HIGHER PHYSICS

Electricity

http://blog.enn.com/?p=481

HIGHER PHYSICS

a) MONITORING and MEASURING A.C.

Can you talk about:

- a.c. as a current which changes direction and instantaneous value with time.
- monitoring a.c. signals with an oscilloscope, including measuring frequency, and peak and r.m.s. values.

b) CURRENT, VOLTAGE, POWER and RESISTANCE

Can you talk about:

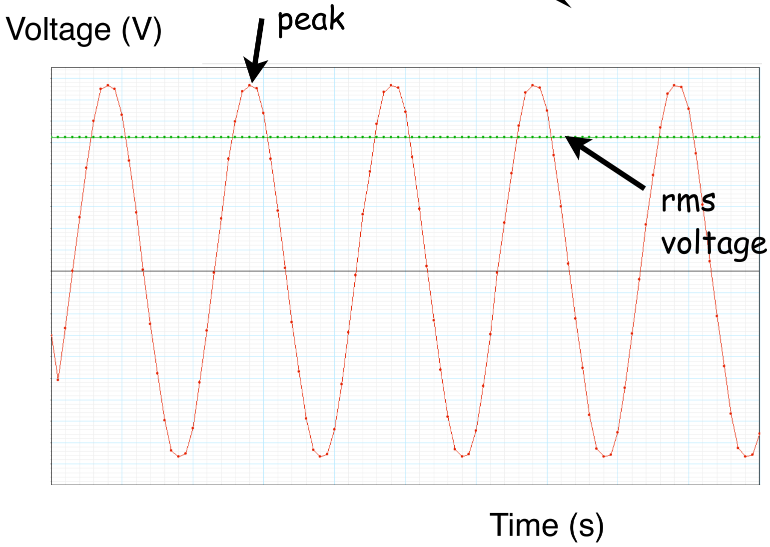
- **Current**, **voltage** and **power** in **series** and **parallel** circuits.
- Calculations involving voltage, current and resistance may involve several steps.
- **Potential dividers** as **voltage controllers**.

c) ELECTRICAL SOURCES and INTERNAL RESISTANCE

Can you talk about:

- **Electromotive force**, **internal resistance** and **terminal potential difference**.
- **Ideal supplies**, **short circuits** and **open circuits**.
- Determining internal resistance and electromotive force using **graphical analysis**.

A.C. / D.C.



This graph displays the a.c. and d.c. potential differences required to provide the same power to a given component. As can be seen the a.c. peak is higher than the d.c. equivalent. The d.c. equivalent is known as the root mean square voltage or V_{rms}. Similarly the peak current is related to the root mean square current.

Ohm's law still holds for both **d.c.** and **a.c.** values, therefore we can use the following equations:

$$V_{peak} = \sqrt{2}V_{rms}$$

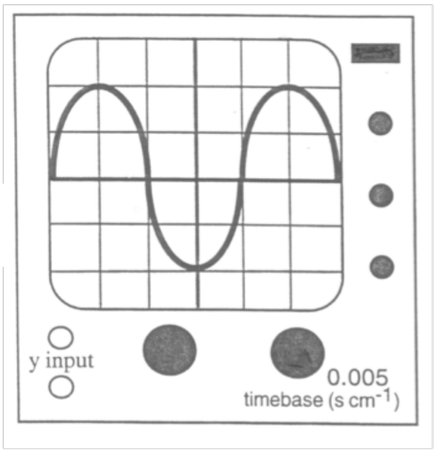
$$I_{peak} = \sqrt{2}I_{rms}$$

In the U.K., the **mains voltage** is quoted as **230 V a.c.** - This is the **r.m.s. value**. It also has a frequency of **50Hz**.

The **peak voltage** rises to approximately **325 V a.c.**

Using a cathode ray oscilloscope (C.R.O.) to measure peak voltage and frequency of an a.c. supply

Y gain
3V cm^{-1}



Two of the main controls a **cathode ray oscilloscope** (**C.R.O.**) are the **Y GAIN** and the **TIME BASE**.

The screen is covered with a square grid - The squares are usually 1 cm apart.

An **a.c. voltage** can be displayed on the screen by connecting an **a.c. supply** to the **Y INPUT** terminals.

Measuring peak Voltage with an oscilloscope

Peak voltage = peak height x Y gain setting
(cm) (Vcm^{-1})
= 2 cm x 3 V cm^{-1}

= 6 V

Measuring Frequency with an oscilloscope

Time for 1 wave = wavelength x time base
(s) = (cm) x (ms cm^{-1})
= 4 cm x 5 ms cm^{-1}
= 20 ms
= 20 x 10^{-3}

Frequency = 1 / time for one wave
= 1 / 20 x 10^{-3}
= 50 Hz

Current

Current is the **rate of flow** of charge in a circuit and can be calculated using

quantity of charge/ coulombs (C)

time (s)

$$\boxed{Q = It}$$

current (A)

In a complete circuit containing a cell, a switch and a bulb the **free electrons** in the conductor:

Will experience **a force** which will cause them **to move** drifting away from the **negatively charged** end towards the **positively charged** end.

Electrons are **negatively** charged.

Potential Difference

If **one joule** of work is done in moving **one coulomb** of charge between two points then the **potential difference (p.d.)** between the two points is 1 volt. (This means that work is done when moving a charge in an electric field)

work done in moving quantity of charge between 2 points in an electric field/ joules (J)

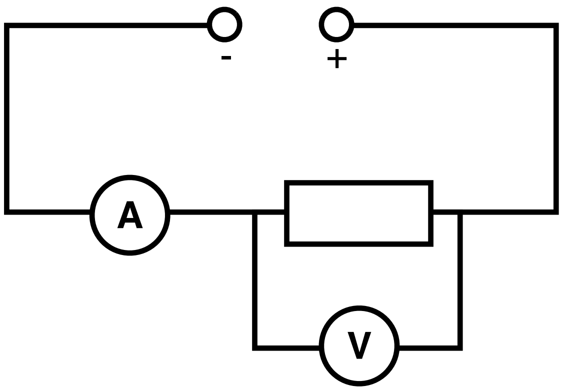
quantity of charge/ coulombs (C)

$$\boxed{E_w = QV}$$

potential difference between 2 points in an electric field/ joules per coulomb (JC^{-1}) OR volts (V)

When **energy is transferred** by a component (eg electrical to light and heat in a bulb) then there is a **potential difference (p.d)** across the component.

Using Ammeters and Voltmeters



Ammeters are connected in **series** with components and measure the current in amperes.

Voltmeters are connected in **parallel** (across a component) and measure the potential difference.

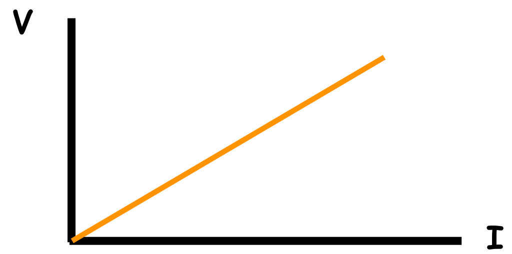
Ohm's Law

For a **constant temperature** for a given resistor:

V α I or V / I = constant

Constant is the **resistance** – measured in **Ohms (Ω).**

Potential difference versus current for a resistor, the line passes through the origin



potential difference/ Volts (V)

resistance (Ω)

$$\boxed{V = IR}$$

current (A)

Calculate the resistance of a 15 V light bulb if 2.5 mA of current passes through it:

$V = IR$
$15 = 2.5 \times 10^{-3} \times R$
$R = 15/2.5 \times 10^{-3}$
$R = 6\,000\ \Omega$

There are **components** which do not have a constant resistance as the current flowing through them is altered - eg a light bulb. Graphs of potential difference against current for this type of component will **not be a straight line**.

Resistance (Ω)

Resistors can be combined in **series** or in **parallel.** In any circuit there may be multiple combinations of resistors in both series and parallel, any combination of resistors will have an effective total resistance.

Series

$$R_T = R_1 + R_2 + \ldots$$

Parallel

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots$$

Power (W)

The **power** of a circuit component (such as a resistor) tells us how much **electrical potential energy** the component transforms (changes into other forms of energy) **every second:**

Power (W)

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

energy (J)

time (s)

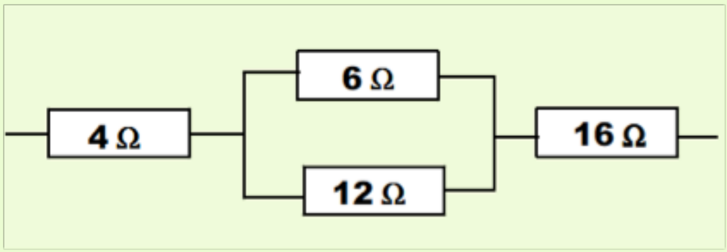
The following formulae are also used to calculate **power** (**P**):

$$P = IV$$

$$P = I^2R$$

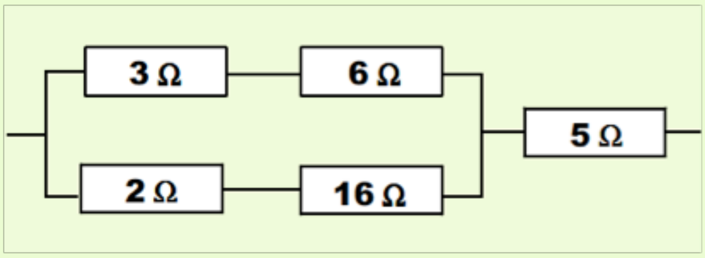
$$P = \frac{V^2}{R}$$

Determine the **total resistance** of the following resistor combinations.



