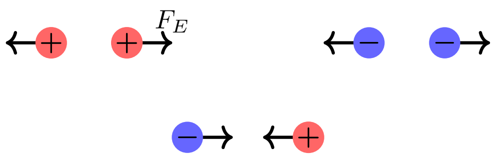
3. Electricity

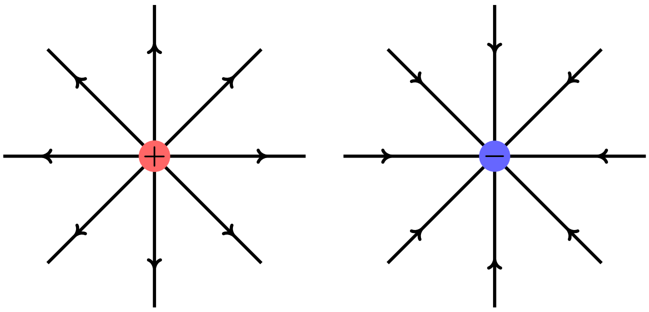
Electric Charge

Electric charge is a property of matter that experiences a force in an electric field and produces its own electric field. It is characterised by a magnitude and a sign, positive or negative. Like charges *repel*, unlike charges *attract*.



Electric charge is *conserved*, meaning the sum of electric charges in any closed system is constant. $\boxed{Q_{\text{tot.}} = \sum_i q_i}$

Electric field lines indicate the direction a positive charge experiences a force i.e. *away* from positive charges and *toward* negative charges.



Exercise 3.1. Which direction would a small positive charge placed at **X** move if

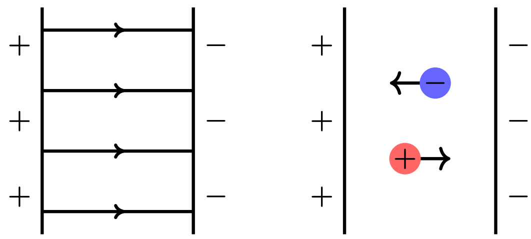
i. $q_a > 0$ and $q_b < 0$

ii. $q_a = q_b > 0$

iii. $q_a > q_b > 0$

How would the answers change if the charge placed at O was instead *negative*?

Example 3.2. Between two oppositely charged parallel plates a positive charge will move directly (in a straight line) from the positive to the negative plate, and a negative charge directly toward the positive plate.



Field lines Forces

Electrical current and circuits

Electric current I is electric charge Q transferred per unit time, or

$$\boxed{Q = It}$$

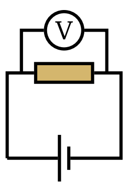
A current may be *direct* or *alternating*, meaning its direction switches e.g. 50 times a second for 50 Hz.

Circuits and potential difference (voltage, V)

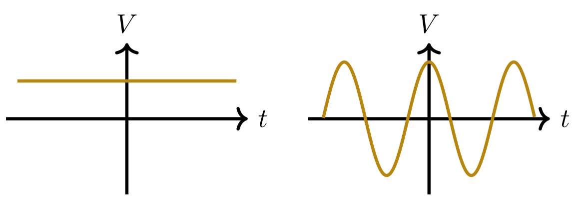
In electronic circuits the charge carries are negatively charged electrons which move due to a **potential difference** (voltage) created by a supply. This is a measure of the energy given to the electrons in the circuit.

A circuit then comprises a supply e.g. cell or *battery* of cells and a number of electronic components (Exercise 3.4).

A **voltmeter** measures the voltage between two points in a circuit. It must be connected in *parallel* and have a high resistance to avoid drawing current (which would affect the reading of V).



Example 3.3. An **oscilloscope** produces a trace of voltage against time and so may be used to determine whether a supply is a.c. or d.c.

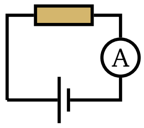


direct current (d.c.) alternating current (a.c.)

