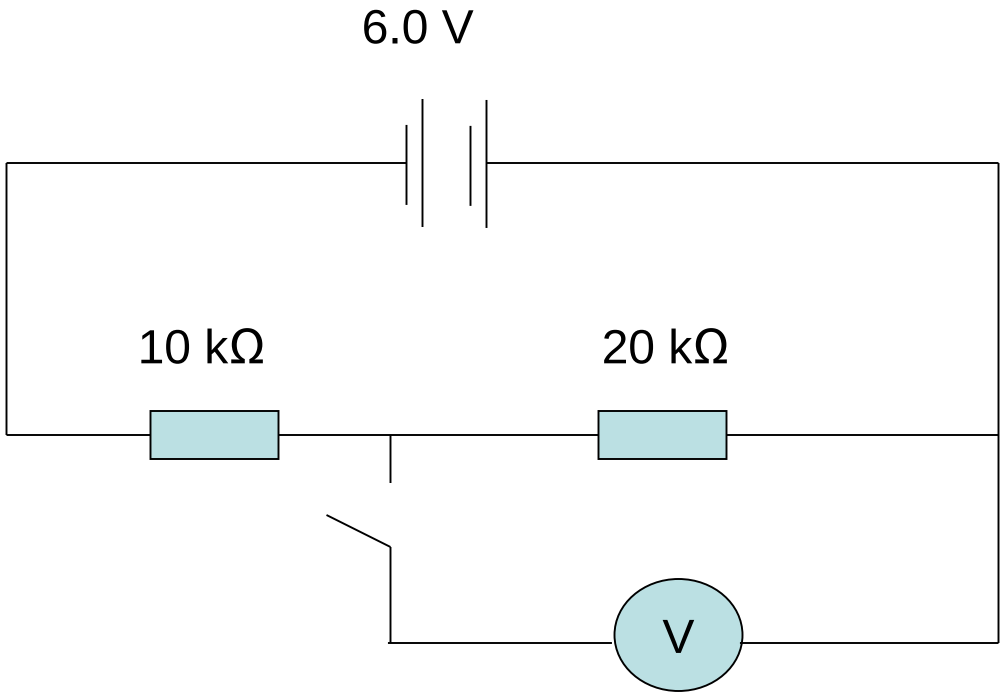


Worked Examples

3. In the circuit below, the voltmeter has a resistance of 20 kΩ. Calculate

(a) the p.d. across the 20 kΩ resistor with the switch open

(b) the reading on the voltmeter with the switch closed.



(a) $$\text{p.d} = \frac{20\times10^3}{(20\times10^3+10\times10^3)}\times 6.0 = 4.0V$$

(b) resistance of 20 kΩ resistor and voltmeter combination, R is given by:

$$\frac{1}{R} = \frac{1}{20\times10^3}+\frac{1}{20\times10^3}$$

$$R = 10\ \text{k}\Omega$$

$$\therefore\ \text{p.d.} = \frac{10\times10^3}{(10\times10^3+10\times10^3)}\times 6.0 = 3.0V$$

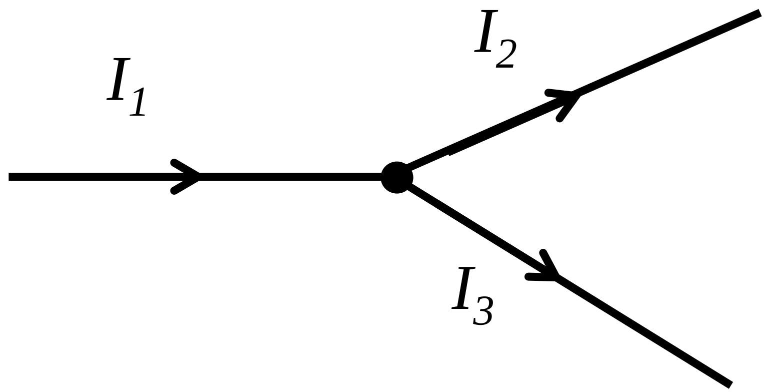
Note: The addition of the voltmeter changed everything. The effective resistance of the 20 kΩ resistor in parallel to the voltmeter was reduced to 10 kΩ. The total resistance of the entire circuit was also changed from 30 kΩ to 20 kΩ.

Kirchhoff's First Law

Kirchhoff's First law states that <u>at a junction, the algebraic sum of the currents is zero</u>.

i.e. the sum of the currents going into the junction is equal to that coming out from it.

Mathematically, $\Sigma I = 0$



$I_1 + (-I_2) + (-I_3) = 0$

$\Rightarrow I_1 = I_2 + I_3.$

Kirchhoff's First Law

Kirchhoff's First law states that <u>at a junction, the algebraic sum of the currents is zero</u>.

i.e. the sum of the currents going into the junction is equal to that coming out from it.

Mathematically, $\Sigma I = 0$

Conservation of charge, in electrical terms

Kirchhoff's Second Law

Kirchhoff's Second law states that round any closed loop, the algebraic sum of the e.m.f.s of the cells is equal to the algebraic sum of the p.d. of all the individual components.