Parallel Section first:
$1/R_T = 1/R_1 + 1/R_2$
$1/R_T = 1/6 + 1/12 = 2/12 + 1/12$
$1/R_T = 3/12$
$R_T = 12/3 = 4\ \Omega$

Now have 3 resistors in series
$R_T = R_1 + R_2 + R_3$
$R_T = 4 + 4 + 16 = 24\ \Omega$



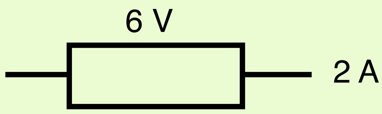
Simplify the parallel branches

Branch 1	Branch 2
$R_T = R_1 + R_2$	$R_T = R_1 + R_2$
$R_T = 3 + 6 = 9\ \Omega$	$R_T = 2 + 16 = 18\ \Omega$

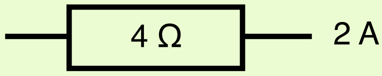
Calculate resistance of parallel section
$1/R_T = 1/9 + 1/18 = 2/18 + 1/18$
$1/R_T = 3/18 \Rightarrow R_T = 18/3 = 6\ \Omega$

Now find total
$R_T = R_1 + R_2 \quad R_T = 6 + 5 = 11\ \Omega$

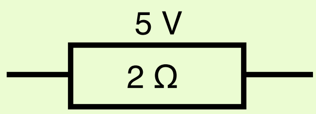
In each case, calculate the **power** of the resistor.



$P = I\,V$
$P = 2 \times 6$
$P = 12\ W$



$P = I^2 R$
$P = 2^2 \times 4$
$P = 16\ W$

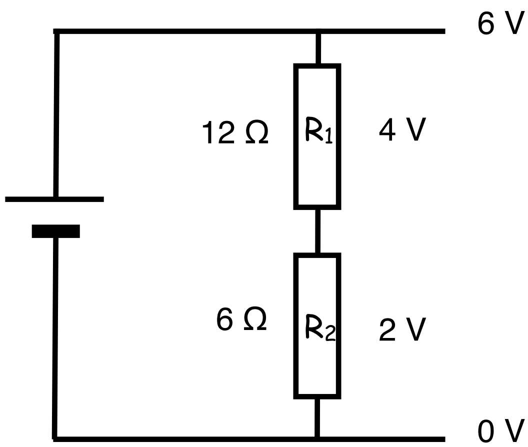


$P = V^2 / R$
$P = 5^2 / 2$
$P = 12.5\ W$

Potential Dividers

Any circuit that contains **more than one component** can be described as a **potential divider** circuit. In its simplest form a **potential divider** is 2 resistors connected across a power supply. If another component is placed **in parallel** with a part of the potential divider circuit, the operating potential difference of this component can be controlled.

The **p.d.** across each resistor in **proportion** to the **resistance** in the circuit. The 12 Ω resistor has **2/3 of the total** resistance, and therefore **2/3 of the total p.d.** is across this resistor.



Potential Dividers - Useful Equations

$$\frac{V_1}{V_2} = \frac{R_1}{R_2}$$

V_1: potential difference across R_1/ Volts (V)

V_2: potential difference across R_2/ Volts (V)

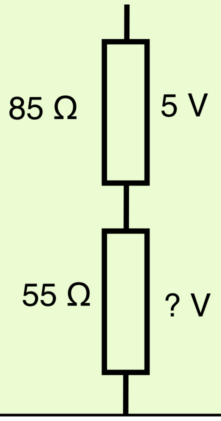
R_1: resistance of R_1/ (Ω)

R_2: resistance of R_2/ (Ω)

$$V_1 = \left(\frac{R_1}{R_1 + R_2}\right) V_s$$

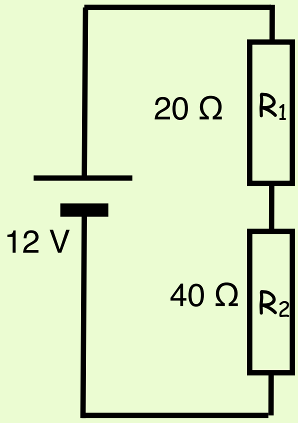
V_s: potential difference of the supply/ Volts (V)

Find the missing **potential difference.**



$V_1/V_2 = R_1/R_2$
$5/V_2 = 85/55$
$5/V_2 = 1.55$
$V_2 = 5/1.55$
$V_2 = 3.24$ V

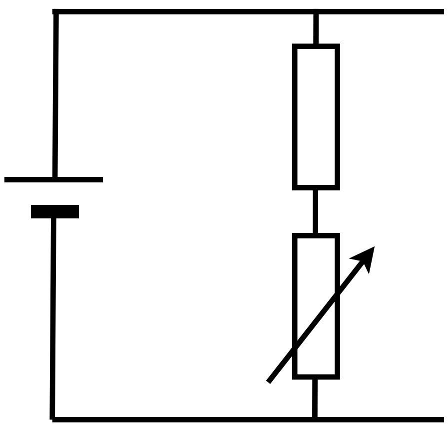
What is the potential difference across R_2?

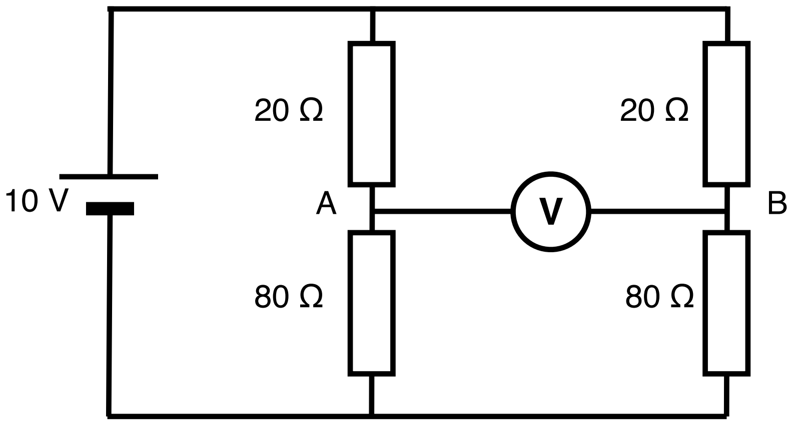


$V_2 = R_2/(R_1 + R_2) \times V_s$
$V_2 = 40/(20 + 40) \times 12$
$V_2 = 8$ V

Potential Dividers as voltage controllers

If a variable resistor is placed in a potential divider circuit then the voltage across this the resistor can be controlled.





Alternatively, **two potential dividers** can be connected in parallel. A voltmeter is connected between the two dividers. Resistors can be chosen such that there is different electrical potential at point a and B. This pd can be controlled by altering the resistors.

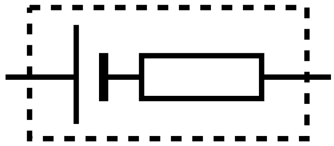
The potential at point A is 10 - 2 = 8 V
The potential at point B is 10 - 5 = 5 V
Therefore the reading on the voltmeter is 8 - 5 = 3 V

Internal Resistance (r) of a Cell

Resistance is the opposition to the flow of electrons. When electrons travel through a cell, they have to pass **resistance** - so every cell has a **resistance** known as its **internal resistance** (**r**).

A cell can be thought of as a source of **emf** (**E**) **in series with an internal resistor** (**r**).

Circuit symbol for cell with emf



Lost Volts

A cell has **internal resistance** therefore **potential difference** (**voltage**) is lost across it (turned into heat) when the cell is connected to a circuit. The **LOST VOLTS** are **not available** to the components in the circuit.
Calculated by either finding Ir or emf - tpd (E - IR)

Terminal Potential Difference (tpd)

As a result of **LOST VOLTS**, the **potential difference** (**voltage**) a cell **is** able to supply to components in a circuit is called its **TERMINAL POTENTIAL DIFFERENCE** (**t.p.d.**)

This is the **potential difference** (**voltage**) across the **cell terminals** when it is connected in a circuit.

electromotive force (emf)

When energy is being transferred from an external source (like a battery) to the circuit then the voltage is known as the **emf**

emf of a source is the electrical energy supplied to each Coulomb of charge which passes through the source.

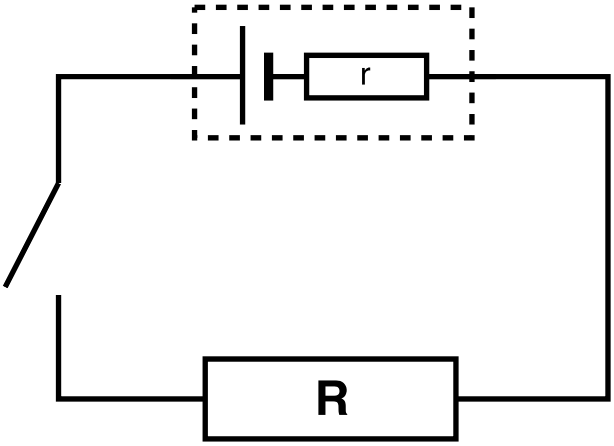
emf of a source tells you how much energy the source gives to the electrons that pass through it. It is measured in joules per coulomb of charge. (This is equivalent to the volt).

emf. is the **maximum** voltage a source can provide.

The **emf** of a **new cell** is the "**voltage value**" printed on it.

To find the **emf** of a cell, we connect a **high resistance voltmeter** across its terminals when **no other components are connected to it**. Because the **voltmeter** has a **high resistance**, no current is taken from the cell - When no current flows, we have an **open circuit**. We say that "**the emf of the cell is the open circuit potential difference (p.d.) across its terminals.**"

An electric circuit can be simplified to the form shown below. The circuit consists of a cell with **e.m.f.** (**E**) and **internal resistance** (**r**) connected to an **external resistor** (**R**) through a **switch**. An **electric current** (**I**) flows round the circuit when the **switch** is **closed**.



When the switch is **open**, a voltmeter connected across the cell terminals will show the cell emf. This is because there is no current flowing and therefore there are no lost volts across the internal resistor.

When the switch is **closed**, a voltmeter connected across the cell terminals will show the cell tpd. This is because there is now a current flowing and therefore there are lost volts across the internal resistor.

