MODULE 4.1 - 4.3: ELECTRICITY

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CHARGE AND CURRENT:

1. **$I = \Delta Q / \Delta t$** where *I* is current, *Q* is charge and *t* is time.

2. **Current:** The rate of flow of charge. It can be defined with the following equation: **$I = \Delta Q / \Delta t$**
   a. Where *I* is current measured in Amperes, *Q* is charge measured in Coulombs, and *t* is time measured in seconds.
3. Current is the movement of electrons in metals and movement of ions in electrolytes.

4. **Metals:**
   a. A metal is a structure of metal ions held together by a sea of delocalised electrons.
   b. The delocalised electrons are able to move throughout the metal lattice.
   c. The electric current in a metal is due to the movement of electrons.

5. **Electrolyte:**
   a. In an electrolyte, electrons are unable to move freely.
   b. Instead, the current is due to the movement of ions.

6. Current is measured in Amperes
   a. **Ampere:** One ampere is defined as the flow of one coulomb per second.
   b. Current is measured using an Ammeter that must be placed in series. Theoretically an ammeter should have negligible resistance. Negligible resistance means that p.d. across the ammeter is minimal/reduced so that it does not affect the readings.
   c. **Conventional current** flows from the positive terminal to the negative terminal. Whereas **Electrons** actually flow from the negative terminal to the positive terminal.

7. **Electric Charge:** The total amount of current that is supplied over a certain period of time. It can be defined with the following equation: **Q = I x t**

8. **Charge** is measured in Coulombs
   a. Coulomb: One coulomb (C) is defined as the amount of charge that passes in 1 second when the current is 1 ampere.
   b. Charge derived into its base units is A x s = As

9. **Elementary Charge:** The elementary charge, e, is the electric charge carried by a single electron. It is 1.60×10^{-19} C
   a. The net charge on a particle or an object is quantised and a multiple of e
   b. An electron has charge −e and a proton a charge +e.

10. To calculate the number of electrons transferred
    a. Charge (C) / elementary charge (1.6×10^{-19} C) or simply *Q / e*.

11. **Kirchhoff's First Law:**
    a. The sum of the currents entering a point / junction is equal to the sum of the currents leaving (the same point)
    b. $\sum I_{in} = \sum I_{out}$
    c. This is a consequence of the conservation of charge, as charge cannot be created or destroyed/ used or lost.

12. **Mean Drift Velocity of electrons:**
    - The displacement travelled by electrons per unit time along the length of the wire.
    - Overtime, the free electrons drift towards the positive end of the supply along the length of the wire.
    - The free electrons also make collisions with metal ions and this gives them a random velocity.

13. **I = nAve**
    a. Where 'I' is current measured in Amperes.
    b. n is the number density of charge carriers per unit volume measured in m^{-3}
    c. A is the cross-sectional area measured in m^2
    d. v is the mean drift velocity of charge carriers measured in ms^{-1}
    e. e is the elementary charge of one electron measured in Coulombs (1.6×10^{-19})

14. $v \propto I$, Double the current, double the mean drift velocity.

15. $v \propto 1/A$, Double the cross-sectional area, half the mean drift velocity.

16. $v \propto 1/n$, Double the number density, half the mean drift velocity.