Mathematically, $\Sigma E = \Sigma V$

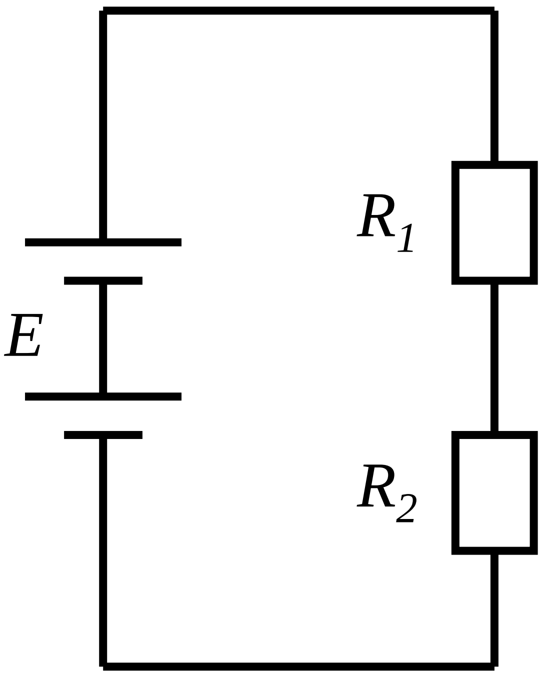
$$\Sigma E = \Sigma IR$$

Conservation of energy,
in electrical terms

Proof

From the law of conservation of energy,

Power supplied by the source	=	Power dissipated by the resistors



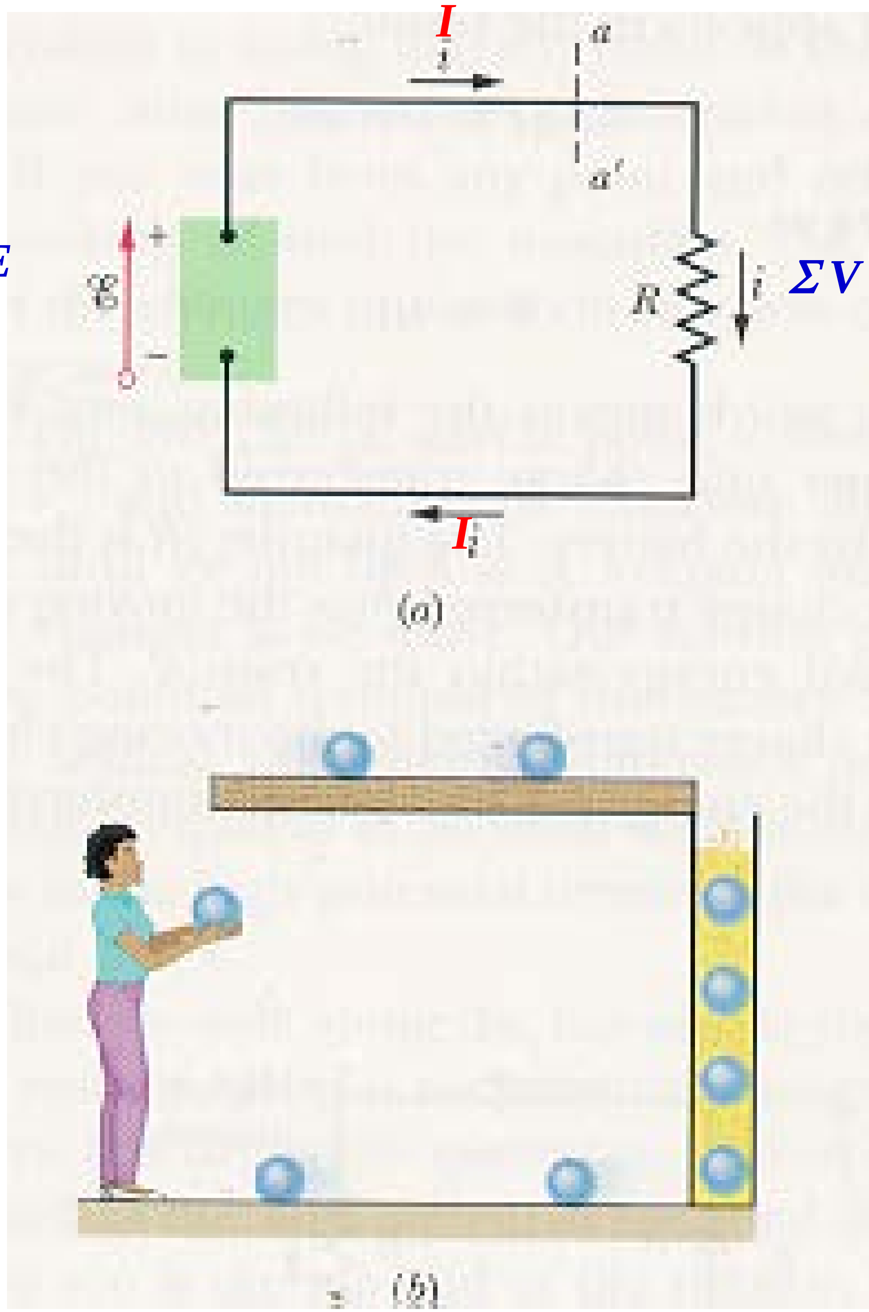
$$I\,E = I^2R_1 + I^2R_2$$

$$E = IR_1 + IR$$

i.e. $E = V_1 + V_2$

or $\Sigma E = \Sigma V$

ΣE



$\Sigma V = \Sigma IR$

$\Sigma I = 0$

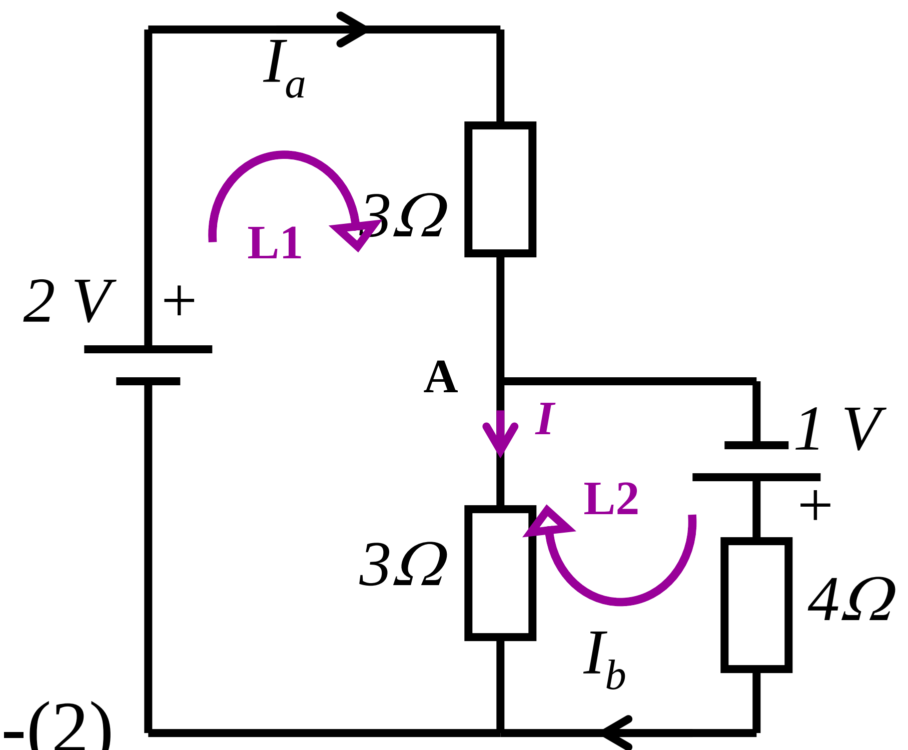
$\Sigma E = \Sigma V$

Application of Kirchhoff's laws

Steps:

1. Assign current directions.
2. Choose and assign loop direction.
3. Apply Kirchhoff's law to the loop taking direction of loop to be positive.

Example (a):



Apply KI to junction **A**:

$I_a = I + I_b$

$I = I_a – I_b$ --(1)

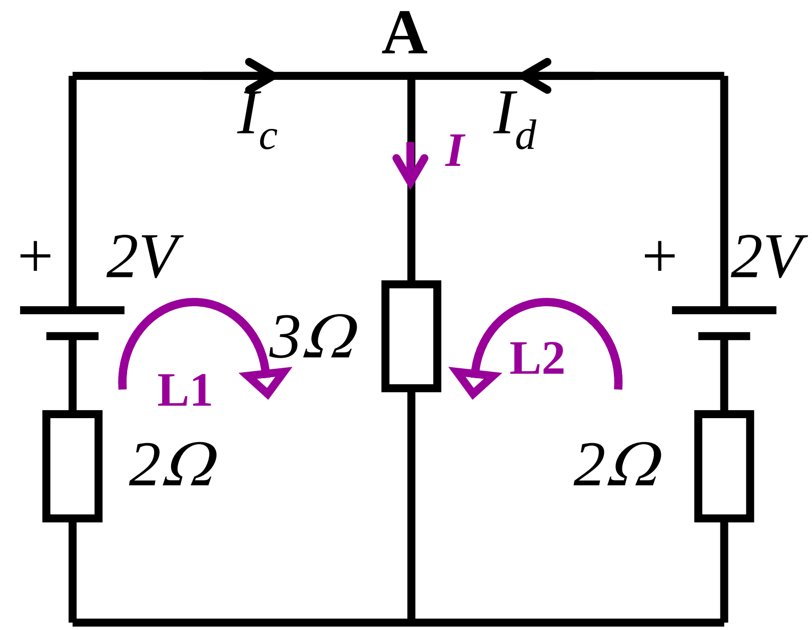
Apply KII to:

L1: $2 = 3\ I_a + 3\ (\ I_a - I_b)$ --(2)

L2: $1 = 4\ I_b - 3\ (\ I_a - I_b)$ --(3)

Solve (2) and (3), I_a = 0.52 A, I_b = 0.36A.

Example (b):



Apply KI to junction **A**:

$I = I_c + I_d$ --(1)

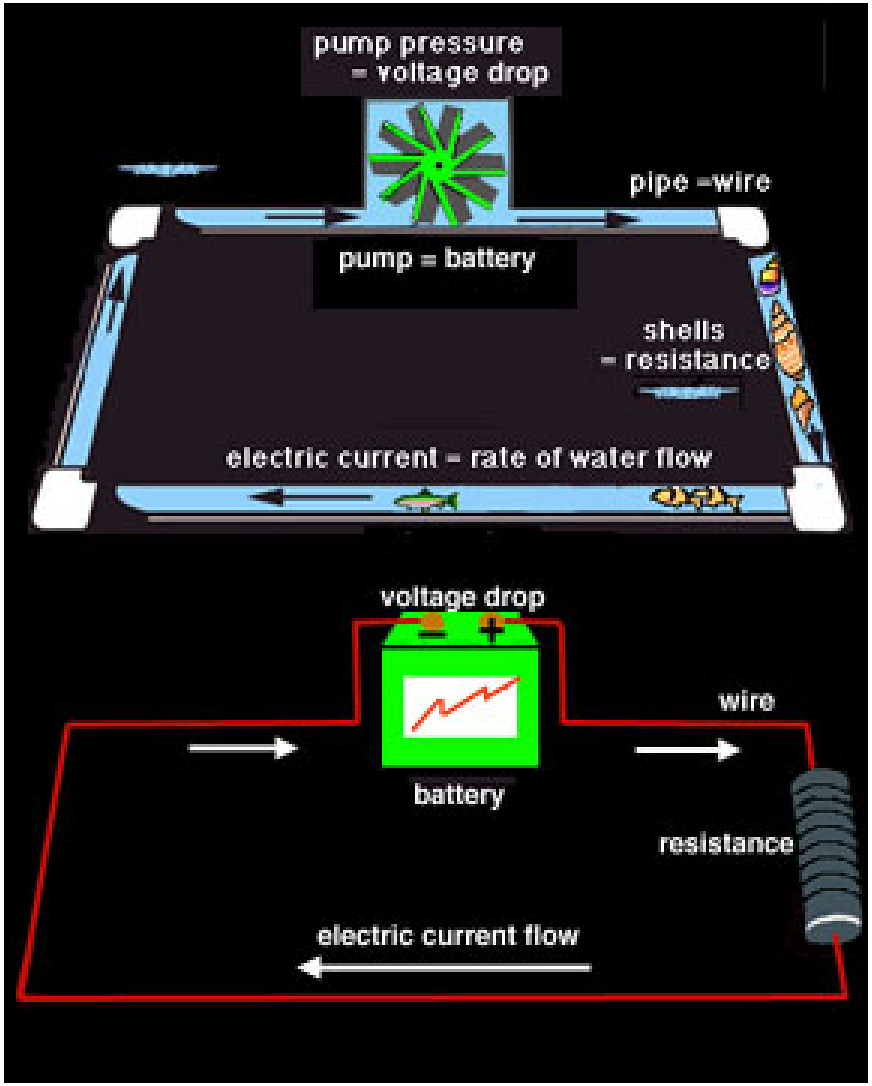
Apply KII law to:

L1: $2 = 3\,(I_c + I_d) + 2\,I_c$ --(2)

L2: $2 = 3\,(I_c + I_d) + 2\,I_d$ --(3)

Solve (2) and (3), $I_c = I_d = 0.25$ A.