Circuit current/ Amperes (A)

Total external load resistance (Ω)

emf/ Volts (V)

Internal resistance (Ω)

$$E = IR + Ir$$

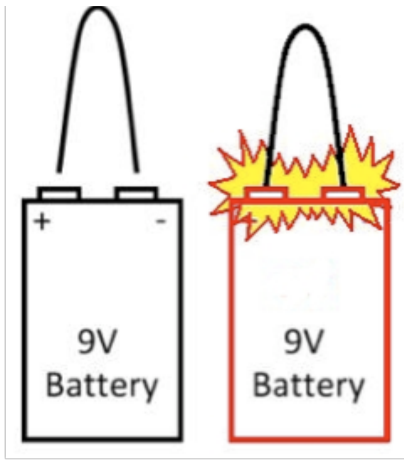
tpd/Volts (V)

Lost Volts/Volts (V)

Short circuit current

When the 2 terminals of a cell are connected together with just a wire, which has (almost) zero resistance, we say the cell has been **SHORT CIRCUITED.**

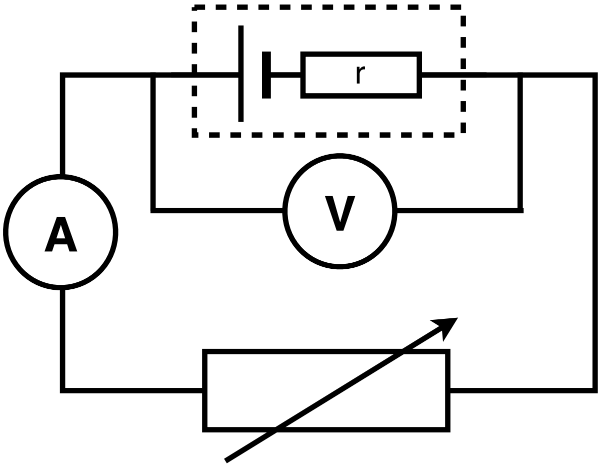
- The **external resistance** (**R**) = 0. In this case: E = IR
- I is known as the short circuit current
- This is dangerous because the cell will heat up as electrical energy is converted to heat due to the internal resistance.



http://www.batteryexpress.org.uk/What-is-a-Short-Circuit.htm

Determine the Internal Resistance

It is possible to find the emf and internal resistance of a power supply using the circuit shown. The load resistance is altered and the corresponding current and tpd values are recorded.

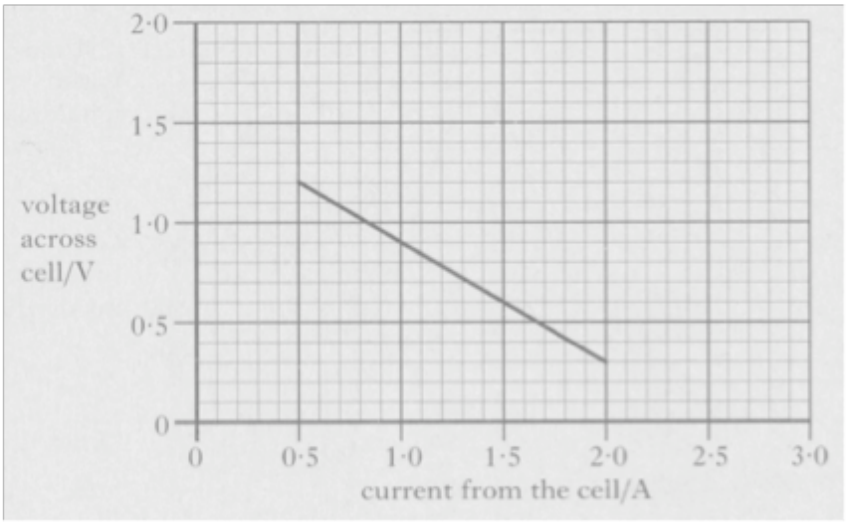


A graph of tpd versus current is plotted. Displaying the equation of this line in the format of $y = mx + C$ we find: $V = -mI + C$

At I=0, V is defined as emf, therefore C = E giving

$$V = -mI + E$$

Comparing to $E = V + Ir$, we see that $r = -m$



y-intercept = emf = 1.5 V

Gradient = - r

$$\text{Gradient} = \frac{\text{Change in y}}{\text{Change in x}}$$

Gradient = 0.5 / 0.85 = 0.59

Internal resistance = 0.59 Ω

In this circuit, when the switch is open, the voltmeter reads 2.0 V. When the switch is closed, the voltmeter reading drops to 1.6 V and a current of 0.8 A flows through resistor R.

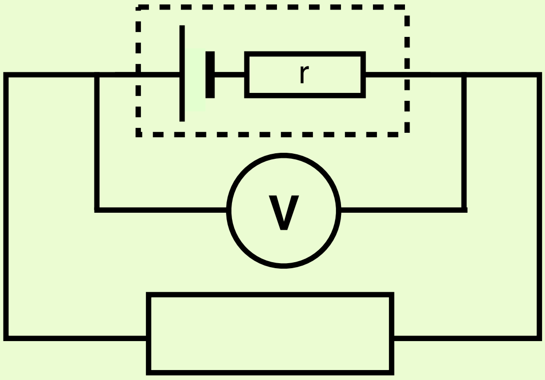
(a) State the value of the cell emf

(b) State the terminal potential difference across R when the switch is closed.

(c) Determine the 'lost volts' across the cell.

(d) Calculate the resistance of resistor R.

(e) Calculate the internal resistance of the cell.



(a) 2.0 V

(b) 1.6 V

(c) E = tpd + lost volts
2.0 = 1.6 + lost volts
lost volts = 0.4 V

(d) tpd = IR
1.6 = 0.8 x R
R = 2 Ω

(e) lost volts = Ir
0.4 = 0.8 x R
R = 0.5 Ω

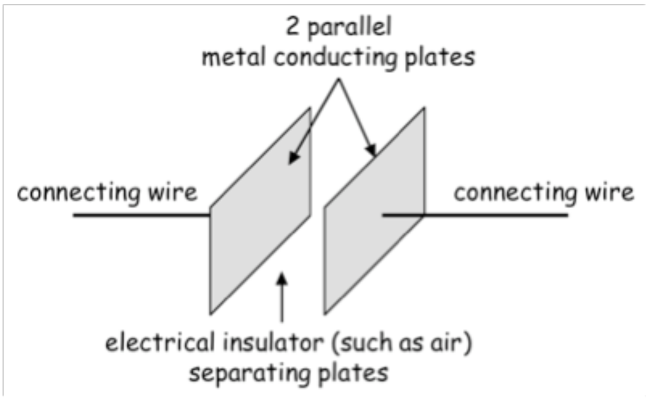
d) CAPACITORS

Can you talk about:

- Capacitors and the relationship between capacitance, charge and potential difference.
- The total energy stored in a charged capacitor is the area under the charge against potential difference graph.
- Use the relationships between energy, charge, capacitance and potential difference.
- Variation of current and potential difference against time for both charging and discharging.
- The effect of resistance and capacitance on charging and discharging curves.

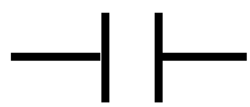
Capacitors - Capacitance, Charge and Potential Difference

Capacitors are very important components in electrical devices. They store **electrical energy** by allowing a **charge distribution** to accumulate across two conducting plates. The ability to store this charge distribution is known as **capacitance**.

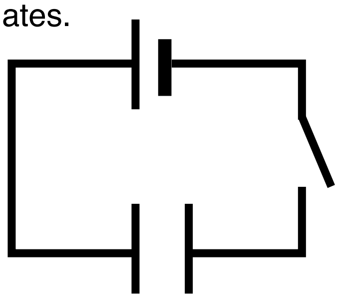


A simple **capacitor** consists of **2 parallel metal conducting plates** separated by an **electrical insulator** such as **air**.

Circuit symbol for capacitor:



To **energise** a capacitor, we connect a **battery** (or **d.c. power supply**) across its conducting plates.

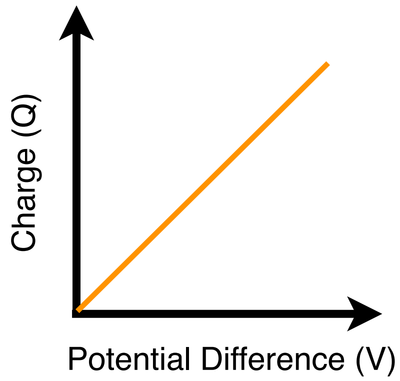


When the switch is closed, **electrons** flow onto plate A, and away from plate B, thus creating a **charge distribution**.

Electric charge is now stored on the conducting plates.

This creates a **potential difference** between the conducting plates which eventually becomes equal to the **battery/supply voltage**.

The **higher** the **potential difference (V)** between the conducting plates, the greater the **charge (Q)** distribution between the plates. The **charge (Q)** stored between the 2 parallel conduction plates is **directly proportional** to the potential difference (V) between the plates. The constant, which equals the ' ratio of charge to potential difference', is called the **capacitance** of the capacitor.



