5.1 Electric fields

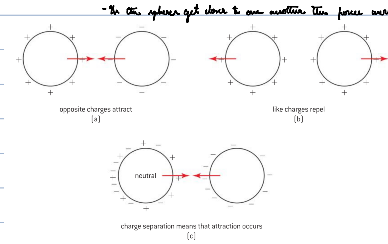
- **Equations**
  - Current - charge relationship: $I = \frac{\Delta q}{\Delta t}$
  - Coulomb's law: $F = \frac{k q_1 q_2}{r^2}$
  - The coulomb constant: $k = \frac{1}{4\pi\varepsilon_0}$
  - Potential difference definition: $V = \frac{W}{q}$
  - Conversion of energy in joules to electron-volt: $W(J) = \frac{W(eV)}{e}$
  - Electric field strength: $E = \frac{F}{q}$
  - Drift speed: $I = nAvq$
- **Explaining electrostatics**
  - Positively charged objects are attracted to negative ones
  - There can also be an attraction between an uncharged and charged objects due to the separation of charge in the uncharged object.
    - In the example with figure 1C the electrons are attracted to charged sphere 2.
    - This is because of the fact that the charged particles from the charged sphere will be attracted to the opposite charges on the neutral sphere.
      - As the spheres get closer to one another the force increases.
  - 

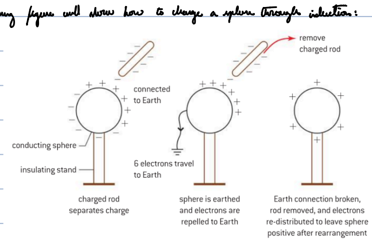
Figure 1 Attractions between charges.
  - An object with an exact balance of electrons and protons will be termed to be neutral.
    - In conducting materials the electrons are delocalised, therefore the material can be positively charged.
  - Charge is conserved: In a closed system the amount of charge is constant.
  - The following figure will show how to charge a sphere through induction:
    - 

Figure 2 Charging by induction.

- **Measuring and defining charge.**
  - Charge is in coulomb (C).
    - It's a scalar quantity.
    - The coulomb is defined as the charge transported by a current of one ampere in one second.
  - Electrons will have a charge of $-1.6 \cdot 10^{-19}$ C, this amount is known as the elementary charge.
    - Elementary charge has the symbol "e".
    - Quarks will have a fractional charge which appears as $\pm\frac{1}{3}e$ or $\pm\frac{2}{3}e$.
- **Forces between charged objects**
  - The force between two small point charges separated by distance "r" is proportional to: $\frac{1}{r^2}$.
    - This is an inverse-square law.
  - The magnitude of the force F is between two point charges of charge q_1 and q_2 separated by distance r in a vacuum is given by:
    - $F = \frac{k q_1 q_2}{r^2}$
      - Where k is the coulomb constant.
    - The coulomb constant is given by: $k = \frac{1}{4\pi\varepsilon_0}$, where "$\varepsilon_0$" is the permittivity of free space.
    - In the case of the force not occuring in a vacuum the ε_0 will change to a ε.
    - The direction of the force isn't given by the equation $F = kq_1q_2$.

- Therefore, the direction left to right will be assigned the positive direction.

- Worked example

  - $F = \frac{k(10\cdot10^{-9})^2}{(15\cdot10^{-3})^2}$

    $= 4.0\cdot10^{-3}\,N$

  - $F = \frac{(5\cdot10^{-6})(3\cdot10^{-6})}{4\pi(8.9\cdot10^{-12})\,1.5^2}$

    $= 9.3\cdot10^{-2}\,N$

- Electric fields

  - The term field is used in physics when two separate objects exert forces on each other.

    - E.g comb picking up paper, the paper is in the electric field due to the comb.

  - Mapping fields

    - There are some conventions for drawing these electric field patterns:

      - The lines start and end on charges of opposite sign.

      - The arrow is essential to show the direction in which a positive charge would move.

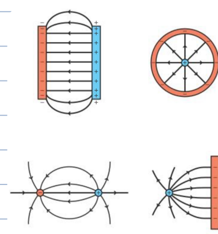
        - Therefore the arrows will go from the positive charge to the negative one.

      - The field is strongest where the lines are close together.

        - The lines act to repel one another.

      - The lines never cross.

      - The lines will meet a conducting surface at 90°.



▲ Figure 8 Electric field patterns.

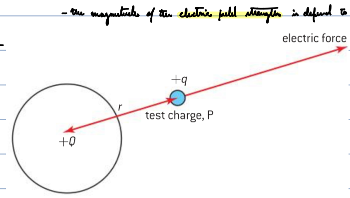
- Electric field strength

  - The electric field strength is defined using the concept of a positive test charge.

    - Imagine an isolated charge Q sitting in space. To know the field strength at point P at distance r away from the isolated charge, we put another positive test charge of size q at point P, to measure force F.

    - The magnitude of the electric field strength is defined to be: $E = \frac{F}{q}$.

  -



▲ Figure 9 Definition of electric field strength.

  - The units of the electric field strength are NC^{-1}.

  - Electric field strength is a vector, it has same direction as the force F.

  - The formal definition of electric field strength at a point: the force per unit charge experienced by a small positive point charge placed at that point.

    - Q is the isolated point charge, and q is the test charge.

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

      - Therefore, $E = \frac{kQ}{r^2}$.

  - The electric field strength of the charge at a point is proportional to the charge, and inversely squared to the distance from the charge.