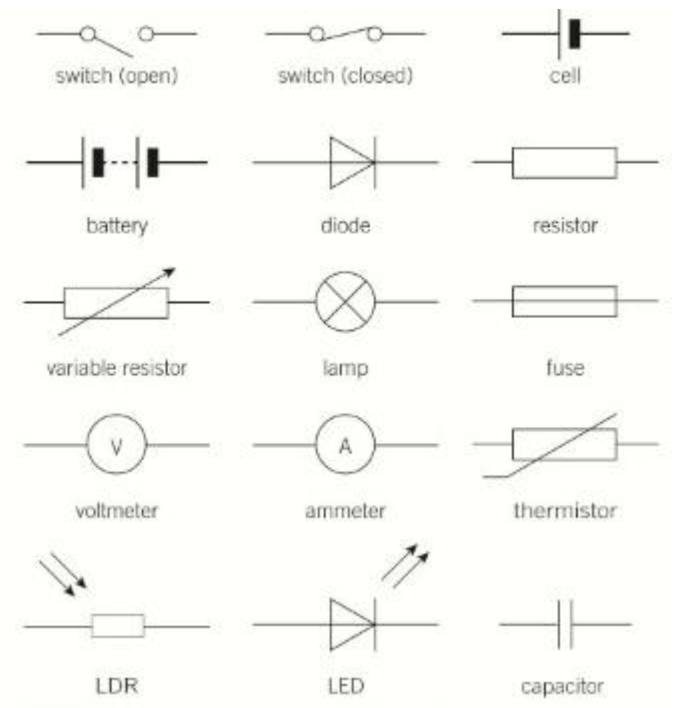
17. If the current and number density are constant (and e is always constant), then the mean **drift velocity $\propto$ 1/A** , therefore the smaller the cross-sectional area of wire, the greater the mean drift velocity and vice versa.

18. For a cylindrical wire, if the radius halves, the cross sectional area will decrease by a factor of 4, so the mean drift velocity must increase by a factor of 4.

19. **Material Categories:**
    a. Conductors such as copper have a very high number density, semiconductors are lower, and insulators are very low.
    b. Since $v \propto 1/n$, conductors will have very low mean drift velocities and insulators will have very high mean drift velocities.
    c. This is because the current is the same, so the electron mean drift velocity will increase in order to pass the same charge in the same time.

ENERGY, POWER AND RESISTANCE:

1. These symbols must be used when drawing circuits:



2. **Potential difference:** The energy transferred from electrical energy to other forms of energy (heat, light, etc) per unit charge.

3. Potential difference can be defined by the equation $V=W/Q$
   a. Where V is p.d. measured in volts, Q is the charge in coulombs, and W is the energy transferred/work done by charge Q.

4. **Electromotive force:** the energy transferred from chemical, mechanical or other forms of energy into electrical energy per unit charge.

5. Examples of sources of e.m.f. are power supplies and cells.

6. Electromotive Force can be defined by the equation $\varepsilon=W/Q$
   a. Where ε is e.m.f. measured in volts, Q is the charge in coulombs, and W is the energy transferred/work done by charge Q.

7. **Volt:** One volt is the p.d. across a component when 1J of energy is transferred per unit charge passing through the component.
   a. $1V = 1\ JC^{-1}$

8. A **Voltmeter** is used for measuring p.d. and e.m.f.
    a. Always connected in parallel
    b. They measure the amount of energy transferred in Joules per coulomb of charge across a component.
    c. An ideal voltmeter should have infinite resistance, so that no current passes through the voltmeter itself. High resistance means that negligible current flows through the voltmeter.

9. When a charged particle is accelerated by a potential difference, the energy transferred to it is equal to the work done on the particle. The energy transferred is equal to the kinetic energy gained by the electron.
    a. Since W = VQ
    b. And for an electron W = Ve
    c. And W = work done = kinetic energy = ½ mv^2
    d. Therefore, $\boldsymbol{eV = \frac{1}{2} mv^2}$

10. When an electron and a proton are accelerated by the same p.d. the velocity of the electron will be greater than the proton. The kinetic energy of each will be the same, but since the mass of the proton is greater, it travels more slowly at the same kinetic energy.

11. **Resistance:**
    a. resistance is the potential difference per unit current
    b. The property of a component that regulates the electrical current flowing through it
    c. The SI unit of Resistance is the Ohm (Ω).

12. $Resistance = \frac{Potential\ Difference}{Current}$

13. **Ohm (Ω)**: A component has a resistance of 1 Ω if a potential difference of 1V makes a current of 1A flow through it. Ohms in terms of base units: $kgm^2s^{-3}A^{-2}$

14. **Ohms Law:** at a constant temperature, current through an Ohmic conductor is directly proportional to the potential difference across it.

15. **Why resistance is effected by temperature:**
    a. Increase in temperature causes an increase in internal kinetic energy, which means ions in the metallic lattice will vibrate more vigorously.
    b. Therefore, delocalised electrons will be more likely to collide with the ions, losing their energy as they travel through.
    c. This causes an increase in resistance. Similarly, a decrease in temperature would cause a decrease in resistance.