5.3 Electric cells



5.3 Nature of Science

Long-term risks: Scientists need to balance the research into electric cells that can store energy with greater energy density to provide longer device lifetimes with the long-term risks associated with the disposal of the chemicals involved when batteries are discarded

Electromotive force *(e.m.f.)*

Definition: Electromotive force (e.m.f)

Energy converted from other forms (eg. chemical, mechanical) into electrical energy per unit charge within the source /

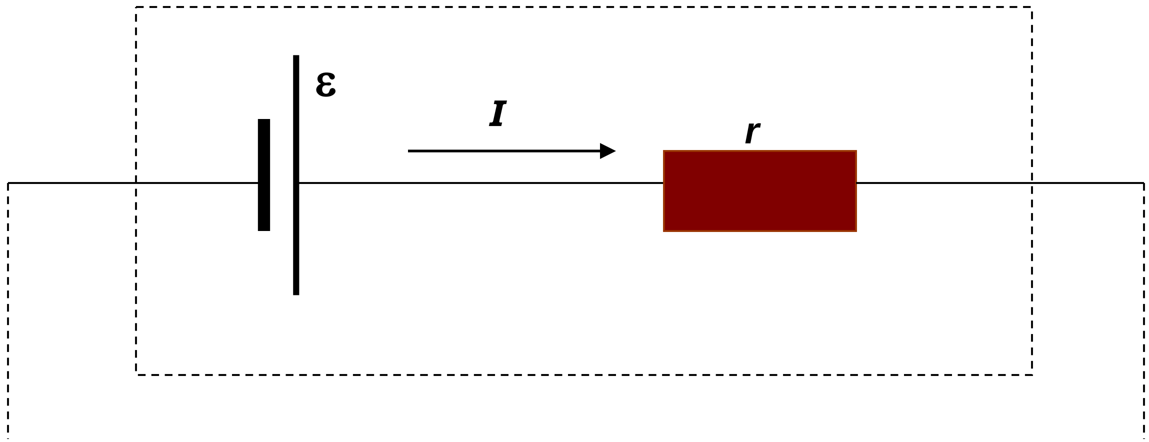
electrical power supplied by the source per unit current delivered by the source.

- In the case of a battery, the *work done* to move a *unit charge* across the battery is defined as the *e.m.f.*
- Thus e.m.f. has the same units as potential difference of the volts.

Internal Resistance

- When a 6V battery is connected in a circuit, some energy will be used up inside the battery itself. In other words, the battery has some ***internal resistance***. The rest of the energy will be dissipated in the components in the circuit.
- The energy difference per unit charge from one terminal of the battery to the other is less than the total made available by the chemical reactions in the battery.
- For historical reasons, the total energy difference per unit charge around a circuit is called the electromotive force.
- Remember that e.m.f. is *not* a force measured in Newtons but an energy difference per charge measured in volts.
- In practical terms, e.m.f. is exactly the same as potential difference if no current flows.

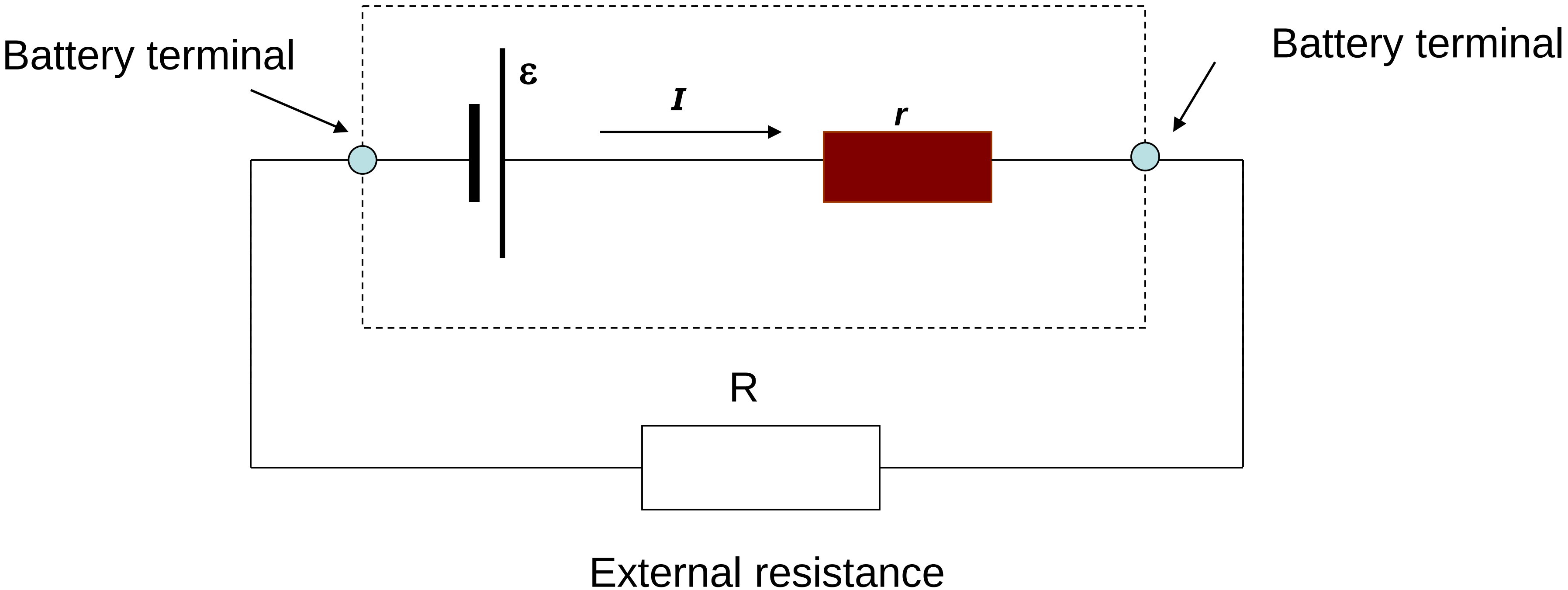
Internal Resistance



- The battery itself has an internal resistance *r* and we may assume that it is connected in series to the cell.
- If the current that leaves the battery is I, then the potential difference across the internal resistance is Ir. In other words, the internal resistance reduces the voltage from a value of ε to a value of ($\varepsilon - Ir$)
- The potential difference across the battery is thus V = $\varepsilon - Ir$. We see that

V = ε when $I = 0$. This gives an alternative but less precise definition of e.m.f.

Internal Resistance



$$\varepsilon = I \times R_{total}$$

$$\varepsilon = I(r + R)$$

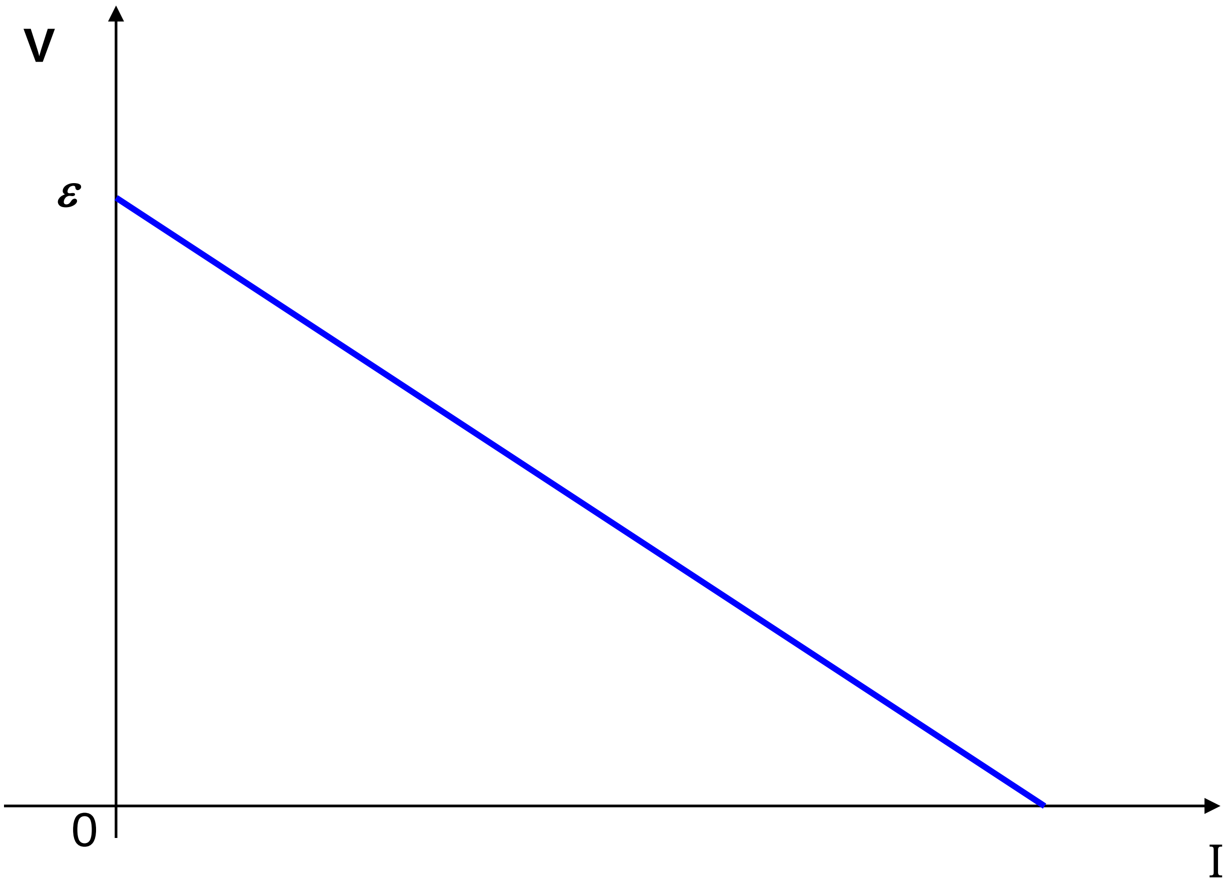
$$\varepsilon = Ir + IR$$

Terminal p.d.