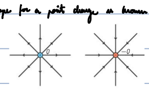
    - If Q is positive, then E is also positive

      - When the point charge is positive, the field lines will be pointing out.

      - When the point charge is negative, the field lines will point in.

  - The field shape for a point charge is known as a radial field.

    -



▲ Figure 10 Radial fields for positive and negative point charges.

  - Worked example

    - $E = \frac{kq}{r^2}$

      $= \frac{(8.99\cdot10^9)(10\cdot10^{-6})}{1.5\cdot10^{-2}}$

      $= 4.0\cdot10^{8}\,NC^{-1}$

    - $E = \frac{kq}{r^2}$

      $= \frac{(8.99\cdot10^9)(-0.85\cdot10^{-3})}{2.5^2}$

      $= -1.2\cdot10^{6}\,NC^{-1}$ The field direction is towards the point charge.

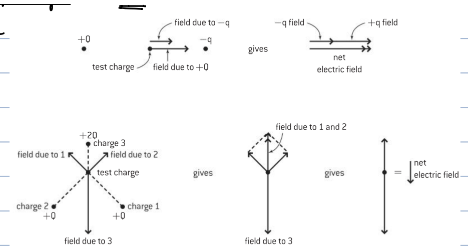
    - $q = -8e,\ r = 0.68\cdot10^{-9}$

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

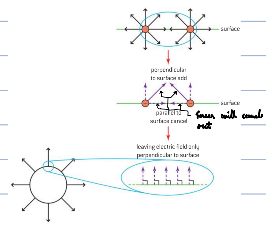
      $= \frac{(8.99\cdot10^9)(-8\cdot1.6\cdot10^{-19})}{(0.68\cdot10^{-9})^2}$

      $= -2.5\cdot10^{10}\,NC^{-1}$

  - The electric field strength can be added.



▲ Figure 11 Vector addition of electric fields.

- Close to conductor
  - what occurs near the surface of a conductor is:
    - When you're close enough to a surface, it will appear to be flat.
    - All electrons are equally spaced.
      - This is because of the fact that all electrons near the surface will equally push one another away causing a state of equilibrium.
    - Any force which is parallel to the surface will be cancelled out.
      - Perpendicular to the surface the field vectors will add up.
  - 

▲ Figure 12 Close to conducting surfaces.

- Conducting sphere
  - For a conducting sphere the radial field will look exactly the same as a point charge.
  - Inside the sphere there is no electric field, hollow or solid. - The total charge is equal to the total charge spread over the sphere.
- Worked example
  - the resultant electric field strength inbetween point charges x and y is:

$$E_1 = \frac{kq}{r^2} \qquad E_2 = \frac{kq}{r^2}$$

$$= \frac{(8.99\cdot10^9)(25\cdot10^{-9})}{(0.25)^2} \qquad = \frac{(8.99\cdot10^9)(15\cdot10^{-9})}{(0.25)^2}$$

$$= 3.6\cdot10^3\,NC^{-1} \qquad = 2.2\cdot10^3\,NC^{-1}$$

$$E = 3600 - 2200$$

$$= 1400\,NC^{-1}$$ Towards Y.

  - the distance for the electric field to be zero is:

$$E_x = -E_y$$

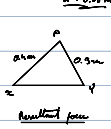
$$\frac{(25\cdot10^{-9})k}{d^2} = \frac{(15\cdot10^{-9})k}{(0.5-d)^2}$$

$$\frac{d}{(0.5-d)} = \sqrt{\frac{2.5}{1.5}}$$

$$d = 0.65 - 1.3d$$

$$d = \frac{0.65}{2.3}$$

$$d = 0.28\,m$$

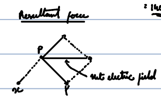
  - 

$$E = \frac{kq}{r^2} \qquad E = \frac{kq}{r^2}$$

$$= \frac{(8.99\cdot10^9)(25\cdot10^{-9})}{(0.4)^2} \qquad = \frac{(8.99\cdot10^{-9})(15\cdot10^{-9})}{(0.3)^2}$$

$$= 1400\,NC^{-1} \qquad = 1500\,NC^{-1}$$

Resultant force



the magnitude for the resultant force is: $\sqrt{1400^2 + 1500^2}$
$= 2100\,NC^{-1}$

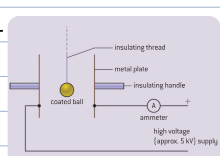
- Moving charges
  - 

Figure 13

- When a current is supplied to the circuit, an excess of electrons will appear on the plate which is connected to the negative supply.
    - The other plate will have a deficit of electrons making it positive.
- When the ball touches one of the plates, it will either gain or lose electrons.
    - When it touches the negatively charged plate, electrons will flow into the ball causing it to become negatively charged.
        - This will then mean that the ball is repelled by the negative plate, and be attracted to the positively charged one.
    - Once the ball arrives at the positive side, it will transfer its electrons to the positive side, causing it to become positively charged, resulting in it being repelled by the positive end, and attracted to the negative side.
- What the ammeter shows is that there is a flow of electrons giving evidence that:
    - An electric current results when charges move.
    - The charge is moved by the presence of an electric field.
- A mechanism for electric current
    - Electrical conduction is possible in gases, liquids, solids, and a vacuum.
    - Conduction metals
        - Metal atoms in a solid are bound together by metallic bonds.
        - In a metal, the atoms are arranged into a lattice, and their electrons are delocalised.
            - This means that the electrons aren't bound to a singular atom, and therefore, will be able to conduct electricity.
            -

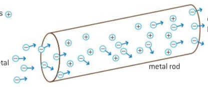


Figure 14 Conduction by free electrons in a metal.