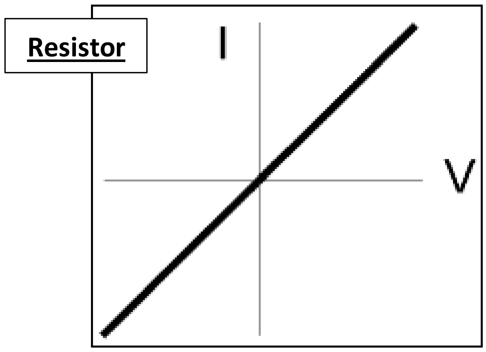
16. I-V Characteristics of a Resistor at constant temperature.

a. The current flowing through the conductor is proportional to the potential difference across it, meaning that resistance is constant.

b. Resistance = $\frac{1}{gradient}$ if 'V' is on x axis and 'I' is on the y axis.

c. Passes through the origin, proving that the constant of proportionality is resistance.

d. This graph is OHMIC.



17. I-V characteristics of a filament lamp:

a. Initially, with positive potential differences, the current is directly proportional to the p.d.

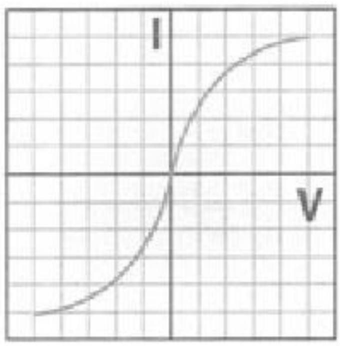
b. However, as the current through the filament increases, the temperature of the filament lamp also increases.

c. This causes an increase in the resistance of the filament.

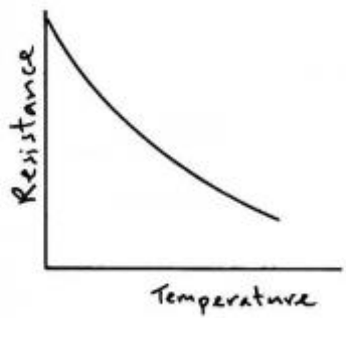
d. As a result the rate of increase of the current decreases (decrease in gradient) and a greater change in the potential difference is required to cause a change in the current.

e. This same pattern is repeated when a negative potential difference is applied across the filament.

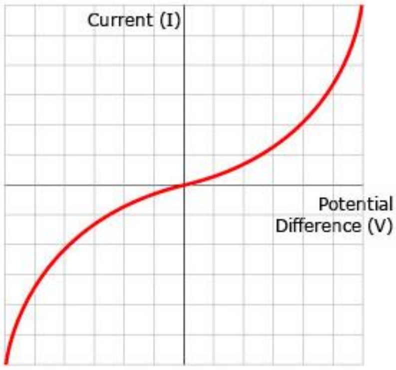
f. A filament lamp is non-Ohmic component because there is a change in temperature, so current is *not* proportional to p.d.



18. Thermistor: A thermistor is a resistor with a resistance that depends on its temperature. The resistance of a negative temperature coefficient (NTC) thermistor decreases as the temperature increases.



19. **I-V characteristics of a Thermistor (NTC):**
    a. Increasing the current through an NTC thermistor increases its temperature. Warming the thermistor releases more electrons. More charge carriers means a lower resistance.
    b. A Thermistor does not obey Ohm's law.
    c. An increase in temperature causes a decrease in the resistance of the thermistor.
    d. As a result the rate of increase of the current increases or in other words the gradient increases.



20. **Diodes:** Diodes (including LEDS) are designed to let current flow in one direction only. Diodes have a forward and reverse bias.

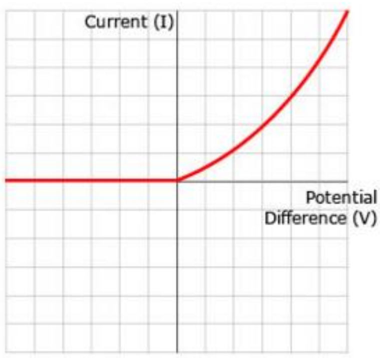
21. **Forward Bias:** This is the direction in which the current is allowed to flow in a diode/LED.