$$IR = \varepsilon - Ir$$

“lost” volts

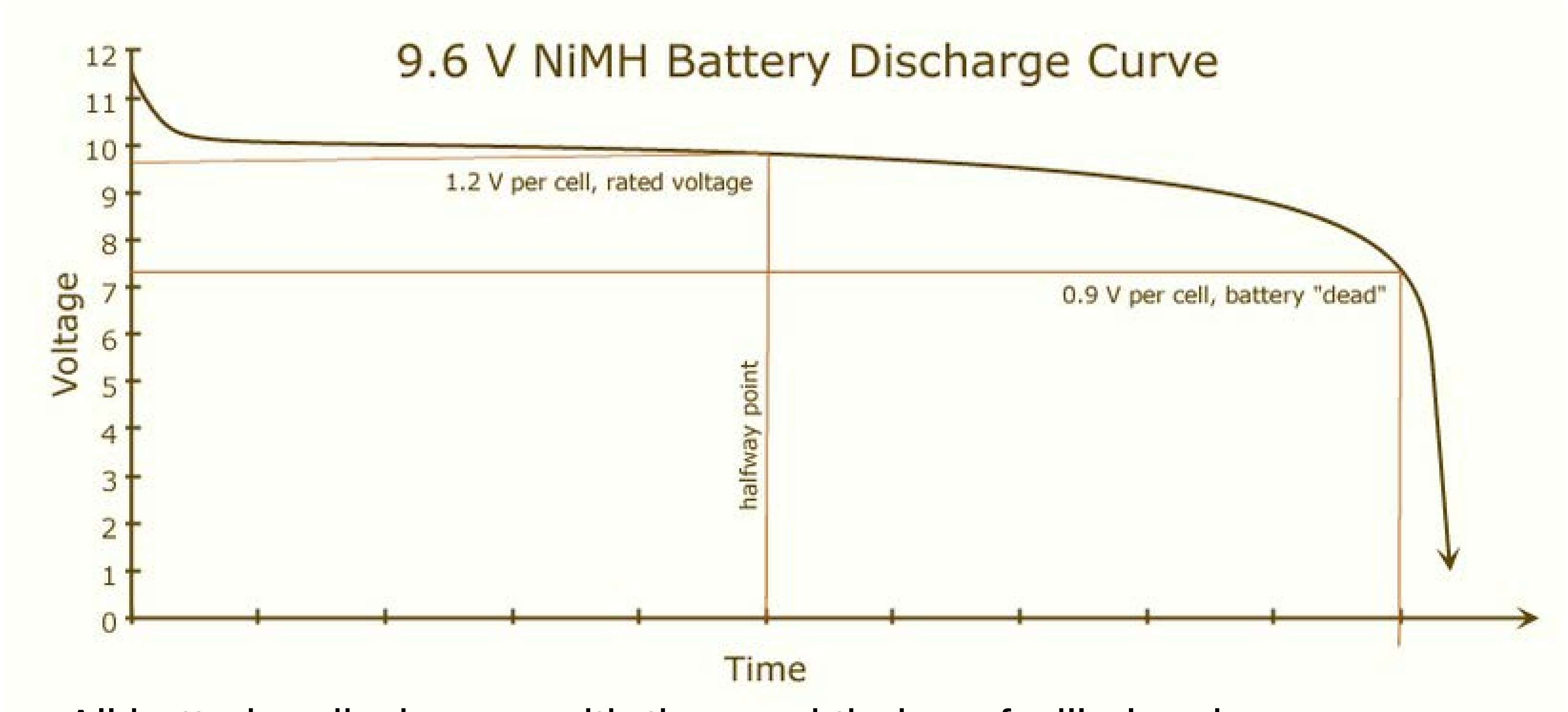
$$V = \varepsilon - Ir$$



$$V = \varepsilon - Ir$$

If we were to plot a graph of V against I, a straight line graph as shown with the y-intercept as the value of the e.m.f. of the cell ε ; and the gradient as the internal resistance *r*.

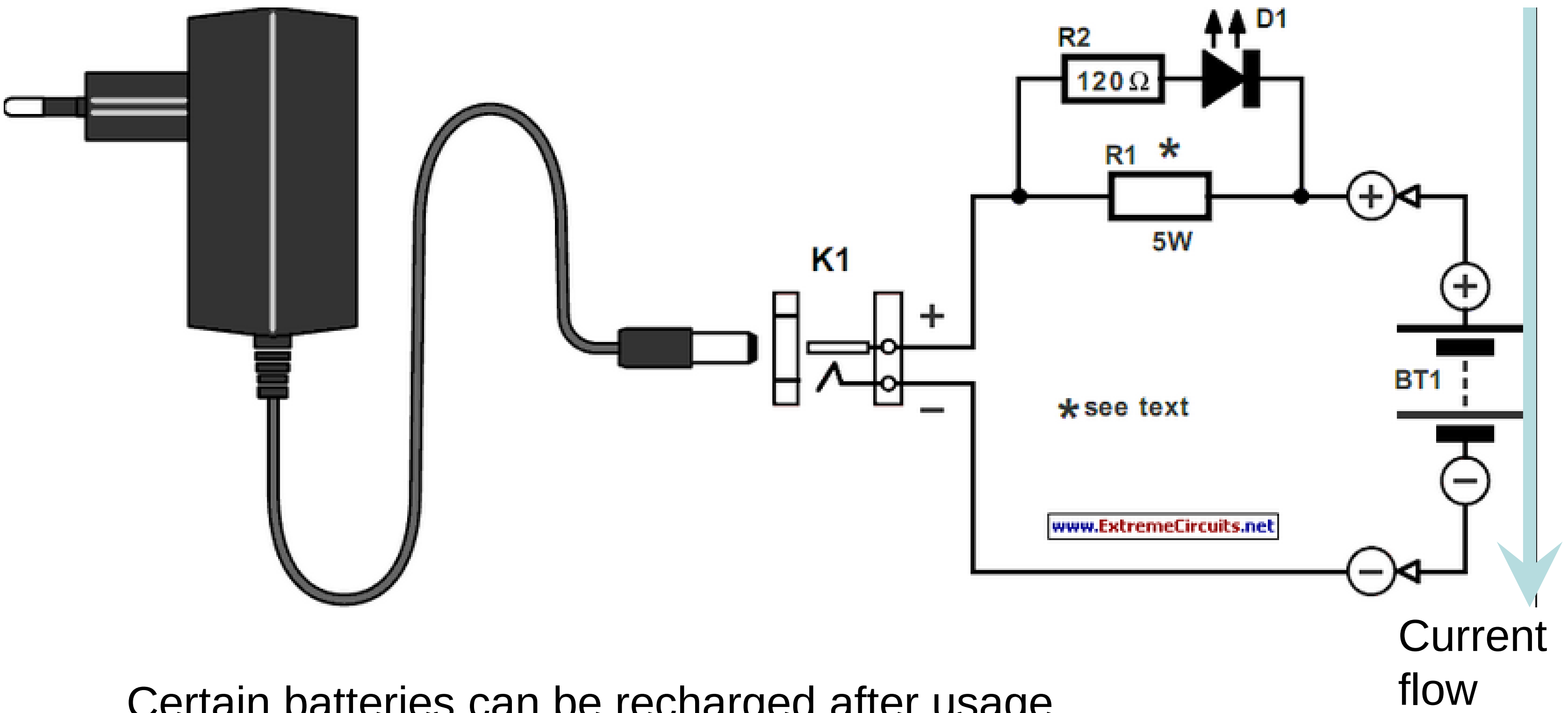
Battery Performance with Time



All batteries discharges with time and their emf will also decrease as the discharging occurs.

The discharge curve can be affected by temperature.