A graph of **charge** versus **potential difference** for a capacitor illustrates the **direct proportionality** between charge and pd. The gradient of this line (the **ratio** between **Q and V**) is defined as the **capacitance (C)** of the capacitor. This leads to the the relationship below.

$$\boxed{Q = CV}$$

Charge/Coulombs (C)

potential difference/ Volts (V)

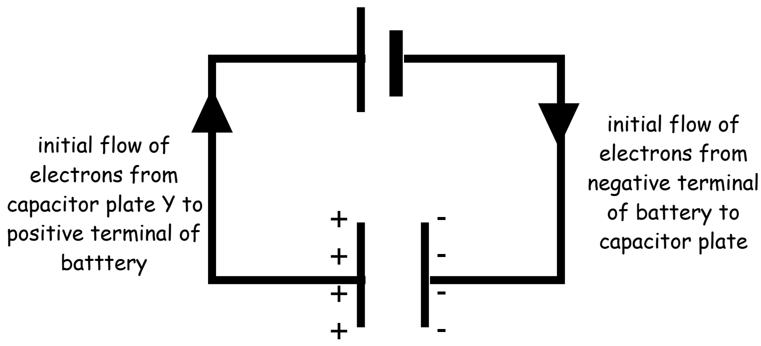
Capacitance/ Farads (F)

Note about the Farad

The farad is a very large unit - Too large for the practical capacitors used in our household electronic devices (televisions, radios, etc). These practical capacitors have smaller "sub-units":

microfarads (μF) ...x10^{-6}F nanofarads (nF) ...x10^{-9}F picofarads (pF)...10^{-12}F

Word Done Charging a Capacitor

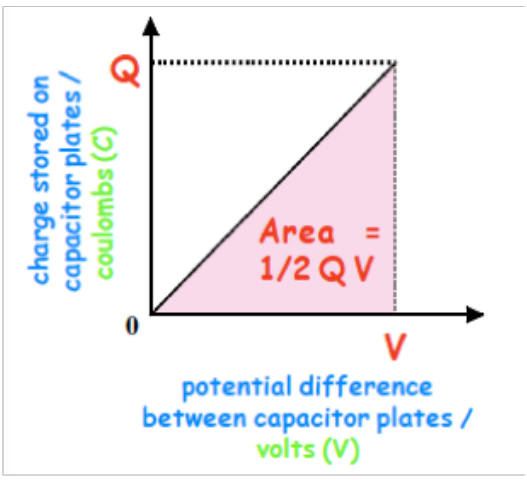


This circuit represents the **energising of a capacitor**. Negatively charged electrons flow and build up on plate X. Plate X becomes negatively charged. As a result, negatively charged electrons on plate Y of the capacitor are repelled and travel through the wire towards the positive terminal of the battery. Plate Y becomes **positively charged**.

To push electrons onto the negatively charged plate, the battery must do **work** against the potential difference between the capacitor plates.

WORK MUST BE DONE TO CHARGE A CAPACITOR

The work done charging a capacitor equals the area under the QV graph for charging a capacitor.



Energy Stored in a Capacitor

Work done by a battery/power supply in **'charging'** a capacitor is stored as **electrical potential energy** in an **electric field** which exists between the charged capacitor plates.
This **electrical potential energy** is released when the capacitor is **discharged**, e.g., by connecting both plates of the capacitor to a light bulb.

E = energy stored in capacitor/ joules (J)
Q = charge stored on capacitor plates/ coulombs (C)
V = potential difference between capacitor plates/ volts (V)
C = capacitance of capacitor/ farads (F)

Equations for energy stored in a capacitor

$$E = \frac{1}{2}QV \qquad E = \frac{1}{2}CV^2 \qquad E = \frac{1}{2}\frac{Q^2}{C}$$

Calculate the energy stored in a 15 V capacitor with a stored charge of 2.0×10^{-6}

$E = 1/2\ QV$
$E = 0.5 \times 2.0 \times 10^{-6} \times 15$
$E = 1.5 \times 10^{-5}$

Calculate the capacitance of a capacitor with 0.005 J of energy stored and a pd of a 2 V.

$E = 1/2\ CV^2$
$0.005 = 0.5 \times C \times 2^2$
$C = 2.5 \times 10^{-3}$ F

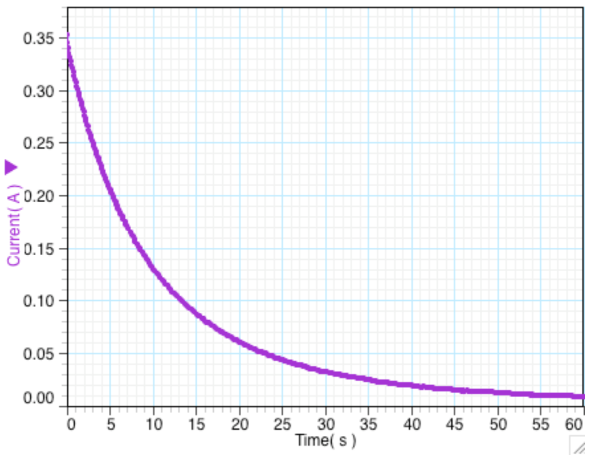
Calculate the charge stored on the plates of a capacitor with 6.0×10^{-3} J of energy and a capacitance of 3 microFarads.

$E = 1/2\ Q^2/C$
$6.0 \times 10^{-3} = 0.5 \times Q^2 / 3 \times 10^{-6}$
$Q^2 = 3.6 \times 10^{-8}$
$Q = 1.9 \times 10^{-4}$ C

Current-Time Graphs for a Charging Capacitor

The **resistor** in the circuit sets the value of the **maximum current** which can flow.

At any instant during the **charging process**, the size of the **current** flowing depends on the **potential difference** across the resistor at that instant and the **resistance** of the resistor. The capacitor is in series with the resistor, therefore the current flowing through both components will be the same at any particular point in time. A graph of current versus time can be plotted.



The **maximum current** which can flow is found by calculating **V_{supply}/R.**

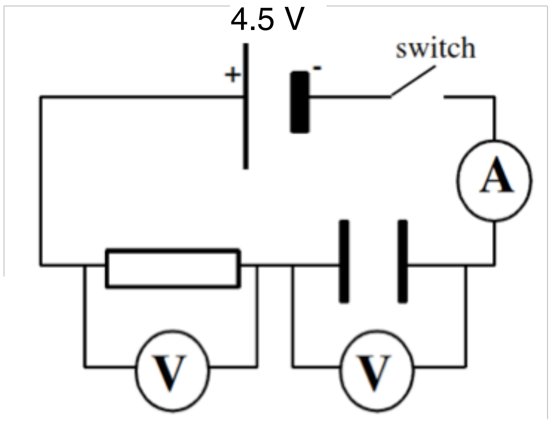
As the **capacitor energises**, there is **greater resistance** to flow of charge in the circuit. When the capacitor is **fully energised** (has a p.d. equal to the supply p.d.) **no current** can flow.

Voltage-Time Graphs for a Charging Capacitor

This electric circuit can be used to investigate the charging of a **capacitor**.

(The **resistor** is present to set the value of the ***maximum current*** which can flow).

Current starts to flow ***immediately the switch is closed***.



In the circuit, the capacitor and resistor are connected in series. This means that, at any time:

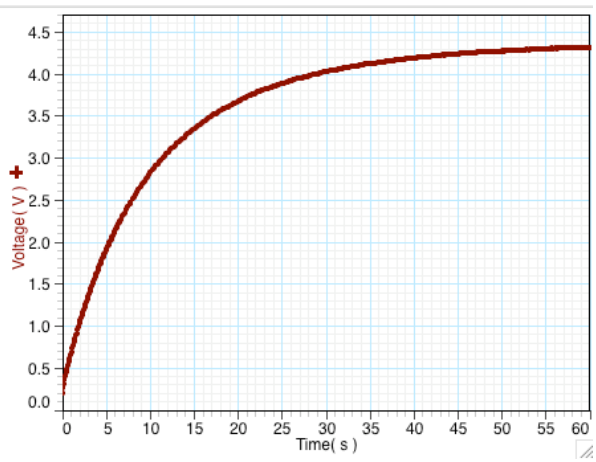
potential difference across capacitor + potential difference across resistor = supply voltage

At the **instant** the switch is closed (time = 0.0 s), the **capacitor is not charged**. The potential difference across it is **0.0 V**. Therefore the potential difference across the **resistor** is **4.5 V**.

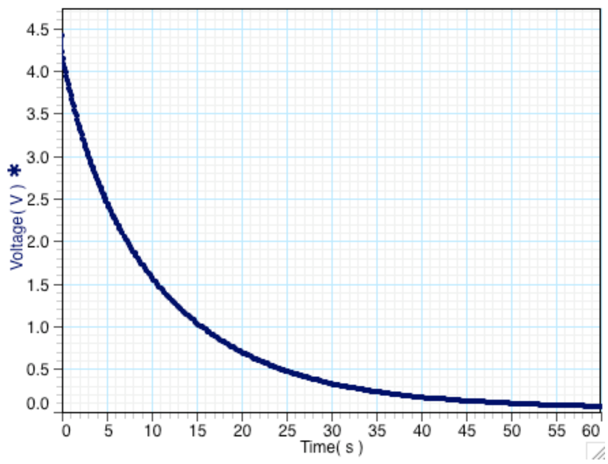
As time passes, the potential difference across the **capacitor increases**. Therefore the potential difference across the **resistor decreases**.

After a certain time, the capacitor will become 'fully charged'. The potential difference across it will be 4.5 V and the potential difference across the resistor equals 0.0V.

Capacitor



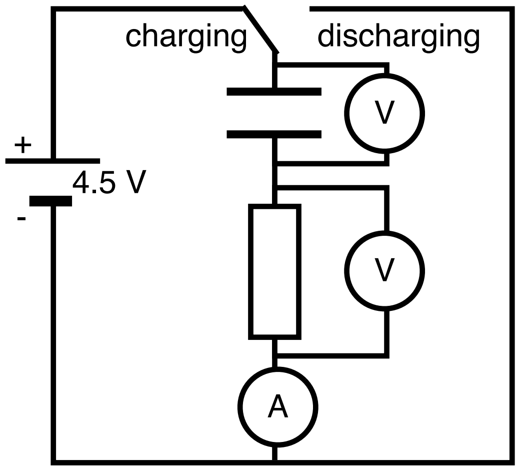
Resistor



Note that for any particular time, the sum of the voltage across the capacitor and the potential difference across the resistor is equal to the supply potential difference (in this case 4.5 V).

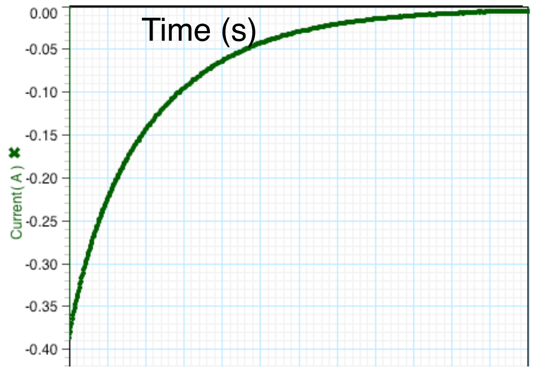
Current-Time and Voltage-Time Graphs for a Discharging Capacitor

This electric circuit can be used to investigate the **discharging of a capacitor.**
(The **resistor** is present to set the value of the **maximum current** which can flow).
The **capacitor** is **'fully charged'** - No current is flowing. The **capacitor** will **discharge** and **current** will start to flow **immediately the switch is moved to the right** – **Electrons** will flow from the **bottom capacitor plate**, through the resistor and ammeter to the **top capacitor plate**, until the **potential difference** (**voltage**) between the plates becomes **zero**, when no more electrons will flow - The **current** will be **zero**.