22. **Reverse Bias:** This is the direction in which the current isn't allowed to flow in a diode/LED. The resistance of a diode is very high and the current that flows is very tiny.

23. **Threshold Voltage:** The minimum forward voltage value across the terminals of a diode at which the diode will start to conduct current. Most diodes require a threshold voltage of about 0.6V

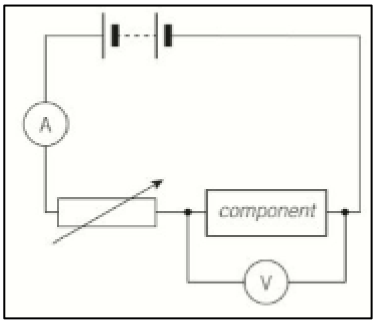
24. **LED:** Components that are diodes but emit light when they conduct. They emit light of a single wavelength.

25. **I-V characteristics of a Diode/LED.**
    a. A diode/LED only allows current to flow in one direction.
    b. When connected in the forward bias direction, they give a low resistance.
    c. When connected in the reverse bias direction, they give a high resistance.
    d. A diode is a non-Ohmic component.



26. Determining the electrical characteristics of a component:

- **a.** Equipment: Power pack/cells, Wires, chosen component, variable resister, ammeter and voltmeter.
- **b.** Produce the setup as shown.
- **c.** Take readings from voltmeter and ammeter.
- **d.** Use the variable resistor to alter the potential difference across the component.
- **e.** Take more readings and repeat results. Take averages to reduce the effect of random errors.
- **f.** Plot graph of current against p.d. Resistance is 1/gradient.

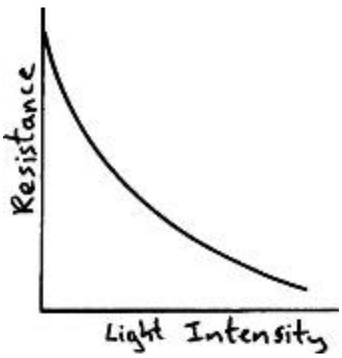


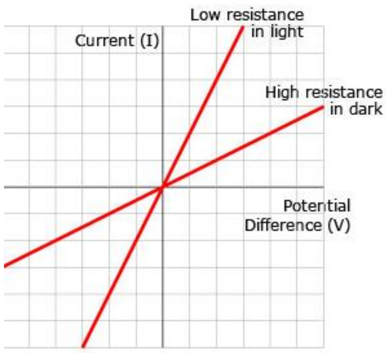
27. Benefits of LEDs:

- **a.** switch on instantly
- **b.** are very robust
- **c.** operate on low potential differences
- **d.** long working life
- **e.** Can be used as an indicator to see if part of a circuit has current running through it.

28. Light Dependent Resistor: LDR

- **a.** The greater the intensity of light shining on an LDR, the lower its resistance.
- **b.** The greater the intensity of light shining on an LDR, the more the number of electrons released. More charge carriers means a lower resistance.





29. **Resistivity:**
    a. The resistivity of a material is defined as the resistance of a piece of material having a length of one metre and a cross sectional area of one square metre.
    b. The following formula can be used to find the resistance of any conductor, providing that its dimensions and its resistivity are known: $\mathbf{R} = \frac{(\rho L)}{A}$
    c. Where
    R = resistance (Ω)
    ρ = resistivity (Ωm)
    L = Length (m)
    A= cross-sectional area (m^2)

30. **Resistivity of Metals:**
    a. Increasing temperature increases the amount of energy that metals have.
    b. Since its volume stays the same, the increase in energy comes in the form of kinetic energy caused by the vibration of atoms. Therefore, the delocalised electrons must progress through a more turbulent mass of atoms.
    c. This increases the resistance and in turn increases the resistivity.

31. **Resistivity of Semiconductors:**
    a. The resistivity of a semiconductor decreases with temperature.
    b. As the temperature increases, more electrons can break free of their atoms to become conduction electrons.
    c. At the same time, there are more collision, but this number is small in comparison.
    d. This increases the current as there are more charge carriers, which decreases the resistance, and in turn decreases the resistivity.