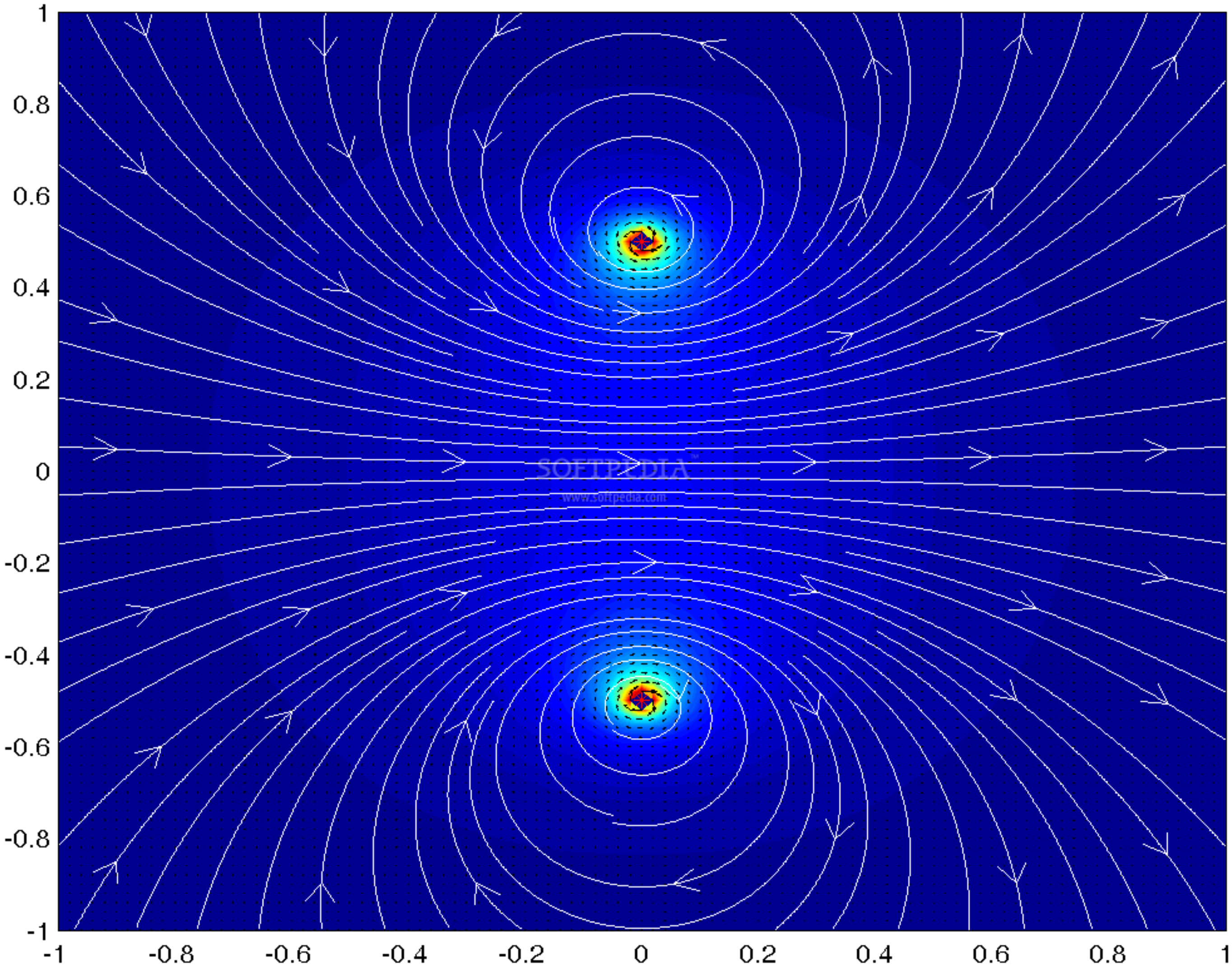
Battery Charging



Certain batteries can be recharged after usage.

It is important to note that during charging, the current flows into the positive terminal of the batteries, opposite to what happens during discharging.

5.4 Magnetic effects of electric current



Parts adapted from Giancoli Lecture Powerpoint, Chapter 5, EW

Lesson Objectives:

(A) Magnetic fields

1. State that moving charges give rise to magnetic fields
2. Draw and annotate magnetic field patterns due to currents (straight wire, flat circular coil, solenoid)

(B) Magnetic forces

1. Determine the direction of the force on a current-carrying conductor in a magnetic field.
2. Determine the direction of the force on a charge moving in a magnetic field.
3. Define the magnitude of the magnetic field strength B.
4. Solve problems involving the magnetic forces, fields, and currents.

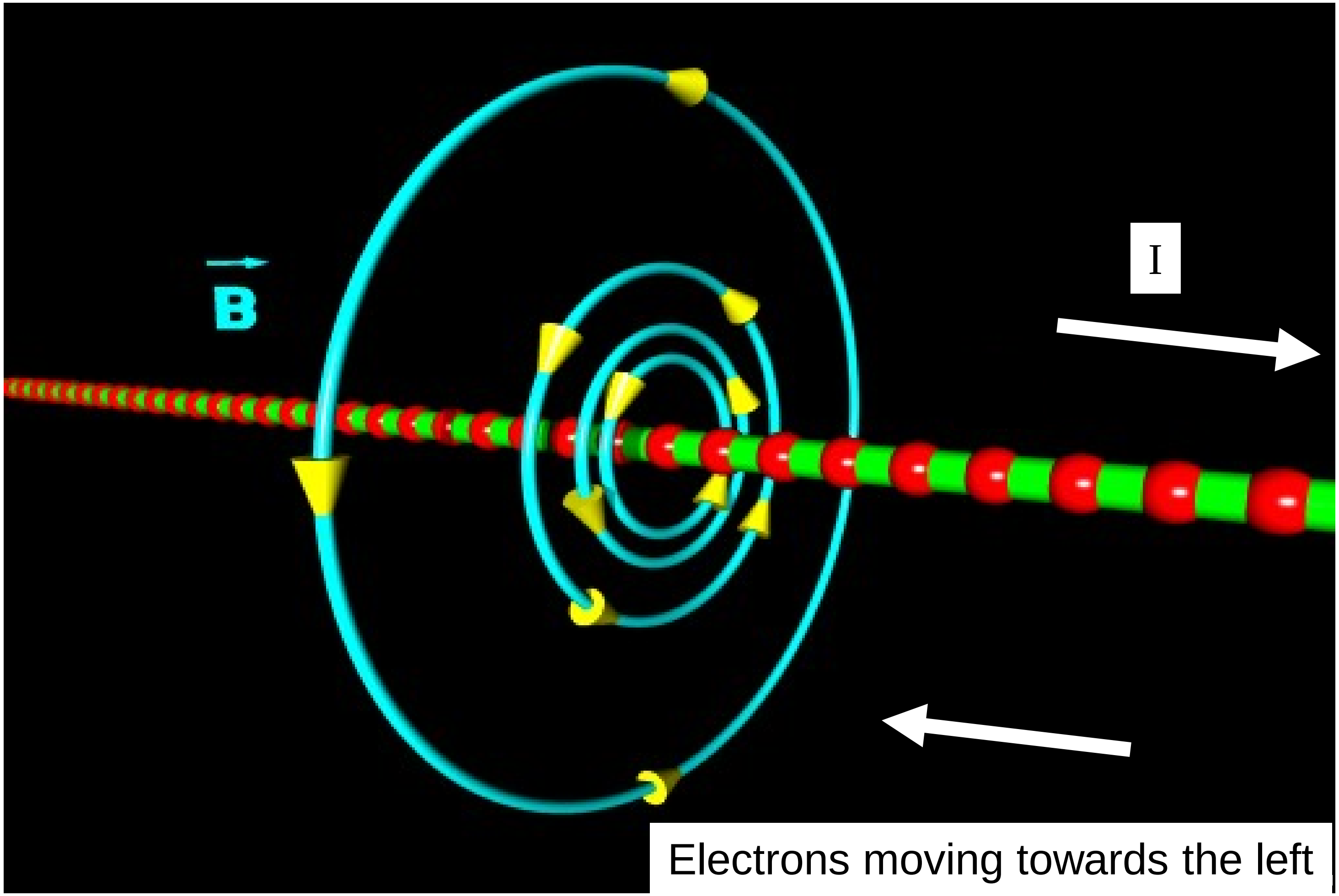
5.4 Nature of Science

Models and visualization: Magnetic field lines provide a powerful visualization of a magnetic field. Historically, the field lines helped scientists and engineers to understand a link that begins with the influence of one moving charge on another and leads onto relativity

A1. State that moving charges give rise to magnetic fields

All moving charges give rise to a magnetic field being produced.

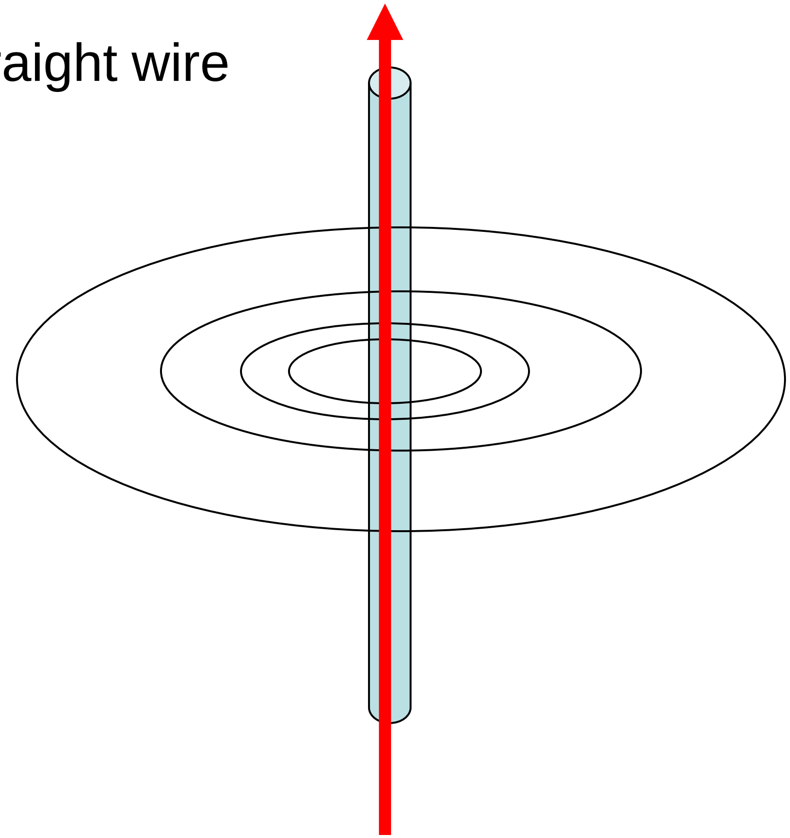
- An electric current in a current-carrying wire is due to electrons moving within the wire.
- The direction of conventional current is opposite to the direction of the electrons moving.