            - The positive ions sit in fixed positions on the lattice.
                - There are ions on each lattice site because each atom has lost an electron.
            - There is still interaction between the electrons and atoms.
                - The electrons will collide with the vibrating ions and transfer kinetic energy.
                    - This is Resistance.
            - The energy transfer is:
                -

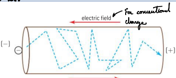


Figure 15

        - In a metal, the electrons will be travelling at random and average speeds, which are close to the speed of sound in the material.
            - This is without an electric field being present.
        - When an electric field is present, then an electrical force will act on the electrons with their negative charge.
            - The force of electrons will be in the opposite direction of the electric field, as the electric field is for conventional charge.
            - The electrons will drift along the conductor.
                - They're known as charge carriers.
                - Their movement is in a random direction.
    - Conduction in gases and liquids
        - Electrical conduction will occur in other materials as well.
            - Some gases and liquids will contain ions.
                - The ions will then become the charge carriers.
                    - Causing a current.
                - Positive in the direction of the field, and negative the opposite way.
        - If the electric field is strong enough, then ions in the gas are formed, leading to a phenomenon known as electrical breakdown.
            - E.g lightning during a storm.
- Electric current
    - A current is charge flowing in a conductor.
        - Measured in Amperes, or amps (A).
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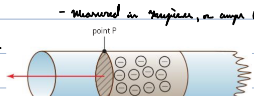


Figure 16 Charge flow leading to current.

- One ampere (amp) can be defined as the number of coulombs that pass a certain point per second.

- Mathematically current is given by: electric current, $I = \frac{\text{total charge moving past a point}}{\text{time taken for charge to move past it}} \longrightarrow I = \frac{\Delta Q}{\Delta t}$.

- **Worked example**

  - $f = 0.67\,Hz$, $q = 72\,nC$

    $I = \frac{72 \cdot 10^{-9}}{0.75}$ $T = \frac{1}{f} = 0.75\,s$

    $= 96 \cdot 10^{-9}$ Amps

  - $4.5 \cdot 10^{11}$ electrons

  - $I = 36 \cdot 10^{-3}\,A$, $t = 60\,s$

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

    $q = 2.16\,C$

    $\simeq 2.2\,C$

- **Charge carrier drift speed**

  - The slow speed at which the ions move along the conductor is known as the drift speed.

  - For a conductor with a current I, cross-sectional area A, containing charge carriers with charge q.

    - We assume that each charge carrier will have a speed v, and that there are n charge carriers in $1\,m^3$ of conductor, known as charge density.

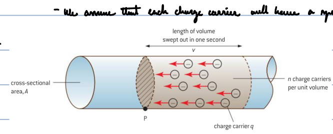
  - 

Figure 18 A model for conduction.

  - In one second, a volume Av of charge carriers passes P.

  - The total number of charge carriers in this volume is nAv and therefore the total charge in the volume is $nAvq$.

    - The current is therefore given by: $I = nAvq$.

  - **Worked example**

    - diameter $= 0.65 \cdot 10^{-3}\,m$, $I = 0.25\,A$, $n = 8.5 \cdot 10^{28}$, $q = 1.6 \cdot 10^{-19}\,C$

      - $I = nAvq$ $v = \frac{I}{nAq}$

        $= \frac{0.25}{(8.5 \cdot 10^{28})\,\pi \left(\frac{0.65 \cdot 10^{-3}}{2}\right)^2 (1.6 \cdot 10^{-19})}$

        $= 5.54 \cdot 10^{-5}\,m\,s^{-1}$

  - The reason that the drift velocity is so small is because of the fact that there are many free electrons available for conduction in the metal.

  - Even though the electrons move at such a slow speed, the information of them having to move travels through the conductor at nearly the speed of light, meaning that it will be able to turn on appliances instantly.

- **Potential difference**

  - Potential difference (pd) is a measure of the electrical potential energy transferred from an electron when it's moving between two points.

    - The potential difference is defined by: the work done (energy transferred) W when one unit of charge Q moves between two points.

    - This is given by the equation: $pd\,(V) = \frac{W}{Q}$.

    - The units for potential are: $J\,C^{-1}$ or V (volts).

    - The potential difference between two points is one volt if one joule of energy is transferred per coulomb of charge passing between the two points.

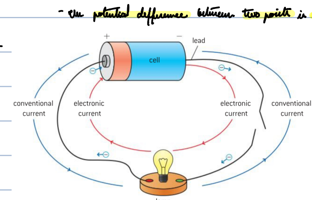
  - 

Figure 19 Conventional and electronic current in a circuit.

    - When the switch is closed, electrons will flow through the circuit.

    - Conventional current will be in the opposite direction of the actual current.

      - The actual current (how electrons will flow in the circuit), will go from the negative electrode (side) to the positive electrode of the cell/battery.

      - The conventional current will be going from the positive electrode to the negative.

  - As the electron moves around the circuit they will gain electric potential energy as it moves through the cell.

    - The electrons will lose all the electric potential energy which they gained at the cell.

      - The electrical potential energy is used to do work when the electrons move through the lamp.

      - Lamps (resistors) are designed so that as much electrical potential energy is gained from the electrons.