32. **Determining Resistivity of a metal/wire:**
    a. Find the cross sectional area of the test material. If you are using a wire then use a micrometer to measure the diameter of the wire.
    b. Clamp the test material/wire to a ruler where the ruler reads zero.
    c. Attach a flying lead to the wire.
    d. Record the length of the test wire connected in the circuit, the voltmeter reading and the ammeter reading.
    e. Use your readings and the formula ‘V=IR’ to calculate the resistance of the length of wire.
    f. Repeat for several lengths.
    g. Plot a graph of resistance against length.
    h. The gradient of the line of best fit is equal to R/L. Multiply it by A to find the resistivity of the material.

33. **Power:** Power is defined as the rate which energy is transferred (to a component) with respect to time. Power is measure in Watts (W)
    a. 1 **Watt** is equivalent to 1 Joule of work done per second.
    b. **P = W/t**

34. Power in electrical circuits: **P = VI**
    a. Where P = Power (W)
    b. Where V = Potential difference (V)
    c. Where I = Current (A)

35. How to use current and p.d. to obtain power: P = IV

$$current = \frac{coulombs}{second}, \quad potential\ difference = \frac{joules}{coulomb}, \quad power = \frac{joules}{second}$$

Therefore $$current \times p.d. = \frac{coulombs}{second} \times \frac{joules}{coulomb} = \frac{joules}{second} = power$$

36. The definition of resistance, V = IR , can be combined with P = IV:
    a. P = I(IR) ➔ **P = I^2 R (No V)**
    b. P = V(V/R) ➔ **P = V^2 / R (No I)**

37. Which equation for power you should use depends on what quantities are given in the equation.

38. **Energy Transfer:** $\boldsymbol{W = VIt}$
    a. Where W = energy transferred (J)
    b. Where V = Potential difference (V)
    c. Where I = Current (A)
    d. Where t = Time (s)
    e. Remember that *P = VI*, so the following equation of energy transferred can also be formed:
        i. $\boldsymbol{W = I^2Rt}$
        ii. $\boldsymbol{W = \frac{V^2\ t}{R}}$

39. **Kilowatt-hour:** 1 kW h is the energy transformed by a 1 kW device in a time of 1 hour. The kilowatt-hour is a unit of energy used for domestic energy consumption.

    a. **Work done (kWh) = Power (kW) x Time (h)**
    b. **1 kWh = 3.6 x 10^6 Joules**
    c. It is easier for companies to measure in kilowatt-hours. The typical energy consumption per month in a home is about 100kWh, which easier to deal with than 3.6 x 10^8 J. To the average person, numbers in standard form make it difficult to conceptualise energy use, and large numbers can also scare people. Therefore, the kilowatt-hour is used to mask this effect.

ELECTRICAL CIRCUITS:

1. **Kirchhoff's First Law:**
    a. The sum of the currents entering a point / junction is equal to the sum of the currents leaving (the same point)
    b. $\sum I_{in} = \sum I_{out}$
    c. This is a consequence of the conservation of charge, as charge carriers cannot be created or destroyed.

2. **Kirchhoff's Second Law:**
    a. The sum of the e.m.f. around a loop/series circuit is equal to the sum of the p.d. across each component in the same loop/series circuit.
    b. ***∑ e.m.f = ∑ p.d***
    c. This is a consequence of the conservation of energy, as energy cannot be created or destroyed.

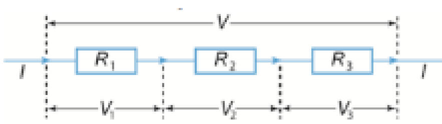
3. **Series Circuits:**
    a. A series circuit is a circuit in which the components are connected end-to-end and therefore are in the same loop, so there is only one path for current to flow.