A2. Draw and annotate magnetic field due to current.

An electric current can also cause a magnetic field.

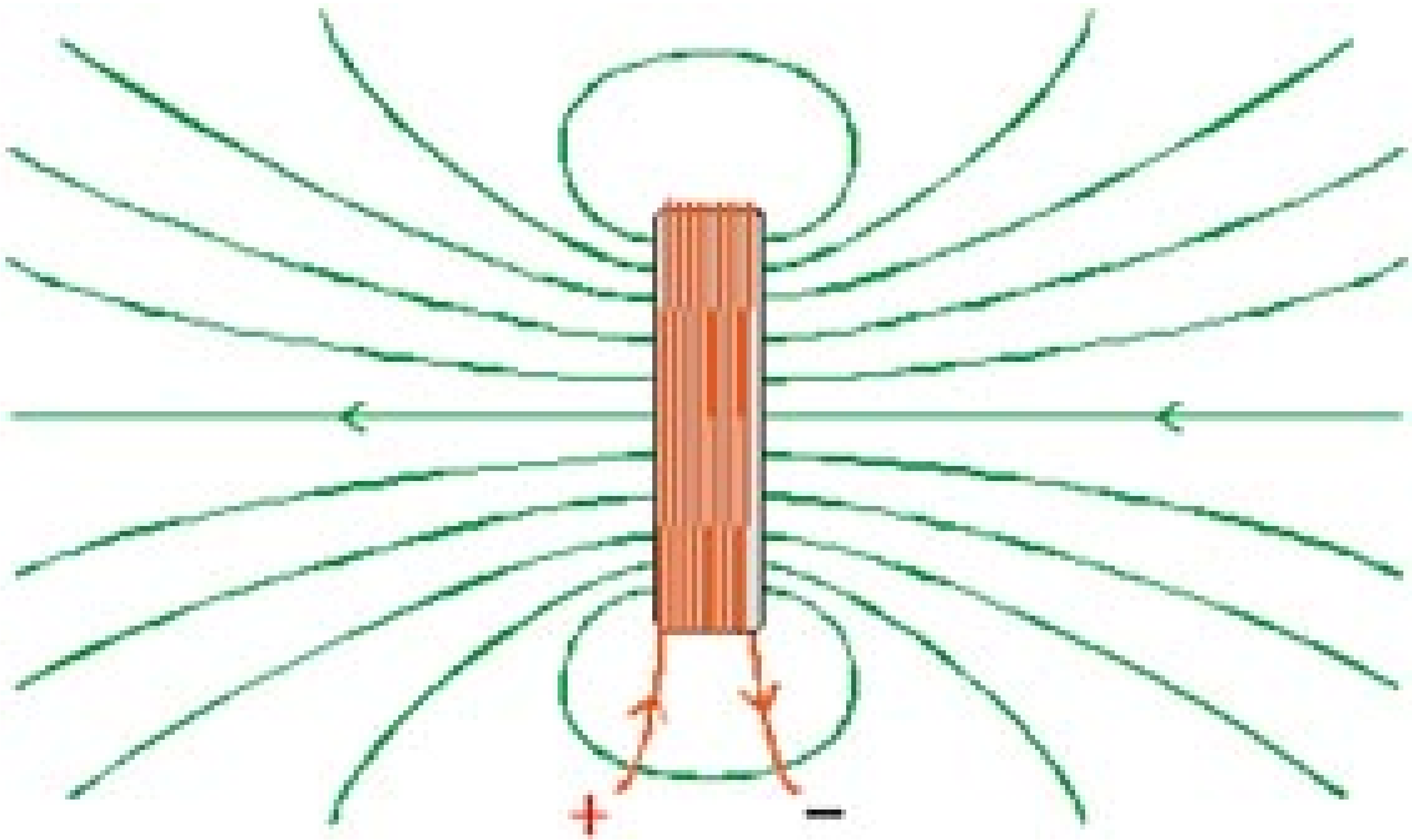
(a) fields due to a straight wire



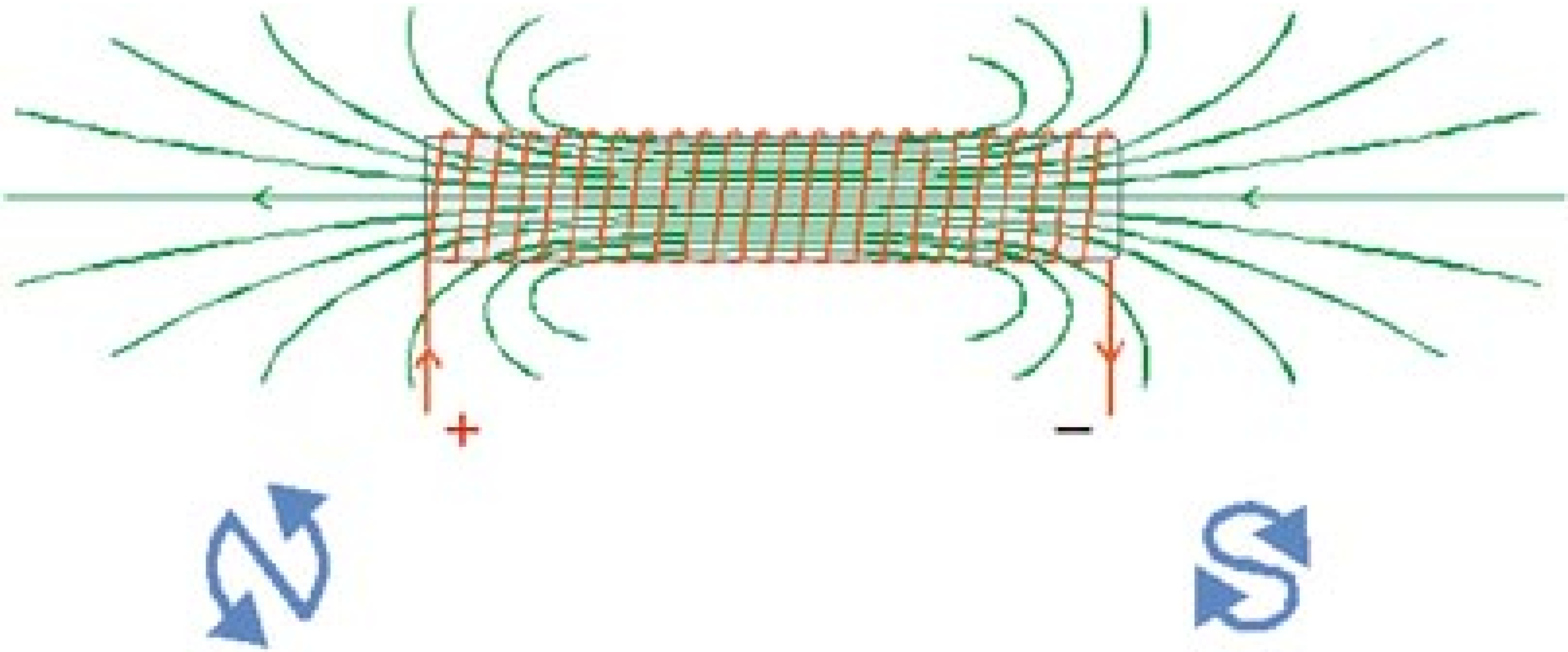
Question: Show the direction of the field lines which can be determined using the Maxwell's corkscrew rule or the Right hand grip rule.

The field lines are circular around the current-carrying wire. The direction of the field lines can be remembered with the right hand grip rule. If the thumb of the right hand is arranged to point along the direction of the current, the way the fingers curl will give the direction of the field lines.