- The electrical potential energy transferred by the electrons to the atoms in the light will mean that the atoms in the lamp will vibrate with greater amplitude and speeds, resulting in the filament starting to glow.
- Therefore, the pd across the lamp will be high due to the fact that a lot of the electrons energy is being transferred to the atoms in the resistor.

- Worked example

  - $V = 240\ JC^{-1}$, $I = 50\ mA$ $= 50 \cdot 10^{-3}\ Cs^{-1}$, $t = 7200\ s$

    $\Delta q = I \Delta t$
    $= (50 \cdot 10^{-3})(7200)$
    $= \underline{360\ C}$

    Energy transferred (W) $= Vq$
    $= (240)(360)$
    $= \underline{86400\ J}$

  - $V = 1.5\ JC^{-1}$, $q = 460\ C$

    $W = (1.5)(460)$
    $= 690\ J$

  - $I = 5\ mA$
    $\Delta q = I \Delta t$
    $\Delta t = \frac{\Delta q}{I}$
    $= \frac{460}{5 \cdot 10^{-3}}$
    $= 9.2 \cdot 10^{4}$ seconds

- Electromotive force

  - Electromotive force isn't a force, but instead is used when energy is transferred to the electrons in a battery (eg).

  -

Device					pd or emf?
Cell	converts energy from	chemical	into	electrical	emf
Resistor		electrical		internal	pd
Microphone		sound		electrical	emf
Loudspeaker		electrical		sound	pd
Lamp		electrical		light (and internal)	pd
Photovoltaic cell		light		electrical	emf
Dynamo		kinetic		electrical	emf
Electric motor		electrical		kinetic	pd

→ Electrons do work resulting in them losing energy, and therefore a pd occurring.

- Power, current, and pd

  - In time Δt, the charge Q that moves through the conductor is equal to $I\Delta t$.
    - The energy transferred in time Δt is: $W = IV\Delta t$
  - Electrical power is given by: $P = IV$
    - The unit of power is watt, W.

- Worked example

  - $3V$, $1.5W = P$

  - $P = IV$
    $I = \frac{1.5}{3}$
    $= 0.5$ Amps

  - $W = I \Delta t V$
    $= (3)(0.5)(2400)$
    $= \underline{3.6 \cdot 10^{3}\ J}$

  - $V = 12\ JC^{-1}$, $m = 1.5\ kg$, $\Delta h = 1.5\ m$, $\Delta t = 7\ s$, efficiency $= 0.4$

    $E = mg\Delta h$
    $= (0.1)(1.5)(9.81)$
    $= 1.47\ J$

    $W = I \Delta t V$
    $I = \frac{1.47}{7 \cdot 12}$
    $= \underline{0.018\ \text{Amps}}$

    $\frac{0.018}{0.4} = \underline{0.045\ \text{Amps}}$
    $= \underline{4.5 \cdot 10^{-2}\ \text{Amps}}$

- The electronvolt

  - If a singular electron moves through a potential difference of 1 V, then the energy transferred to the electron will be ($V = \frac{W}{q}$) $1 \cdot e = 1.6 \cdot 10^{-19}\ J$.
    - Since the value is so small, it is more convenient to use the unit "electronvolt" (eV).
    - 1 electron-volt will be equal to $1.6 \cdot 10^{-19}\ J$.

  - Worked example

    - $V = 180\ JC^{-1}$
      $W = Vq$
      $= (180)(1.6 \cdot 10^{-19})$
      $= 2.88 \cdot 10^{-17}$
      $\approx 2.9 \cdot 10^{-17}\ J$

      $2.9 \cdot 10^{-17} = \frac{1}{2} mv^2$
      $\sqrt{\frac{5.8 \cdot 10^{-17}}{9.1 \cdot 10^{-31}}} = v$
      $\underline{v = 8.0 \cdot 10^{6}\ ms^{-1}}$

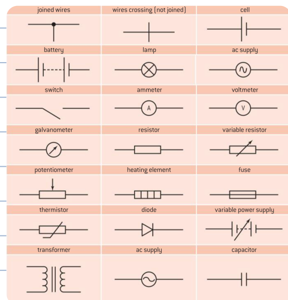
    - $\Delta W = 250\ MeV$

      $250 \cdot 10^{6}\ eV \times 1.6 \cdot 10^{-19} = J$
      $J = \underline{4 \cdot 10^{-11}\ J}$
      $v = \underline{2.2 \cdot 10^{8}\ ms^{-1}}$

5.2 Heating effect of an electric current

- Equations

  - Resistance definition: $R = \frac{V}{I}$
  - Electrical power: $P = IV = I^2 R = \frac{V^2}{R}$
  - Combining resistors in series: $R_{total} = R_1 + R_2 + R_3 + \ldots$
  - Combining resistors in series: $\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$
  - Resistivity definition: $\rho = \frac{RA}{L}$

- Effects of electric current
    - Effects that occur when charge flows through a circuit.
        - Heating effect: When energy is transferred to a resistor as internal energy.
        - Chemical effect: When chemicals react together to alter the energy of electrons and move them, or when electric current in a material causes chemical change.
        - Magnetic effect: When a current produces a magnetic field, or when magnetic fields change near conductors and induce an emf in the conductor.
- Drawing and using circuit diagrams
    - Circuit symbols
        - 