Exercise 3.4. For each of the following components, give a circuit symbol and brief function *cell, lamp, switch, resistor, voltmeter, ammeter, LED, motor, microphone, loudspeaker, photovoltaic cell, fuse, diode, capacitor, thermistor, LDR, relay, transistor*.

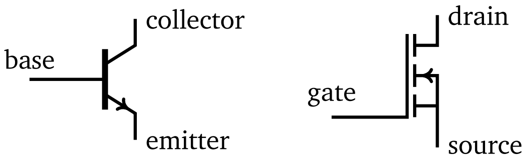
Electric current and circuits (cont.)

An **ammeter** measures the current through a path in a circuit. It must be connected in *series* and have a low resistance to prevent voltage drop (which would affect the reading of I).



Transistor switching circuits

Transistors may be used as electronic switches. We look at `NPN` and `MOSFET` types:

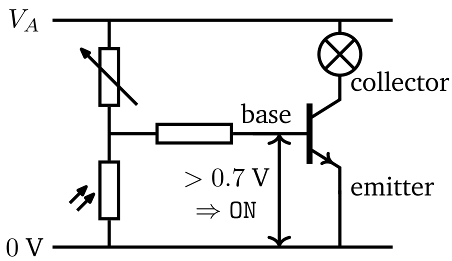


`NPN` `MOSFET`

Both types of transistors has three connections. For the `NPN` transistor, these are labelled *base*, *collector* and *emitter*. These are semiconductors arranged such that current starts flowing through emitter and collector when the voltage between based and collector exceeds a certain threshold; 0.7 V for Silicon transistors. Hence the transistor acts as a switch for the *collector* loop which turns `ON` when the base-emitter voltage exceeds 0.7 V (Example 3.5).

`MOSFETS` transistors function similarly but now current flows through *source-drain* once *gate-source* voltage exceeds 2 V.

Example 3.5. In the circuit below the resistance of the LDR increases as it gets dark, hence so does the voltage across it and base-emitter. Once this reaches 0.7 V, the transistor will switch the light on.



The variable resistor may be used to alter the light level at which the transistors switches on (higher R means lower V across LDR for a given light intensity).

Exercise 3.6. If in Example 3.5 $V_A = 5$ V and the variable resistor is set to $300\ \Omega$, what is the minimum resistance across the LDR for which the lamp is on?

[Hint: Let the resistance of the LDR be R and use Ohm's law from the next section for the variable resistor-LDR path].

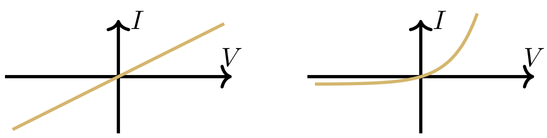
Ohm's law

Ohm's law states that the current I through a conductor (at a constant temperature) is directly proportional to the voltage V across it,

$$\boxed{V = IR}$$

where R is the resistance of the conductor.

A graph of I vs V for a component satisfying Ohm's law is a straight line passing through the origin of slope $I/V = 1/R$. Components for which Ohm's law does *not* hold are said to be *non-Ohmic* and have non-linear I-V curves.



Ohmic non-Ohmic

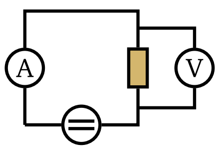
The resistance R of a conductor is determined by

i. the material used
ii. its length—R increases with L
iii. its cross-sectional area—R decreases with A
iv. its temperature (if non-Ohmic)—R increases with T

From the last point it is clear that in an experiment to determine the resistance of a component the current drawn should not become too large, as this may lead to heating of the component and so the breakdown of Ohm's law.

Example 3.7. Ohm's law is an empirical law that holds for a large number of materials. Non-Ohmicity i.e. non-constant resistance R is typically observed if the temperature of a conductor varies considerably during operation (e.g. lamp).