- The **discharge current** decreases from a maximum value of to zero.

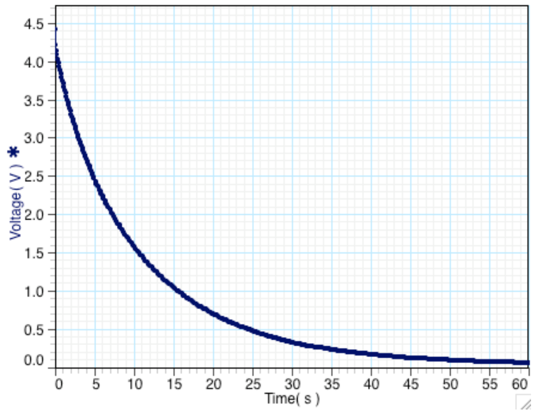
  The **discharge current** flows in the opposite direction to the charging current, so it is common to draw the **discharging current-time** graph in this form:

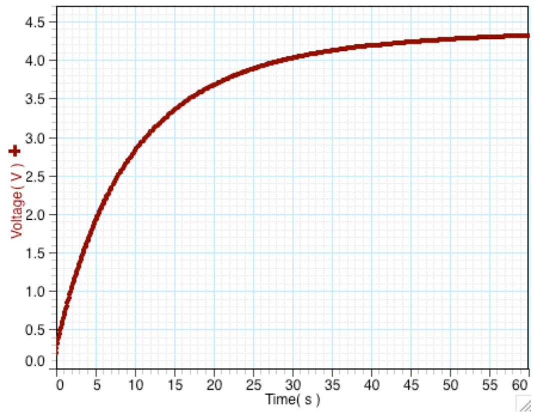


- The **potential difference** (**voltage**) across the **capacitor** decreases from the **battery voltage** to **zero**.

- The **potential difference** (**voltage**) across the resistor decreases from the **battery voltage** to **zero** (as the current in the circuit decreases).

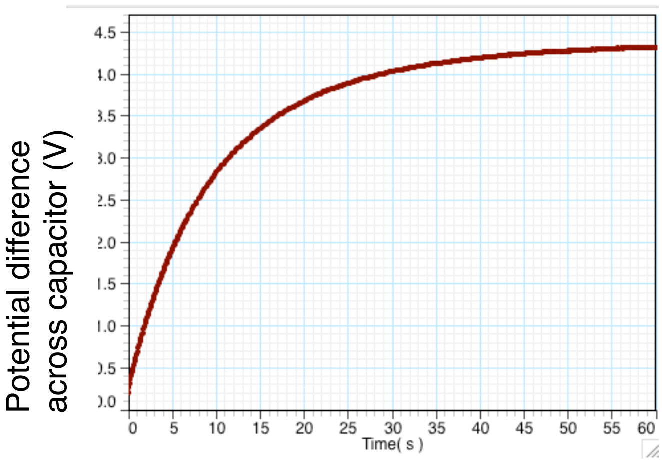
The potential difference across the capacitor always equals the potential difference across the resistor.

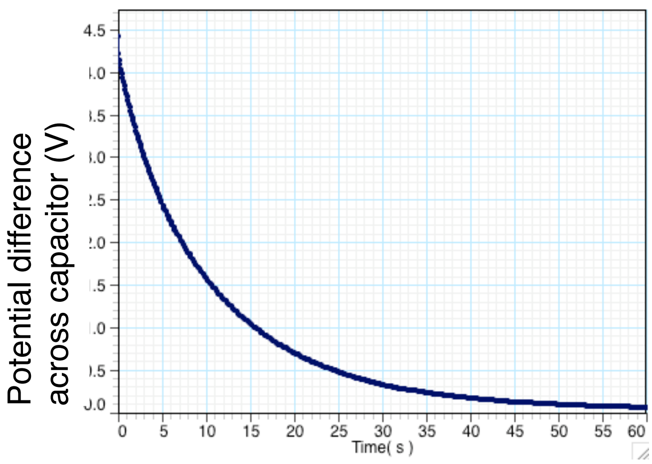


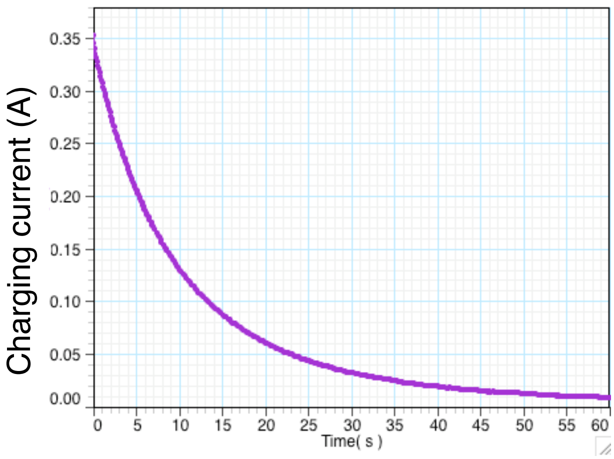


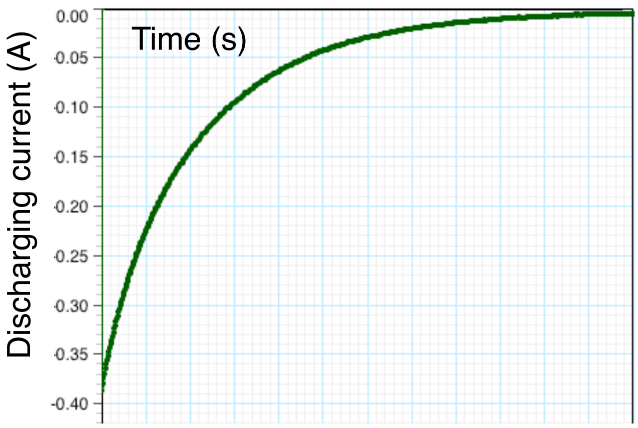
Comparison of Graphs for Charging and Discharging Capacitors

Charging	Discharging









Time For A Capacitor to Charge and Discharge

The **time** taken for a capacitor to charge or discharge depends on the **capacitance of the capacitor** and the **resistance of the resistor** connected in series with it.

Increasing the capacitance, **increases** the charging and discharging time because **more** charge is stored on the capacitor.

Increasing the resistance, **increases** the charging and discharging time because **less** current flows at the start of the process.

Uses of Capacitors

Storing Energy

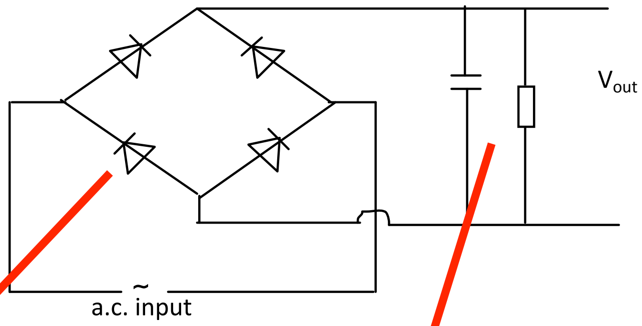
A camera flash requires a **rapid** release of **energy**, this cannot be achieved from a battery, however a battery can be used to charge a capacitor, this capacitor can then provide a very high current.

Time Delays

Capacitors can introduce a time delay into electronic circuits due to the time they take to charge. They can also allow lights to flash at regular intervals.

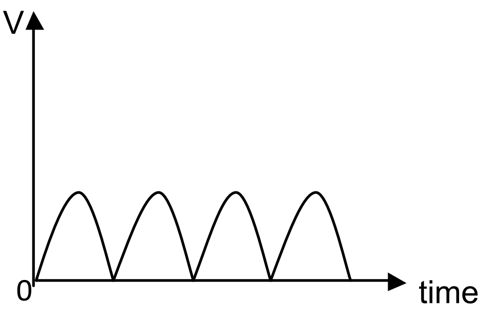
Full wave rectification

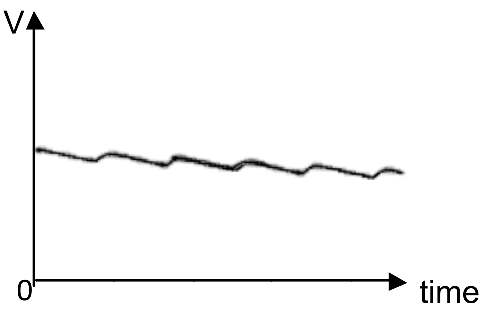
Full Wave Rectification is when a number of capacitors are used to smooth a rectified d.c. signal. A rectified d.c. signal is produced when four diodes connected as shown below to produce a d.c. output from an a.c. input.



If a capacitor is connected in parallel with the supply, the constant **charging and discharging** will reduce the rectified voltage to an almost smooth voltage with a small "ripple".
This is how **d.c is produced** from the **mains a.c voltage** in the power packs used in the lab.