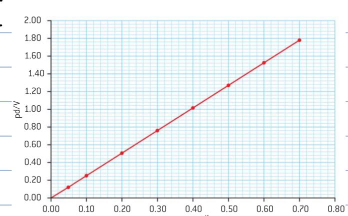
        - Some symbols are meant for direct current (dc), such as cells and batteries.
            - Direct current is where the charge will flow in one direction.
                - E.g phones and low-voltage flashlights.
        - Other electrical circuits will use alternating current (ac).
            - This is where the current will alternate in its directions.
            - The time between the change is usually $\frac{1}{100}$ th of a second.
            - This type of current is used for high power devices.
        - The difference between a cell and a battery is that a battery will be an arrangement of cells, arranged by having positive terminal to negative.
    - Circuit conventions
        - Write value with symbol of the object.
        - If two wires are connected at one point, then a point is placed where they connect.
            - This point is called a junction.
- Resistance
    - As a current passes through a wire it will heat up due to the fact that the electrons will constantly interact with the wire atoms causing them to gain kinetic energy, causing them to vibrate at greater speeds, and greater amplitudes.
        - This is what causes resistance in wires.
        - Different wires will have different resistance values, e.g at the same size tungsten will have a greater temperature rise than copper.
    - Resistance is defined as: $\frac{\text{potential difference across component}}{\text{current in the component}} \rightarrow R = \frac{V}{I}$.
        - Units are Ohms (Ω).
    - Ohm's law
        - 

        Figure 6 pd against current from the table.
        - When the resistance will increase by the same value, then the resistor is said to be Ohmic.
            - Meaning $V \propto I$
        - Ohm's law states that the potential difference across a metallic conductor is directly proportional to the current in the conductor.
            - This is the case if the physical properties are the same.
            - This means that the temperature and other variables.
        - If the resistance will not increase in a straight line when it's plotted, meaning V isn't proportional to I, then the resistor will be non-ohmic.
            - E.g filament bulb.

- this can be due to varying temperatures.

- Annotation:

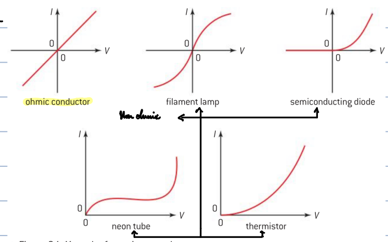


Figure 8 I–V graphs for various conductors.

- Semiconducting diodes
  - these are designed to have current only flow in one direction
  - symbol: ▷|
- Thermistors
  - these are made of one two elements that are electrical semiconductors: silicon and germanium.
  - the negative temperature coefficient thermistor is designed that when the temperature of the NTC thermistor increases, its resistance falls.
    - the opposite that occurs in metals
  - semiconductors have fewer free electrons per cubic meter compared with metals.
    - their resistance is usually 10^5 times greater than
    - the charge density strongly depends on temp.
      - the higher the temperature, the more charge carriers are available.
  - As the temp of germanium increases:
    - the lattice will vibrate more impeding the movement of charge carriers.
      - leading to an increase in resistance (same as metals).
    - As the temperature increases, then more charge carriers would become available.
      - leading to resistance falling.
      - this effect will be greater than the first, meaning that as temp increases, the resistance will fall.

- Resistivity
  - the size and shape of a material will also affect its resistance.
    - the resistance of a conductor is:
      - proportional to its length "L".
      - inversely proportional to its cross-sectional area A (which is proportional to d^2).
        - $R \propto \frac{1}{A}$
    - this leads to a definition of a new quantity called resistivity (ρ):
      - $\rho = \frac{RA}{L}$
      - the units are Ωm.
  - Worked example:
    - $r = 0.16 \cdot 10^{-3} m$, $L = 7.5 m$, $\rho = 7 \cdot 10^{-7} \Omega m$

      $\frac{\rho L}{A} = R$ $\quad$ $\pi r^2 = A$

      $A = 8.04 \cdot 10^{-8} m^2$

      $\underline{R = 65 \Omega}$

    - $L = 0.012 m$, width $= 0.75 mm$, thickness $= 12 mm$, $\rho = 1.7 \cdot 10^{-8} \Omega m$

      cross sectional area $= 0.75 \cdot 10^{-3} \cdot 12 \cdot 10^{-3}$

      $= \underline{9 \cdot 10^{-6} m^2}$

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

      $= \underline{0.023 m\Omega}$

  - Practical resistors
    - small resistors can have a large resistance, but can only dissipate a modest amount of energy every second.
      - If the power generated in the resistor is too large, then a thermal fuse can occur.
  - Combining resistors
    - series is when a resistor is followed by another.
      - Parallel, is when they're connected in a junction, and are lined up close to one another.

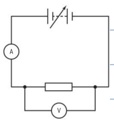


Figure 10

- In series have the same current in each component.
    - The number of electrons leaving the first component will be equal to the number of electrons entering the second component.
- In series the pds will add up.
    - In parallel, the components will have the same pd across them.
- In parallel, when two resistors are added together, the cell will supply a greater current than if they were alone.
    - To be precise, it will have to supply the sum of the separate currents.
-

	Currents ...	Potential differences ...
In series	...are the same	...add
In parallel	...add	...are the same