4. **Series Circuit Rules:**
    a. The current (I) is the same all the way around a series circuit. This is because there are no junctions.

    b. The sum of the e.m.f. around a series circuit is equal to the sum of the p.d. across each component in the same series circuit.
        i. $\varepsilon = V_1 + V_2 + V_3 + \cdots + V_n$

    c. The sum of the p.d.s across each component in a series circuit is equal to the total p.d.
        i. $V_{\text{Total}} = V_1 + V_2 + V_3 + \cdots + V_n$

    d. The sum of the resistances across each component in a series circuit is equal to the total resistance.
        i. $R_{\text{Total}} = R_1 + R_2 + R_3 + \cdots + R_n$



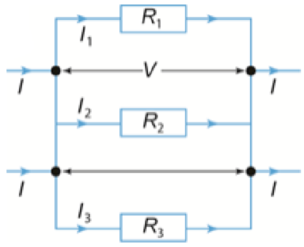
        ii. Proof:
            1. $V_{\text{Total}} = V_1 + V_2 + V_3 + \cdots + V_n$
            2. $\mathrm{V} = \mathrm{IR}$, so if I is constant
            3. $IR_{\text{Total}} = IR_1 + IR_2 + IR_3 + \cdots + IR_n$
            4. Dividing through by I gives $R_{\text{Total}} = R_1 + R_2 + R_3 + \cdots + R_n$

5. **Parallel Circuits:**
   a. A parallel circuit is a circuit in which there is more than one loop connected to the power supply, therefore more than one path for current to flow.

6. **Parallel Circuit Rules:**
   a. **Current is split at each junction**, so $I_{\text{Total}} = I_1 + I_2 + I_3 + \cdots + I_n$

   b. **The p.d. is the same across each component in a parallel circuit.** This is proven by Kirchhoff's 2nd law. The sum of e.m.f equals the sum of individual p.d.s in a certain loop.

   c. The inverse of the total resistance of a parallel circuit is equal to the sum of the inverse of the resistances of each branch of the circuit.

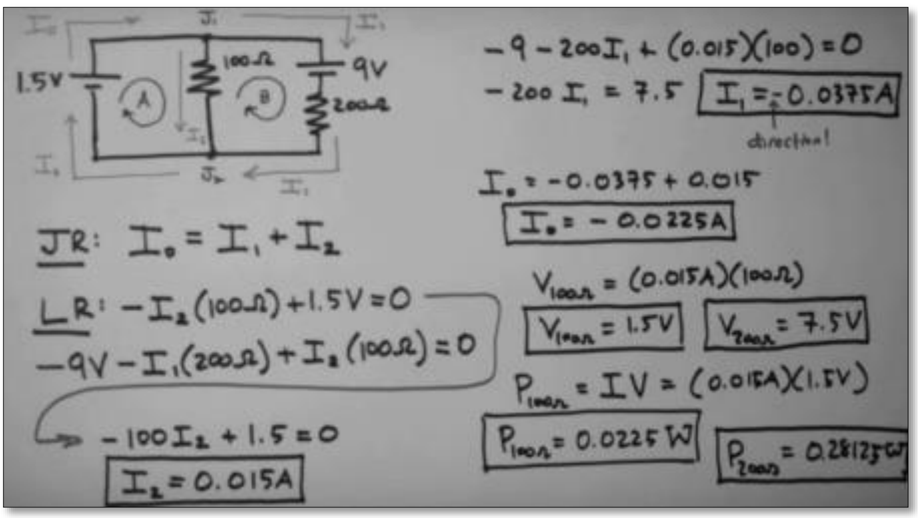


      i. $\dfrac{1}{R_{total}} = \dfrac{1}{R_1} + \dfrac{1}{R_2} + \dfrac{1}{R_3} + \cdots + \dfrac{1}{R_n}$

      ii. **Proof:**
         1. $I_{\text{Total}} = I_1 + I_2 + I_3 + \cdots + I_n$
         2. $\mathrm{V} = \mathrm{IR}$, so if V is constant
         3. $\dfrac{V}{R_{total}} = \dfrac{V}{R_1} + \dfrac{V}{R_2} + \dfrac{V}{R_3} + \cdots + \dfrac{V}{R_n}$
         4. Dividing through by V gives $\dfrac{1}{R_{total}} = \dfrac{1}{R_1} + \dfrac{1}{R_2} + \dfrac{1}{R_3} + \cdots + \dfrac{1}{R_n}$

   d. When working out the total resistance of a parallel circuit, don't forget to reciprocate your answer.