(b) field due to a flat circular coil



(c) field due to a solenoid

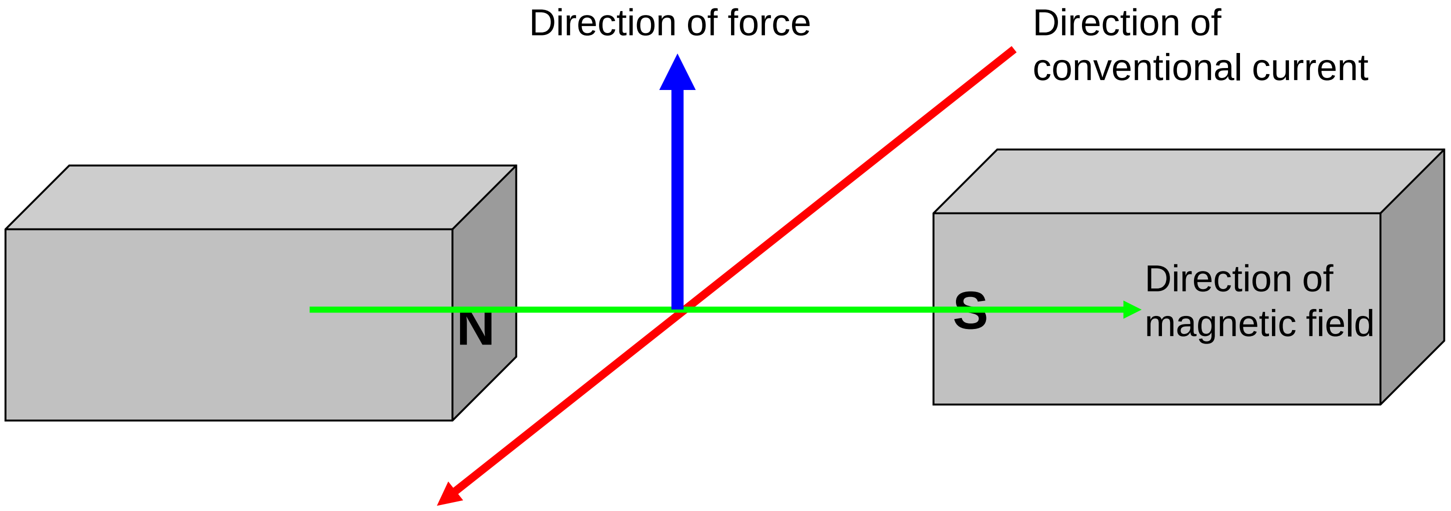


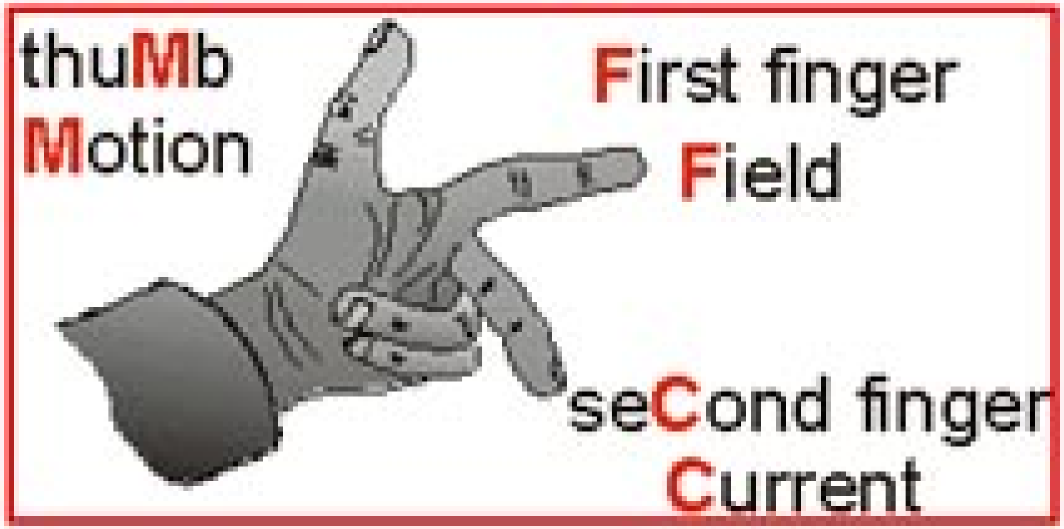
B1. Determine the direction of the force on a current-carrying conductor in a magnetic field.

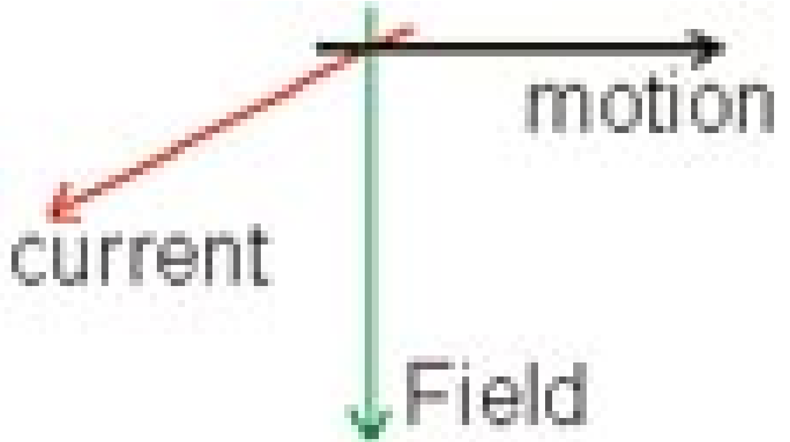
(a) When a current-carrying wire is placed in a magnetic field the magnetic interaction between the two results in a force. This is known as the motor effect.

(b) The direction of this force is at right angle to the plane that contains the field and the current as shown below.

(c) Fleming's left hand rule is used to determine the direction of the force.




thuMb
Motion
First finger
Field
seCond finger
Current


motion
current
Field

(d) Experiments show that the force F is proportional to:

- the magnitude of the magnetic field B,
- the magnitude of the current I,
- the length of the wire, L,
- the angle between the magnetic field and the current, θ.

(e) Hence F = B I L sin θ

(i) when the wire is placed parallel to the field so that $\theta = 0^o$, then $\sin 0^o = 0$; and hence there is no force on the wire.

(ii) when the wire is placed at right angle to the field so that $\theta = 90^o$, $\sin 90^0 = 1$; and hence the force on the wire is maximum at BIL.

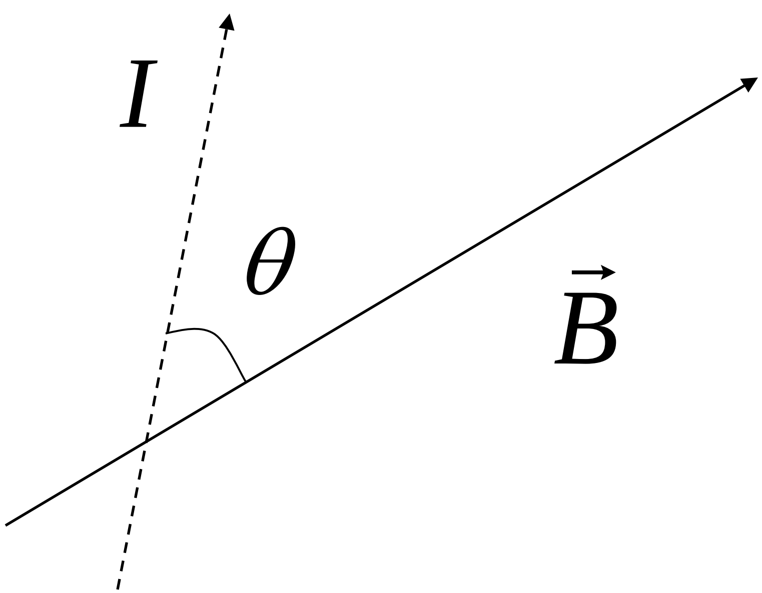
(iii) at any other angle between 0^o and 90^o, the force varies between zero and maximum value.

(f) $B = \dfrac{F}{IL\sin\theta}$. The unit of B is Tesla (T). Hence 1 T is defined as equal to 1 $N\ A^{-1}\ m^{-1}$.

Magnitude of the force on a current-carrying conductor in a magnetic field

$$F = BIL\sin\theta$$

B - the magnitude of the magnetic field,
I - the magnitude of the current,
L - the length of the wire,
θ - the angle between the current (wire) and the magnetic field.



B2. Determine the direction of the force on a charge moving in a magnetic field.

(a) A charge moving through a magnetic field also experiences a force. The force on the moving charge is always at right angle to the velocity of the charge. This means that the charge must move in a circular motion.

(b) The force on the charge is proportional to:

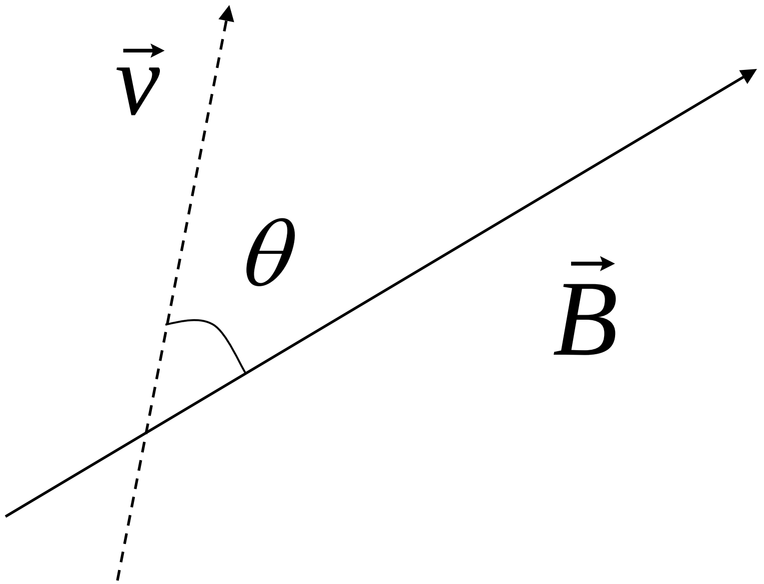
- the magnitude of the magnetic field B,
- the magnitude of the charge q,
- the velocity of the charge v,
- the angle between the velocity and the field θ.