- Resistors in series
    - In series, there are 3 resistors, R_1, R_2, R_3.
        - Since the current in them is the same, then the equivalent resistor of the resistors would be equivalent to: $R_T = R_1 + R_2 + R_3$.
            - This means that the total resistance in series is adding the resistance of all the resistors
- Resistors in parallel
    - The opposite will happen if the resistors are in parallel.
        - In parallel, the resistors will all have the same pd.
        - The total current will be given by: $I_T = I_1 + I_2 + I_3$.
        - The total resistance will be given as: $\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$
            - E.g calculation, $R_1 = 10\,\Omega$, $R_2 = 10\,\Omega$
            - $\frac{1}{R_T} = \frac{1}{10} + \frac{1}{10}$
              $\frac{1}{R} = \frac{2}{10}$ Reciprocal
              $R = 5\,\Omega$
- More complicated networks
    - When working out the total resistance of a network with series and parallel, the steps are.
        - Combine the resistors in parallel into one equivalent resistor.
        - Add resistors in parallel
        - Reciprocal
- Potential divider
    - This is a circuit which is usually used with sensors and to also produce variable potential difference.
        - The most basic potential divider consist of two resistors (R_1 & R_2) in series with a power supply.
            - This is to give a pd between 0 and the emf of the power supply.
            - Figure 13(a)
            -

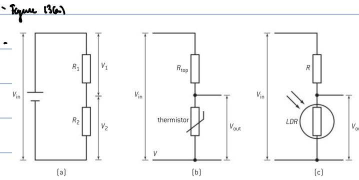
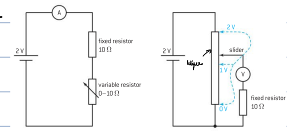


Figure 13 The potential divider.

- The pd across a resistor will be given by the equation: $V_1 = \frac{R_1 V_{in}}{(R_1 + R_2)}$ and $V_2 = \frac{R_2 V_{in}}{(R_1 + R_2)}$
- Using a potential divider with sensors
    - Typical sensor and variable circuits are figure 13(b and c).
    - Figure 13(b) has a thermistor rather than a resistor.
        - As mentioned before, as the temp rises the resistance will fall.
        - Scenario: temp is low, thermistor resistance is high (compared to fixed resistor).
        - $V_{thermistor} = \frac{V_{in} R_{thermo}}{(R_{thermo} + R_{resistor})}$ and $\frac{V_{in} R_{resistor}}{(R_{thermo} + R_{resistor})} = V_{resistor}$
            - Although, if the resistance of the thermistor is overwhelmingly higher than the fixed resistor, then the potential for the thermistor will be approx that of the cell.
                - $R_{thermo} \gg R_{fixed} \rightarrow V_{thermo} \approx V_{in}$.
        - If the resistance of the thermistor were to decrease, then that would mean that the potential across the fixed resistor would increase.
        - The resistance of the fixed resistor is usually the resistance of the thermistor when its at its average temperature.

- This is the same case with LDRs, as the amount of photons incident increase, then the resistance will decrease.

- Using a potential divider to give a variable pd

- 

(a) variable resistor (b) potential divider

- When the variable resistor is set to 0Ω (min value), then there is a pd of 2V across the resistor, and a current of 0.2 Amps.
  - When the variable resistor is at 10 Ω (max value), the total resistance will be 20 Ω in the circuit, and a current of 0.1 Amps.
    - Meaning that only 1V is dropped across the variable resistor.
    - Therefore the range of the pd for the fixed resistor will be equal to 1-2V.
- The potential divider allows a greater range of pd to the test component than the variable resistor.
  - A variable resistor can also called a rheostat.
  - In a potential divider one end of the wire will be connected to cell and fixed resistor, and a second wire will be connected to the variable resistor and other end of the cell.
  - The potential along the resistance winding depends on the position of the slider.
  - The component under test will be connected to a secondary circuit between one terminal of the resistance winding and the slider on the variable resistor.
    - When the slider is all the way to one end, then all 2 V will be available to the resistor under test.
    - When its on the other end, the pd between the ends of the resistor is 0V.

- Worked example
  - $6V$, $1800\Omega = R$, V over resistor $= 1.2V \rightarrow V_{LDR} = 4.8V$ — $V = \frac{(6)(2400)}{(2400+1800)}$

    $V = 3.4V$

    $4.8 = \frac{(6)(R_{LDR})}{(1800+R_{LDR})}$

    $6R_{LDR} = 8640 + 4.8R_{LDR}$

    $R_{LDR} = 7200\Omega$

  - As the temperature increases more charge carriers will be made available, and while this will also mean that the atoms of the thermistor will vibrate with greater amplitude and speed (causing an increase in resistance), the charge carriers effect will overcome the atom's movement increase.

- Heating effect equations
  - The power dissipated in a component is given by: $P = IV$.
  - The energy converted in time is: $E = IV\Delta t$.
    - If I or V aren't known then: $E = IV\Delta t = I^2R\Delta t = \frac{V^2}{R}\Delta t$
    - This is the energy converted in different appliances and components.
  - Worked example
    - $R = 250\Omega$, $V = 10JC^{-1}$ — $P = 9 \cdot 10^3 W$, $V = 250V$ — $P = 2000W$, $V = 110$

      $R = 6.1\Omega$

      $P = \frac{V^2}{R} = \frac{100}{250} = 0.4W$

      $I = \frac{9 \cdot 10^3}{250} = 36 Amps$

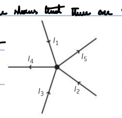
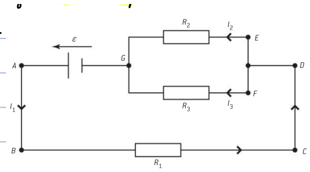
- Kirchhoff's first and second law
- If 10^6 charge carriers flow into a conduction, then 10^6 charge carriers will flow out.
- The figure shows that there are 3 incoming currents and two out going ones.
  - 