The output voltage is d.c. but it is **not smooth**. The diode combination produces this output. Such a circuit is known as a **Rectifier Bridge.**





2a) CONDUCTORS, SEMICONDUCTORS and INSULATORS

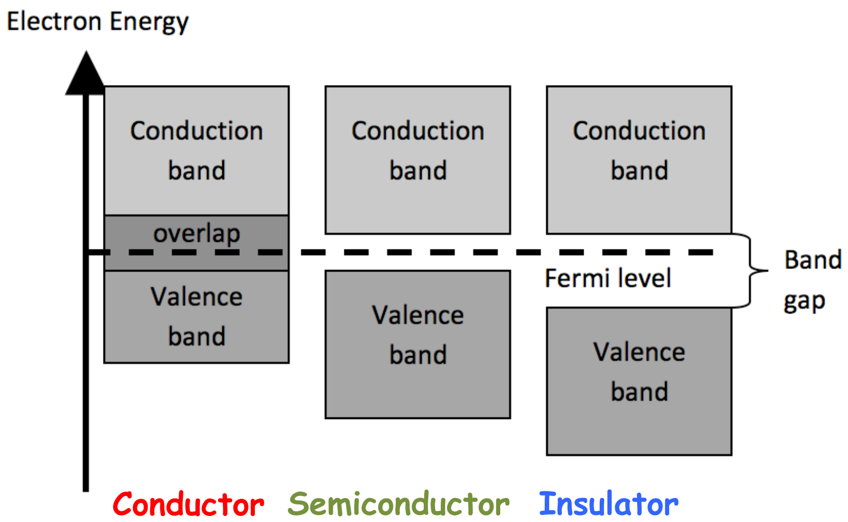
Can you talk about:

- Solids can be categorised into conductors, semiconductors or insulators by their ability to conduct electricity.
- The electrons in atoms are contained in energy levels. When the atoms come together to form solids, the electrons then become contained in energy bands separated by gaps.
- In metals which are good conductors, the highest occupied band is not completely full and this allows the electrons to move and therefore conduct. This band is known as the conduction band.
- In an insulator the highest occupied band (called the valence band) is full. The first unfilled band above the valence band is the conduction band.
- For an insulator the gap between the valence band and the conduction band is **large** and at room temperature there is not enough energy available to move electrons from the valence band into the conduction band where they would be able to contribute to conduction.
- There is no electrical conduction in an insulator.
- In a semiconductor the gap between the valence band and conduction band is smaller and at room temperature there is sufficient energy available to move some electrons from the valence band into the conduction band allowing some conduction to take place. An increase in temperature increases the conductivity of a semiconductor.

Conductors, Semiconductors and Insulators

Solid materials can be classified into **three groups**, depending on their electrical properties.

Conductors	They have lots of free electrons which can be made to flow through the material. Examples are all metals, semi metals like carbon-graphite, antimony and arsenic. In a conductor, the highest occupied band is not completely full. This allows the electrons to move through the material and conduct easily. This band is called the **conduction** band. [In a conductor the valence band overlaps the conduction band.]
Insulators	They have very few free electrons which cannot move easily. Examples are plastic,wood and glass. In an insulator the highest occupied band is full. This is called the **valence** band, by analogy with the valence electrons of an individual atom. The first unfilled band above the valence band is the conduction band. For an insulator the energy gap between the valence band and the conduction band is large and at room temperature there is not enough energy available to move electrons from the valence band into the conduction band, where they would be able to contribute to conduction.
Semi-conductors	They behave like insulators when pure but will conduct on the addition of an impurity and / or in response to a stimulus such as light, heat or a voltage. Example is silicon. In a semiconductor the gap between the **valence** band and the **conduction** band is smaller, and at room temperature there is sufficient energy available to move some electrons from the valence band into the conduction band, allowing some conduction to take place. An increase in temperature increases the conductivity of a semiconductor as more electrons have enough energy to make the jump to the conduction band. This is the basis of a thermistor where an increase in temperature produces a lower resistance.



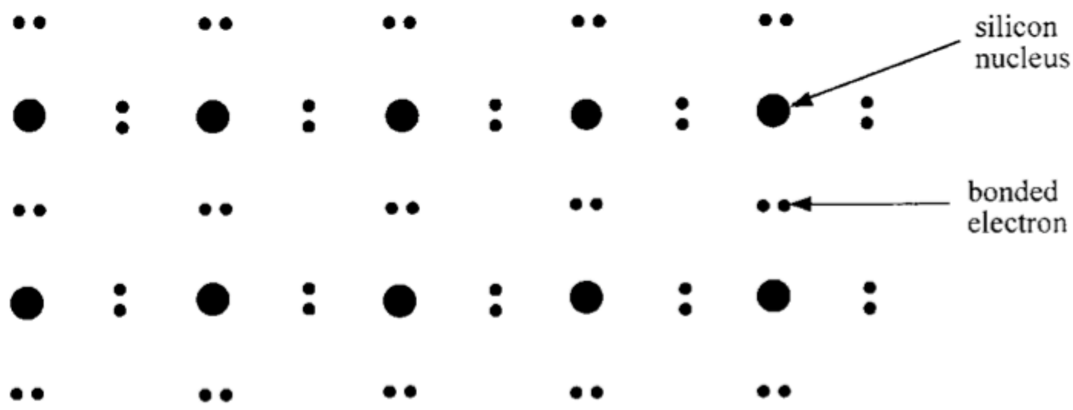
Things to note:
There are groups of energies that are not allowed, creating a **band** gap. Just as the electrons in individual atoms fill the lower energy levels first; the electrons in a solid will fill the lower bands first. The highest occupied band in an atom is called the **valence band**.

Band theory
The electrons in isolated atoms occupy discrete energy levels. However, when arranged in the crystal lattice of a solid the electrons in adjacent atoms cannot occupy the same energy levels. So many more slightly different energy levels come into existence creating a band of permitted energy levels.

Bonding in semiconductors

The most commonly used semiconductors are **silicon** and **germanium**. Both these materials have a **valency of four**; they have **four outer electrons** available for bonding.

In a pure crystal, each atom is bonded covalently to another four atoms; all of its outer electrons are bonded and therefore there are few free electrons available to conduct. This makes the resistance very large. Such pure crystals are known as intrinsic semiconductors.

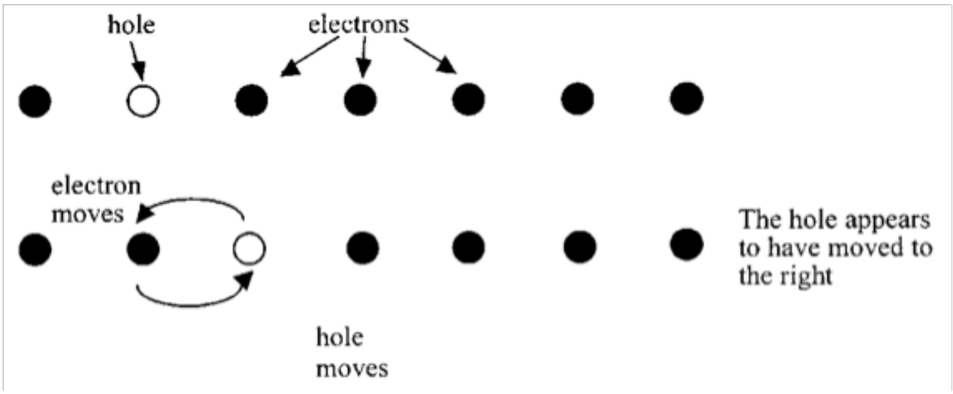


The few electrons that are available come from imperfections in the crystal lattice and thermal ionisation due to heating. A higher temperature will thus result in more free electrons, increasing the conductivity and decreasing the resistance, as in a thermistor.

Holes

When an electron leaves its position in the crystal lattice, there is a space left behind that is positively charged. This lack of an electron is called a **positive hole**.

This hole may be filled by an electron from a neighbouring atom, which will in turn leave a hole there. In this model it is technically the electron that moves but the effect is the same as if it was the hole that moved through the crystal lattice. The hole can then be thought of as a positive charge carrier. In a complex semiconductor it is easier to calculate what is happening in terms of one moving positive hole, rather than many electrons.



2b) P-N JUNCTIONS

Can you talk about:

- During manufacture, the conductivity of **semiconductors** can be controlled, resulting in two types: **p-type** and **n-type**.
- When p-type and n-type material are joined, a layer is formed at the junction. The electrical properties of this layer are used in a number of devices.
- **Solar cells** are p-n junctions designed so that a potential difference is produced when photons enter the layer. This is the **photovoltaic effect**.
- **LEDs** are p-n junctions which emit **photons** when a current is passed through the junction.

Doping

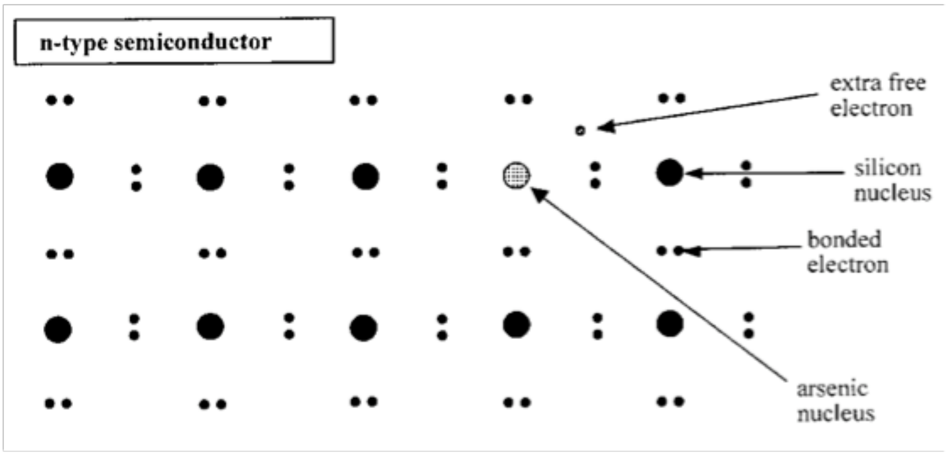
The electrical properties of semiconductors make them very important in **electronic devices** like transistors, diodes and light-dependent resistors (LDRs).