Example 3.8. *Describe an experiment to verify Ohm's law for an unknown resistive component R.*



Connect the component to a variable power supply and place an ammeter in series and a voltmeter in parallel. Record the current I and voltage V across the component for a number of different voltages (e.g. 0, 2,…10 V) provided by the power supply. If the graph of I against V reveals a straight line passing through the origin, Ohm's law holds.

It is important to measure the voltage across the component directly; this may differ from the value provided by the supply due to voltage drop across other elements of the circuit.

Exercise 3.9. The table below shows results from an experiment as described in 3.8. Plot a graph of I versus V for the component and use this to determine its resistance R.

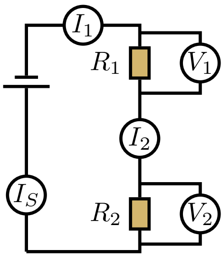
V (V)	1.8	3.9	5.9	7.7	10.1
I (mA)	15.2	32.8	48.9	64.0	86.0

Rules for series and parallel circuits

Series

Current is the same at every point, voltages and resistances add:

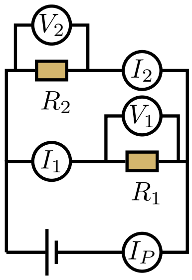
$$I_S = I_1 = I_2 = \ldots$$
$$V_S = V_1 + V_2 + \ldots$$
$$R_S = R_1 + R_2 + \ldots$$



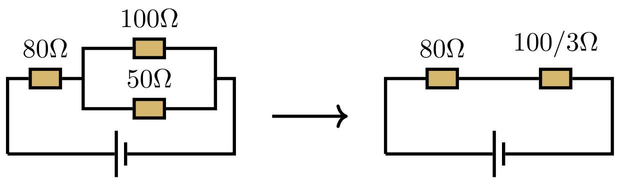
Parallel

Voltage is the same across every branch, currents add and resistances add in a *reciprocal* fashion:

$$I_P = I_1 + I_2 + \ldots$$
$$V_P = V_1 = V_2 = \ldots$$
$$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots$$



Example 3.10. If a circuit contains resistors in series *and* parallel both rules must be used to obtain the total resistance. For example, the resistance of the parallel part of the circuit below is $R_P = 1/(1/100 + 1/50) = 100/3\Omega$ and then $R_T = R_P + 80 = 113\Omega$ using the series rule.



Exercise 3.11. If the cell in 3.10 delivers 12 V, what is the current flowing through the 100Ω resistor?

[Hint: first use R_T to determine the total current]

Electrical power

In an electric circuit energy is transferred from a supply to components where is may be converted to e.g. heat in a resistor or sound from a loudspeaker. **Electrical power** P describes the rate at which energy is transferred,

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

The units of power are Watts (W), which are Joules per second (Js^{-1}).

For resistive (Ohmic) components P may be calculated using

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

Fuse selection

The *power rating* of an electrical appliance influences what *fuse* is suitable to protect from dangerously high current whilst not blowing under normal operating currents for that appliance.

Fuses typically come with 3 A, 5 A or 13 A ratings and one assumes a main supply voltage of 230 V. A rule of thumb is that a 3 A fuse should be selected for most appliances rating up to 720 W and a 13 A fuse for appliances rated over 720 W.

Exercise 3.12. Calculate the power transferred to the 80 Ω resistor in Example 3.10.

Example 3.13. If the power rating of a toaster is 650 W then at 230 V $I = 2.83$ A confirming that a 3 A fuse is appropriate (it will not blow under normal operation). On the other hand, if the power rating was 750 W then $I = 3.26$ A and one would select a 13 A (or 5 A) fuse.

Exercise 3.14. When switched on, a heater connected to the mains (UK) draws a current of 6.52 A. What is its power rating? Give your answer to the nearest W. How much energy would it consume if left on for an entire day and what would this cost assuming an energy price of 45 pence per unit.

[Hint: 1 unit = 1 kWhr, the energy transferred by a $1,000$ W device in 1 hour]