Figure 15 Kirchhoff's first law

  - Therefore, the rule for the outgoing charge will be: $I_1 + I_2 + I_3 = I_4 + I_5$
    - This can be summarised to: for any junction $\Sigma I = 0$.
    - This means that the currents in would be positive, and the ones out as negative (algebraically speaking).
- This is stated in Kirchhoff's first law, which is stated as: the sum of the currents flowing into a junction equals the sum of the currents flowing out of the junction.
  - This is essentially the conservation of charge.
- Kirchhoffs second law is the conservation of energy.
  - It applies to closed circuits.
  - In a complete circuit loop, the sum of the emfs in the loop is equal to the sum of the potential differences in the loop.
  - Symbols: For a closed loop $\Sigma\varepsilon = \Sigma IR$.



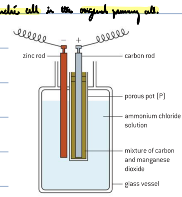
▲ Figure 16 Kirchhoff's second law.

- In this loop there is one source of emf, and two resistors.
  - Therefore, ε (emf of cell) $= I_1R_1 + I_2R_2$ (the total pds across the resistors).

- Worked example
  - $I + 3 = 14$, $I = 11A$
  - $I + 11 + 3 = 5 + 7$, $I + 14 = 12$, $I = -2A$
  - $V = 3V$, $\frac{1}{R} = \frac{1}{9} + \frac{1}{6} = \frac{2}{18} + \frac{3}{18}$, $\frac{1}{R} = \frac{5}{18}$, $R = \frac{18}{5} + 3 = 6.6\Omega$
    $I = \frac{3}{6.6} = 0.45A$
    $V = \frac{3(\frac{18}{5})}{6.6} = 1.6V$
    $0.45 = I_2 + I_3$, $I_3 = 0.45 - I_2 = 0.27A$
    $I_2 = \frac{V_2}{R_2} = \frac{1.6}{9} = 0.18$ amps
  - $R_1 = 250\Omega$, $R_2 = 500\Omega$, $V = 6JC^{-1}$
    $V = \frac{6(250)}{750} = 2V$
  - $R = \frac{1000}{5} = 200\Omega$, $V = \frac{6(200)}{700} = 1.7V$
  - $R = 5\Omega$, $V = 3JC^{-1}$, lamp $= 3V, 300mA$
    $R = \frac{3}{300 \cdot 10^{-3}} = 10\Omega$
    $I = \frac{V}{R} = 0.2A$

5.3 Electric cells

- Equations:
  - emf of a cell: $\varepsilon = I(R + r)$
- Cells
  - Direct current, meaning that the cell charges in one direction.
  - The electron charge carriers move away from the negative terminal of the cell.
    - They will re-enter in the positive terminal.
  - The positive terminal of the cell will have a high potential compared to the negative terminal.
    - So electrons appear to gain energy.
- Primary and secondary cells
  - Primary cells are cells which are used until they're exhausted.
    - This is because the original chemicals have completely reacted.
    - E.g AA batteries.
  - Secondary cells are cells which can be recharged.
    - The chemicals once exhausted can be connected to a charger, and the opposite reaction occurs.
  - The Leclanché cell is the original primary cell.
    -



▲ Figure 1 Leclanché cell and lead-acid accumulator.

- The zinc rod will be the negative terminal.
- It's an electrolytic cell.
- The lead acid battery in cars is a voltaic cell.
- Capacity of cells
  - The capacity of a cell is the quantity used to measure the ability of a cell to release charge.
    - If a cell is discharged at a high rate, then it will run out in a short amount of time.
    - The way that the capacity of a cell is written as is the amount of amps, per the time it can supply it.
      - E.g 2 amps for 20 hours = 40 amp-hours.
        - This would mean that the cell would be able to supply 1 amp for 40 hours.

- A typical discharge curve would look like the following figure:

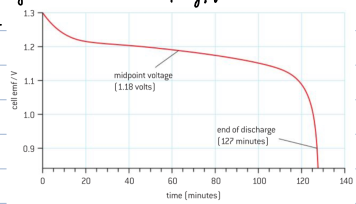


Figure 3 Typical discharge–time graph for a cell.

- Some important features for the graph are:
  - The initial pd will be higher than the quoted one.
    - Although, it will fall down to the stated value in a short amount of time.
  - For most of the discharge time, the value of the emf will remain at the stated emf.
    - Then again, there will be a gradual decline in the emf.
  - As the cell approaches exhaustion, the pd will quickly decrease.
  - If the current is switched off, the pd will eventually go back up to its stated value.
    - When the current is back on, it will quickly fall back to the low value it was at again.
- A secondary battery's capacity will also decrease overtime as it's charged and dis-charged.

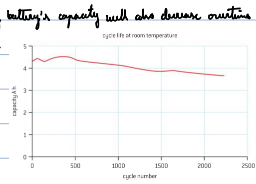


Figure 4 Cycle life of a rechargeable cell.

- Internal resistance and emf of a cell
  - Cells will have an internal resistance due to its material.

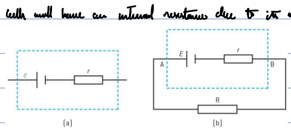


Figure 6

- Inside the dotted box is an "ideal" cell that has no resistance of its own.
  - The "r" box is the internal resistance.
- If the pd across the external resistor is V, then: $\varepsilon = V + Ir$
  - It also can be converted to: $\varepsilon = IR + Ir$
    $= I(R + r)$
- The terminal pd is the pd when no current is supplied. The equation is: $V = \varepsilon - Ir$
- The lost volts represents the energy required to drive the charge carriers through the cell.
  - This causes to the cell to warm up.