In such devices the electrical properties are dramatically changed by the addition of very small amounts of **impurities**. The process of adding impurities to these semiconductors is known as **doping** and once doped they are known as **extrinsic semiconductors**.

n-type semiconductors

If an impurity such as arsenic (As), which has **five** outer electrons, is present in the crystal lattice, then four of its electrons will be used in bonding with the silicon. The fifth electron will be effectively free to **move** about and **conduct**. Since the ability of the crystal to conduct is increased, the **resistance** of the semiconductor is therefore **reduced**. Because of the extra electron energy levels created by the fifth electron; the Fermi level is raised and is closer to the conduction band than in an intrinsic semiconductor.

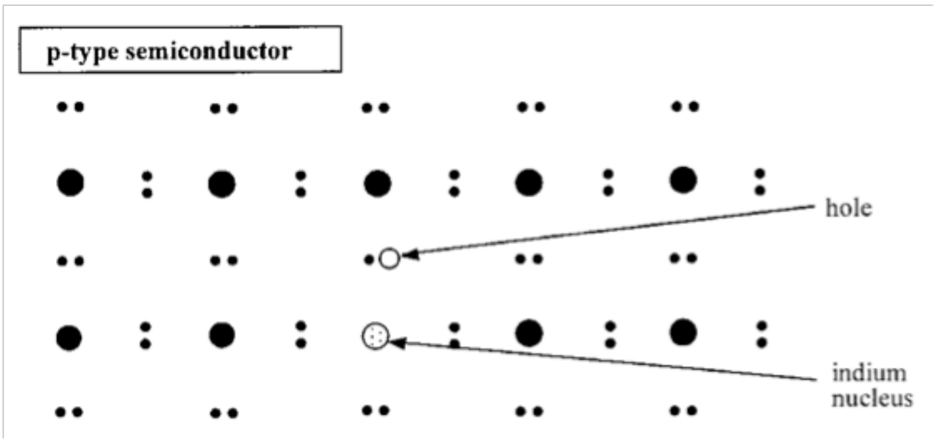
This type of semiconductor is called n-type, since most conduction is by the movement of free electrons, which are, of course, negatively charged.



p-type semiconductors

The semiconductor may also be doped with an element like indium (In), which has only **three** outer electrons. This produces a 'hole' in the crystal lattice, where an electron is 'missing'. Electrons in the valence band can quite easily move in to the energy levels provided by these holes. As a result the Fermi level is closer to the valence band than in an intrinsic semiconductor.

An electron from the next atom can move into the hole created, as described previously. **Conduction can thus take place by the movement of positive holes**. This is called a p-type semiconductor, as most conduction takes place by the movement of positively charged holes.

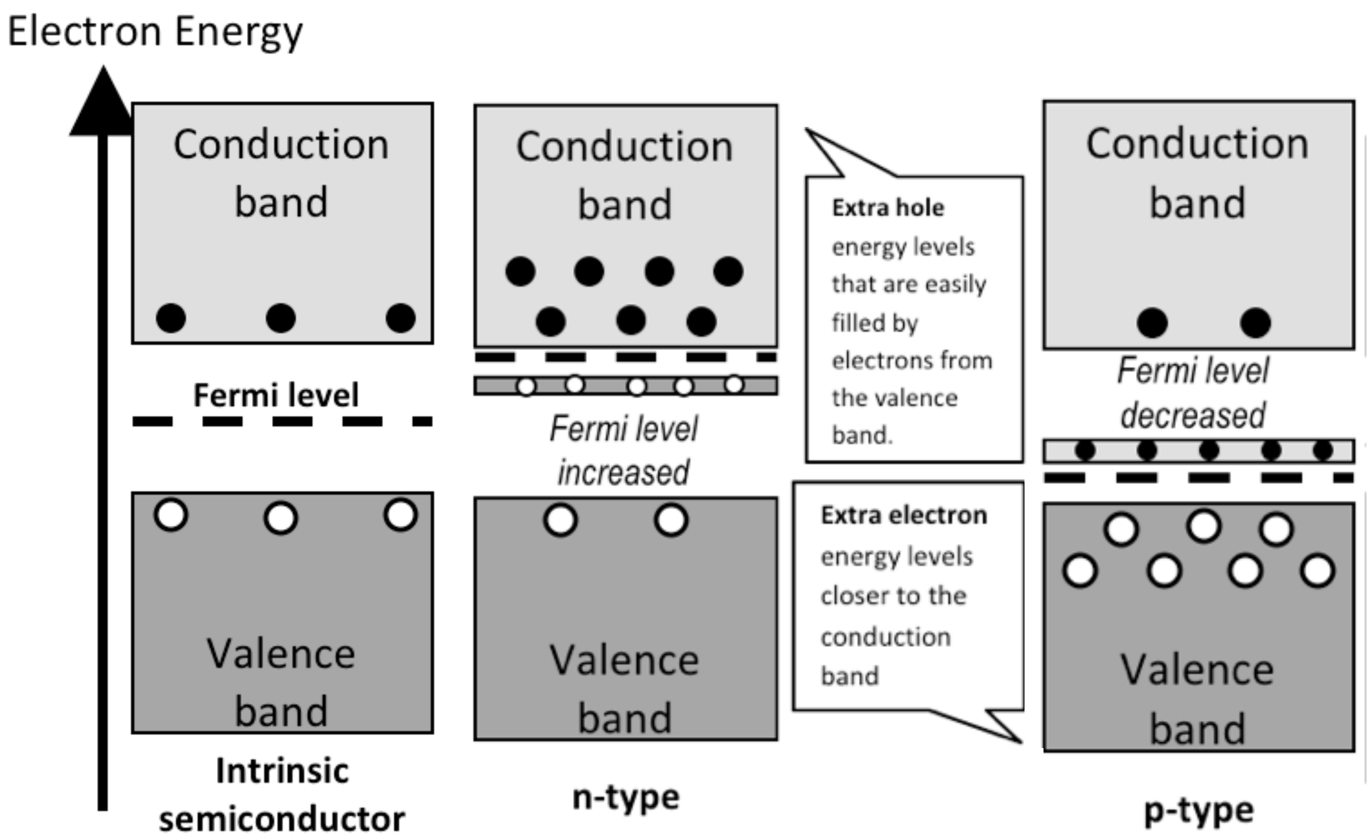


How doping affects band structure

In terms of band structure we can represent the electrons as **dots** in the conduction band, and holes as **circles** in the valence band.

The majority of charge carriers are **electrons in n-type** and **holes in p-type**. *(However, there will always be small numbers of the other type of charge carrier, known as minority charge carriers, due to thermal ionization.)*

The diagrams show how the additional energy levels produced by the impurity atoms change the **Fermi level** (the top of the collection of electron energy levels at absolute zero temperature) and make it easier for electrons to move up to the conduction band in n-type semiconductors and for holes to be created in the valence band of the p-type.



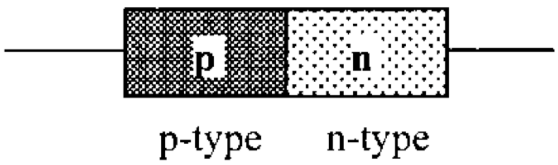
Notes on doping

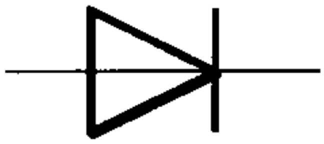
The doping material cannot simply be added to the semiconductor crystal. It has to be added to the pure semiconductor material when the crystal is **grown** so that it becomes part of the atomic lattice. The quantity of impurity is extremely small; it may be as low as one atom in a million. If it were too large it would disrupt the regular crystal lattice.

Although **p-type and n-type** semiconductors have different majority charge carriers, they are **both neutral overall**. (Just as a metal can conduct but is electrically neutral because the overall number of electrons in the metal is balanced by the number of protons in the constituent atoms).

P-N Junctions

When a semiconductor is grown so that one half is p-type and the other half is n-type, the product is called a **p–n junction** and it functions as a **diode**.



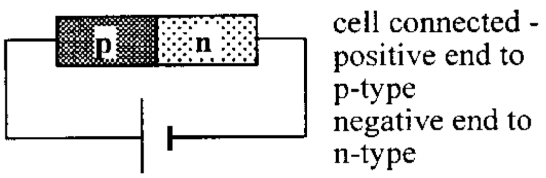


circuit symbol

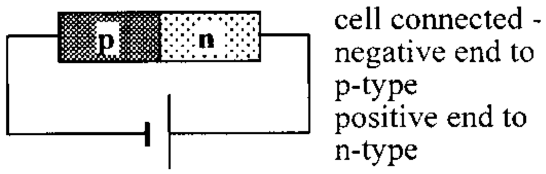
At temperatures other than absolute zero, electrons from the n-type material diffuse across the boundary and recombine with holes from the p-type material, and vice versa. This recombination of holes and electrons results in a lack of majority charge carriers in the immediate vicinity of the junction creating a region known as the **depletion zone/layer**.

The biased diode

When we apply an external voltage we say that the diode is **biased**. There are two possibilities: **forward** and **reverse** bias.



Forward-biased

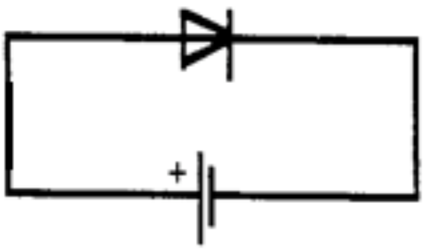


Reverse-biased

Forward Biased

A potential difference of about 0.7 volts exists across the junction of an unbiased diode. To make a diode conduct, a potential difference greater than 0.7 volts must be applied across the diode in the opposite direction.

If the junction is forward biased then the majority **charge carriers** (electrons in the n-type and holes in the p-type) can **flow across the junction** and round the circuit. Electrons flow from the n-type to the p-type.

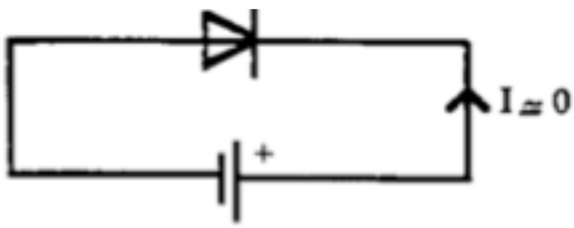


Reverse Biased

If a potential difference is applied across the diode in the **opposite direction** we say the junction is reverse biased.