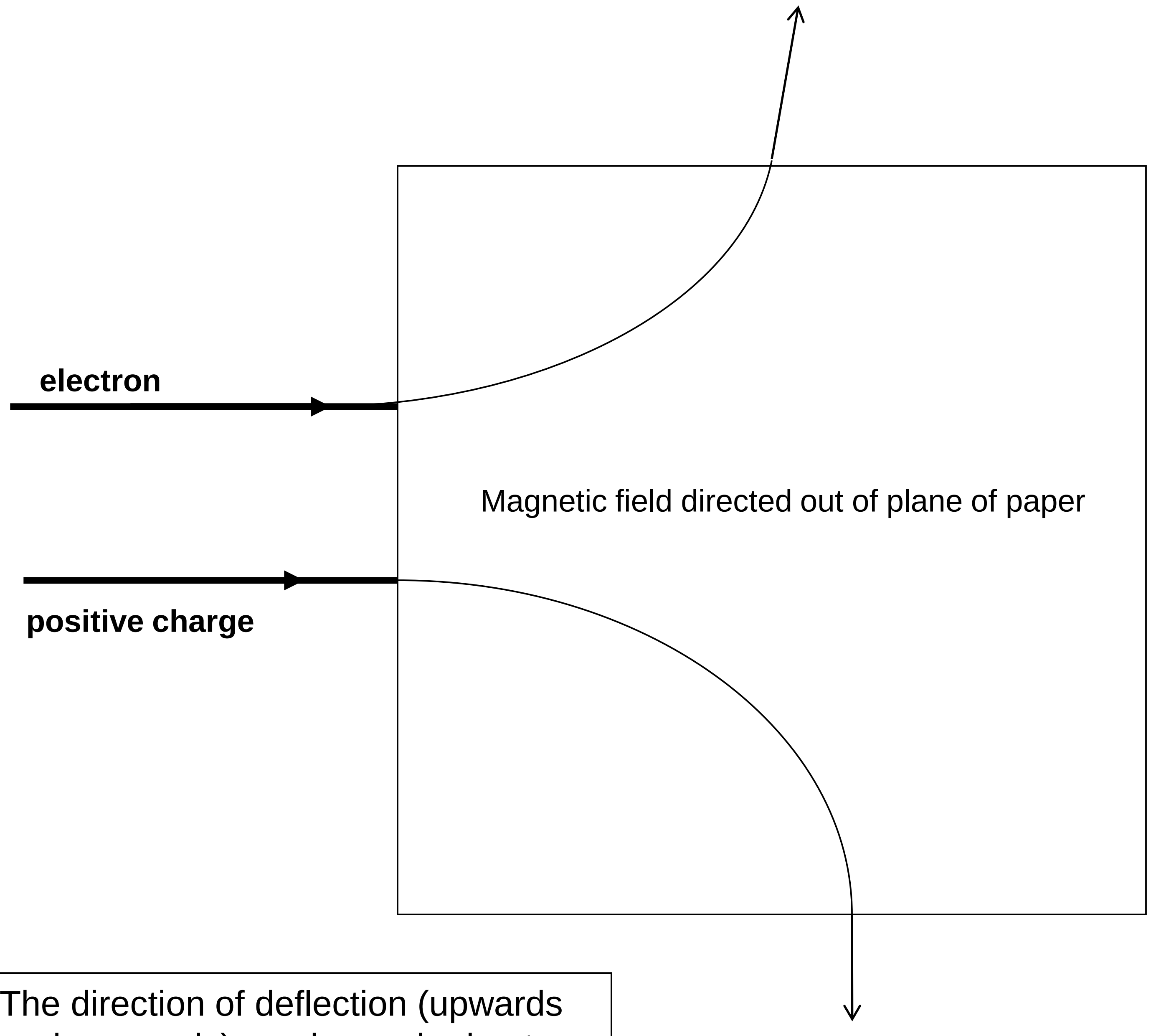
(c) Hence the force is given by $F = B\,q\,v\sin\theta$. The force is zero when the charge is moving parallel to the field or if it is stationary. If the charge is moving at right angle to the field, the force is greatest.

Magnitude of the force on a charge moving in a magnetic field.

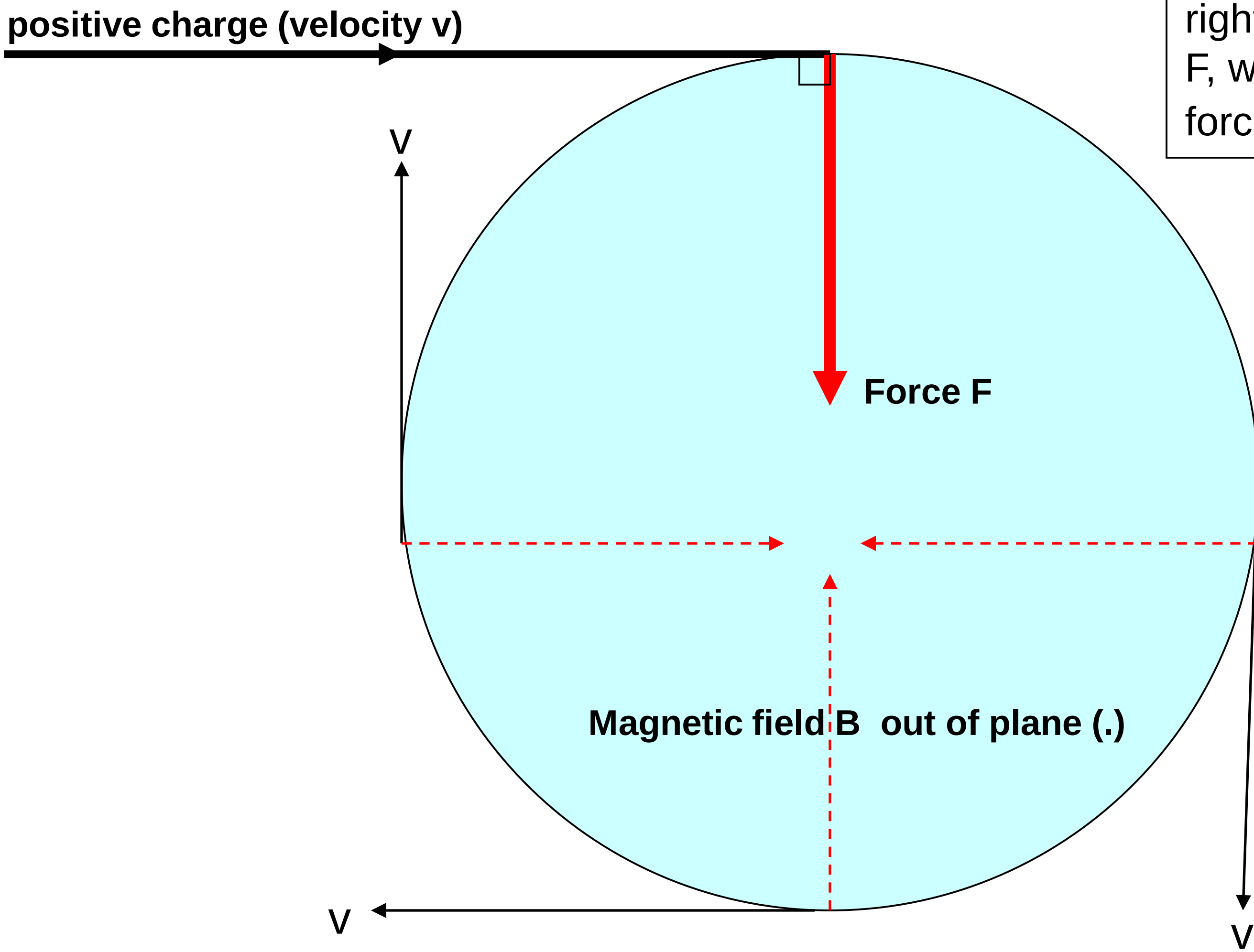
$$F = qvB\sin\theta$$

B - the magnitude of the magnetic field,
q - the magnitude of the charge,
v - the velocity of the charge,
θ - the angle between the velocity and the field.





The direction of deflection (upwards or downwards) can be worked out using Fleming’s left hand rule (for positive charges).



Note: Since the velocity v is always at right angle to the force F, work done by this force is zero.

B3. Define the magnitude of the magnetic field strength B.
B4. Solve problems involving the magnetic forces, fields and currents.

(a) From $B = \dfrac{F}{IL\sin\theta}$ we can define the magnitude of magnetic field as the force on a wire carrying unit current and of unit length placed at right angle to the field. [Note that magnetic field strength is also known as magnetic flux density]

(b) Consider an electron of charge $q = 1.60\times10^{-19}$ C moving at 30^0 to a magnetic field of 0.30 T (Tesla) and at a velocity of 3.5×10^{6} ms^{-1}, the force on the electron will then be equal to $F = B\, q\, v \sin\theta = 8.4\times10^{-12}$ N.

(c) A wire of length 1 m placed at right angle to a magnetic field of strength 0.50 T with a current of 1 A will experience a force of $F = B\, I\, L \sin\theta$ = 0.50 N.