- Worked example
  - $\varepsilon = 6V$, $r = 2.5\Omega$, $R = 7.5\Omega$ – $V = 6 - (0.6)(2.5)$
    $= 4.5V$

    $6 = I(10)$
    $I = 0.6A$

  - $R = 6\Omega$, $I = 1A$, when $R = 3\Omega$, $I = 1.5A$

    $\varepsilon = IR + Ir$ $\quad$ $\varepsilon = 4.5 + 1.5r$
    $\varepsilon = 6 + r$

    $6 + r = 4.5 + 1.5r$
    $\underline{r = 3\Omega}$ $\quad$ $\underline{\varepsilon = 9V}$

- Power supplied by a cell
  - The total power supplied by a non-ideal cell is given by: $P = I^2R + I^2r$.
  - The power delivered to the external resistance is: $P = \frac{\varepsilon^2 R}{(R+r)^2}$

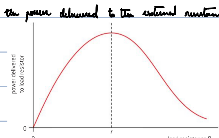
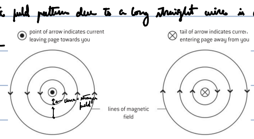


Figure 9 Power delivered to a resistor.

5.4 Magnetic effects of electric currents

- Equations
  - Force on a charge moving in a magnetic field: $F = qvB \sin\theta$
  - Force on a current-carrying conductor in a magnetic field: $F = ILB \sin\theta$
- Magnetic field patterns
  - There is said to be a magnetic field at a point if a force acts on a magnetic pole at that point.
  - Magnetic field lines are similar to electrical lines.
    - Magnetic lines are drawn from the north to south pole.
    - The strength of the field is shown by the density of the lines.
      - Like electric lines, the closer the lines, the stronger the field.
    - Field lines never cross.
    - The field lines are as short as possible.
- Magnetic field due to the current in conductors
  - The magnetic field pattern due to a long straight wire is circular (as seen below):
    - 

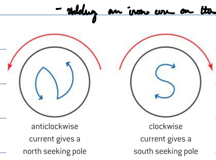
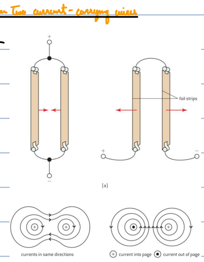
  - The right hand grip rule will show the current and magnetic field around a wire.
    - The hands are the magnetic field, and the thumb is the conventional current.
  - The strength of the magnetic field increases with
    - Increasing the current.
    - Increasing the number of turns per unit length
    - Adding an iron core on the inside of the wire.
  - 

Figure 6 Right hand corkscrew rule and pole direction.

- Forces on moving charges
  - Forces between two current-carrying wires
    - 

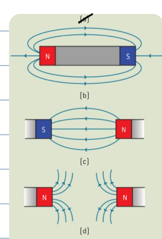
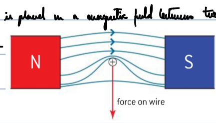
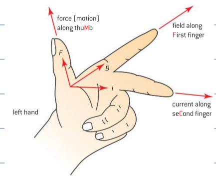
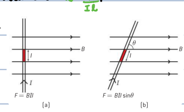


Figure 1 Magnetic field patterns.

    - When the currents are in the same direction, the strips move together due to the magnetic field's force on the strips.
      - When the currents are in the opposite direction, they'll repel one another.
    - When the currents are in the same direction, the field lines from the foils combine to give a pattern in which the field lines loop around both foils.
      - This is can be seen in Figure 1 (c) where the poles are opposite, the magnetic field will merge bring the magnets together.
    - On the other hand, when the currents are the opposite, they'll repel.
  - Force between a bar magnet field and a current-carrying wire
    - When a wire is placed in a magnetic field between two opposite poles, it will disrupt the field.
      - 

- In ~~sum~~ essence, there will be a force applied on the wire.
    - This is called a catapult field
- This is used in speakers and motors, and is called the "motor effect."
- The movement of the wire is given by the left hand rule.
    - 

▲ Figure 9 Fleming's left-hand rule.

- The motor effect
    - The motor effect is the term used when a current carrying wire in the presence of a magnetic field experiences a force.
- Worked example
    - The wire will be attracted to wire P as they're both going in the same direction, causing the magnetic fields to merge, and attract, while the opposite will occur with wire R.
- The magnitude of the magnetic force
    - The force acting on the wire is proportional on:
        - The length (l) of the wire.
        - The current (I) in the wire.
    - We define magnetic field strength as $\dfrac{\text{force acting on a current element}}{\text{current in element} \times \text{length of element}}$.
        - Written as: $B = \dfrac{F}{Il}$.
        - 

        - If the element is at an angle, then sin will be used.
        - The unit is Tesla.
        - The magnetic field of the Earth is 10^{-4} T.
    - The force equation changes to: $F = BIL \sin\theta \rightarrow (90°)\ F = BIL$.
        - $I = \frac{Q}{t} \rightarrow F = B\left(\frac{Q}{t}\right)L \sin\theta \rightarrow F = BQv \sin\theta$
- Worked example
    - $F = BQv \rightarrow F = 4BQv$

    Force is 4 time greater