7.
   a. When you have circuit problems involving series and parallel circuits with more than one sources of e.m.f you can split them up into two different loops. Current is a vector quantity so it can also have direction. This must be taken into fact when solving these type of problems.
      i. e.g. 1A – 2A = -1A (this current is moving in the opposite direction to the positive direction)
   b. Example question and solution:
      i. **https://www.youtube.com/watch?v=Z2QDXjG2ynU**



8. **Internal Resistance:**

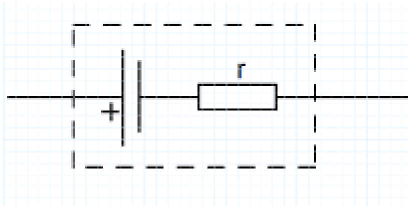
a. All sources of e.m.f. have internal resistance.

b. In a battery, this is due to the chemicals inside of it.

c. In a power supply it is due to the components and wires inside.

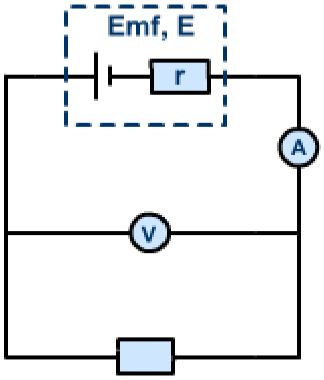
d. An e.m.f. source that has internal resistance is represented by a resistor 'r' within a dashed box.

i.



e. A typical circuit which has internal resistance can be seen below:

i.



ii. Using Kirchhoff's Second Law, $\mathcal{E} = V + v$, or E.m.f. = p.d. across load resistance + p.d. across internal resistance.

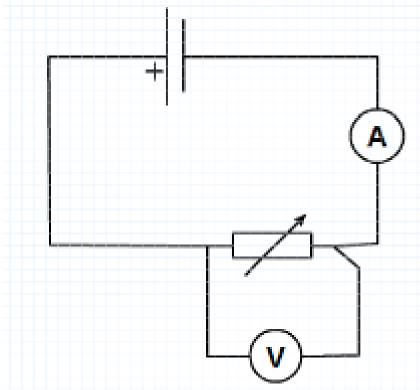
iii. **Terminal p.d.:** The p.d. across the load resistance (R) is the work done when one coulomb of charge flows through the load resistance.

iv. **Lost Volts:** the p.d. across the internal resistance, is equal to the energy wasted per coulomb of charge that overcomes the internal resistance.

v. The e.m.f. can also be calculated using the following formulas. These formulas are derived by using Ohms Law, V=IR.

1. $\mathcal{E} = I(R + r)$
2. $\mathcal{E} = V + Ir$
3. Where *R* is the load resistance and *r* is the internal resistance and *Ir* is the "lost volts".

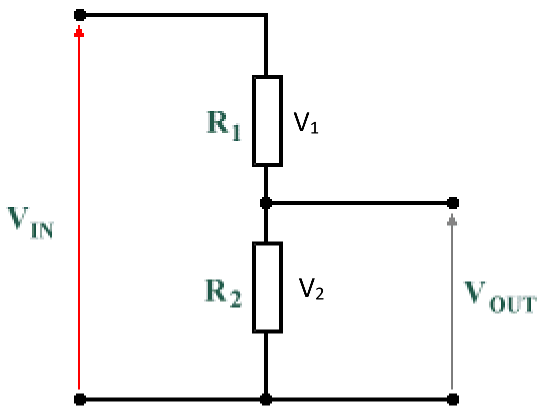
9. How to find the internal resistance of an e.m.f. source.



Set up a circuit with a powerpack, ammeter, variable resistor and a voltmeter.
Set power pack to 10V
Set resistance to low
Record I and V
Change R with the variable resistor.
Record new I and V
Repeat
Plot V against I
Compare to y = mx + c, where y= V , x= I , m = -r and c = e.m.f.

10. Potential Dividers:

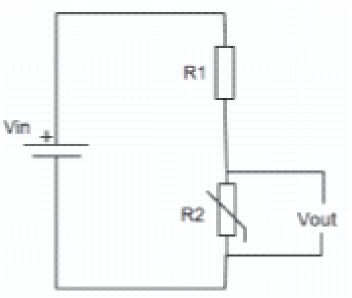
a. A potential divider circuit is a type of circuit containing two components designed to divide up the p.d. in proportion to the ratio of the resistances of the components.
b. A potential divider is a circuit that can be adjusted to produce a desired p.d. , V_{out} , that can be used to power and external circuit.



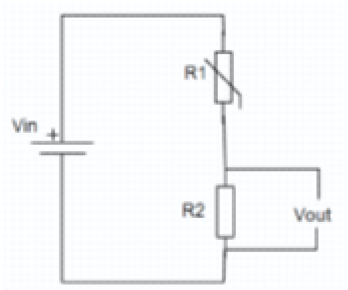
c. In a potential divider: $\frac{V_1}{V_2} = \frac{R_1}{R_2}$
d. In a potential divider: $V_{OUT} = V_{IN} \times \frac{R_2}{R_1 + R_2}$

11. Thermistors in a Potential Divider Circuit:

a. Thermistors can be used in **thermostats**. This is because:
   i. **In Cold** - R_2 Resistance is high, so higher proportion of p.d. will flow through R_2, so V_{Out} increases. Therefore enough p.d. is supplied to trigger a heater to increase.
   ii. **In Warm** - R_2 Resistance is low, so lower proportion of p.d. will flow through R_2, so less p.d. will be applied through V_{OUT}, which turns the heater off.
   iii. If we change R_2 to a variable resistor, we can control and calibrate the range at which V_{OUT} varies, allowing you to set the temperature at which a heater operates.



b. Thermistors can be used in **fridges**. This is because:

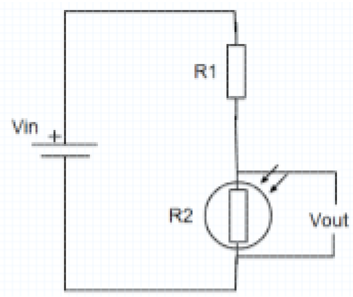


i. **In Cold** - Resistance of R_1 is high, so a lower proportion of the p.d. will be pushed past R_2, meaning that V_{OUT} is low so the fridge does not need to turn on to lower the heat.

ii. **In Warm** - Resistance of R_1 is low, so a higher proportion of the p.d. will be pushed past R_2, meaning that V_{OUT} is high so that the fridge turns on to lower the heat.

12. LDRs in a Potential Divider Circuit

a. LDRs can be used in Roadside lamps because:

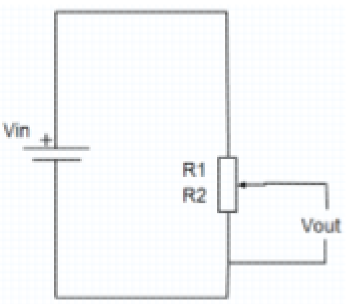


i. **In Dark -** $R_2 > R_1$, so V_{out} is large. This triggers the light to switch on.

ii. **In Light -** $R_2 < R_1$, so V_{out} is small. This triggers the light to switch off.

13. Potentiometers in Potential Divider Circuit:

a. A potentiometer is used in a potential divider circuit because:



i. It is more useful because it consists of a single variable resistor. It still acts as a current limiting resistor, but by moving the sliding contact we can achieve any value of V_{out} between 0V up till the input voltage.

ii. This type of circuit is used in a **stereo.** When you want to change the volume control, the potentiometer can be adjusted to achieve the chosen volume strength:

1. Increase in R_2 = increase in V_{out} = increase in volume.
2. Decrease in R_2 = decrease in V_{out} = decrease in volume.

14. Advantages of using data-loggers to monitor physical changes:

a. eliminate chance of human error
b. plots graphs straight away
c. very good at processing data
d. if a continuous record of temperature or light intensity was needed, then connecting the data logger to the thermistor/LDR because they will produce electrical outputs