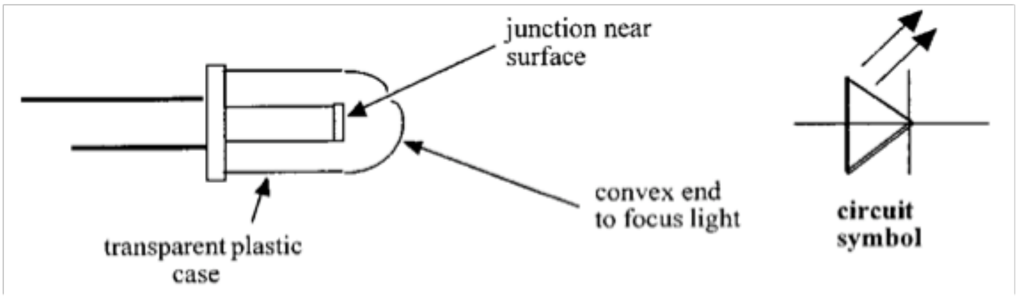
The effect of this reverse potential difference is to **increase** the width of the **depletion** layer forming an even greater barrier to the flow of charge carriers. The diode scarcely conducts.

There is a very small current is known as the reverse or leakage current.



The Light-emitting diode (LED)

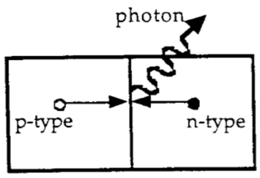
One example of the use of a p-n junction is in a **L.E.D**.



Electron moves from conduction band of n-type semiconductor (across junction) to conduction band of p-type.

Electron falls from conduction band to valance band it looses energy. This is released as a photon of light.

In some semiconductors such as gallium arsenide phosphide the energy is emitted as light. If the junction is close to the surface of the material, this light can escape. This is a light emitting diode (LED). The colour of the emitted light (red, yellow, green, blue) depends on the relative quantities of the three constituent materials.



The recombination energy can be calculated if the frequency of the light emitted is measured. The energy is calculated using the formula:

$$E = hf$$

E: is the energy of the photon emitted which is equal to the recombination energy (J)
h: is Planck's constant: $6{\cdot}63 \times 10^{-34}$ Js
f: is the frequency of the emitted light in hertz (Hz)

Like other diodes, the LED does not work in reverse bias since the charge carriers do not travel across the junction towards each other so cannot recombine.

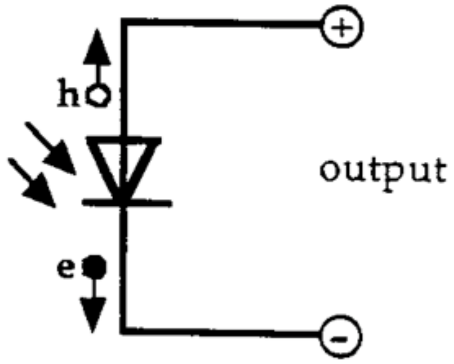
The Photodiode

A p–n junction in a transparent coating will react to light in what is called the **photoelectric effect**.
The photodiode can be used in two modes.

Photovoltaic mode

In this mode the diode has **no bias** voltage applied. Each individual photon that is incident on the junction has its energy absorbed producing **electron-hole pairs**. This results in an excess number of electrons in the n-type and an excess of holes in the p-type producing a **potential difference** across the photodiode.

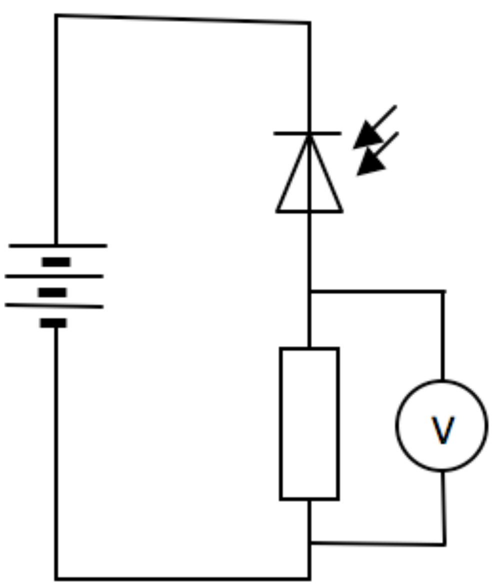
Light has supplied energy to the circuit producing an emf that can be used to supply power to other devices. **More intense light** (more photons) will lead to **more electron-hole pairs** being produced and therefore a **higher voltage**. In fact the voltage is proportional to the light irradiance.



Photodiodes working in the photovoltaic mode are:

- usually referred to as photocells
- form the basis of the solar cells used to supply electrical power in satellites and calculators.
- limited to very low power applications (as listed above)
- A photodiode in this mode acts like an LED in reverse.

Photoconductive mode



In this mode the photodiode is connected in **reverse bias**. If it is kept dark, it acts just like an ordinary reverse-biased p-n junction and will not conduct.

When light is incident on the junction **extra electrons** are created in the **conduction** band of the p-type material and in the n-type **extra holes** are created in the **valence** band. These extra minority charge carriers produce a greater drift current across the junction enabling a current to flow in the circuit.

More intense light (more photons) will lead to more electron-hole pairs being produced and therefore a higher current. The current is proportional to the light irradiance and fairly independent of the bias voltage.

The current can be measured by putting a large resistor in series with the reverse biased photodiode and monitoring the potential difference across the resistor, as shown in the diagram.

It is found that the switching action (the response to a change in light level) of a reverse biased photodiode is extremely fast. A photodiode in this mode is the basis of an **LDR**.

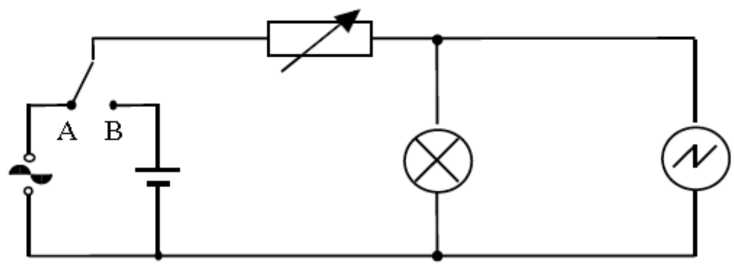
TUTORIAL QUESTIONS

Section 1 A.C./D.C.

1. (a) What is the peak voltage of the 230 V mains supply?

   (b) The frequency of the mains supply is 50 Hz. How many times does the voltage fall to zero in 1 second?

2. The circuit below is used to compare a.c. and d.c. supplies.



The variable resistor is used to adjust the brightness of the lamp until the lamp has the same brightness when connected to either supply.

(a) Explain why the brightness of the lamp changes when the setting on the variable resistor is altered.

(b) What additional apparatus would you use to ensure the brightness of the lamp is the same when connected to either supply?

(c) The time-base of the oscilloscope is switched off. Diagram 1 shows the oscilloscope trace obtained when the switch is in position B. Diagram 2 shows the oscilloscope trace obtained when the switch is in position A. Y gain set to 1 V cm^{-1}

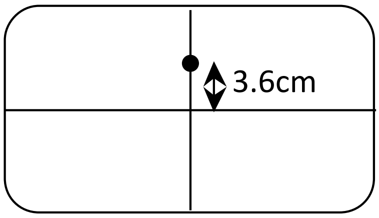


Diagram 1

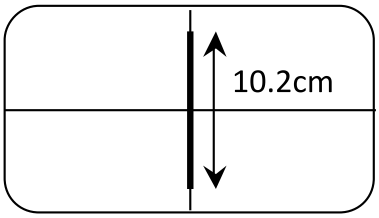


Diagram 2

Using information from the oscilloscope traces, find the relationship between the root mean square (r.m.s.) voltage and the peak voltage of a voltage supply.

(d) The time-base of the oscilloscope is now switched on. Redraw diagrams 1 and 2 to show what happens to the traces.

3. The root mean square voltage produced by a low voltage power supply is 10 V.

(a) Calculate the peak voltage of the supply.

(b) An oscilloscope, with its time-base switched off, is connected across the supply. The Y-gain of the oscilloscope is set to 5 Vcm^{-1}. Describe the trace seen on the oscilloscope screen.

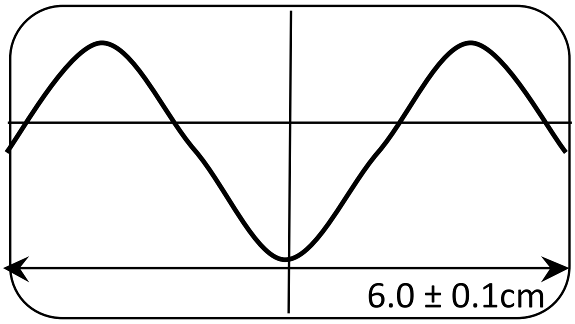
4. (a) A transformer has a peak output voltage of 12 V. Calculate the r.m.s. value of this voltage.

(b) An oscilloscope, with the time base switched off, is connected across another a.c. supply. The Y gain of the oscilloscope is set to 20 Vcm^{-1}. A vertical line 6 cm high appears on the oscilloscope screen. Calculate:

(i) the peak voltage of the input

(ii) the r.m.s. voltage of the input.

5. An oscilloscope is connected across a signal generator. The time-base switch is set at 2·5 ms cm^{-1}. The diagram shows the trace on the oscilloscope screen.



(a) (i) What is the frequency of the output from the signal generator?

(ii) What is the uncertainty in the frequency to the nearest Hz?

(b) The time base switch is now changed to:

(i) 5 ms cm^{-1}

(ii) 1·25 ms cm^{-1}

Sketch the new traces seen on the screen.

6. An a.c. signal of frequency 20 Hz is connected to an oscilloscope. The time-base switch on the oscilloscope is set at 0.01 s cm^{-1}.

Calculate the distance between the neighbouring peaks of this waveform when viewed on the screen.

Section 2 Circuits

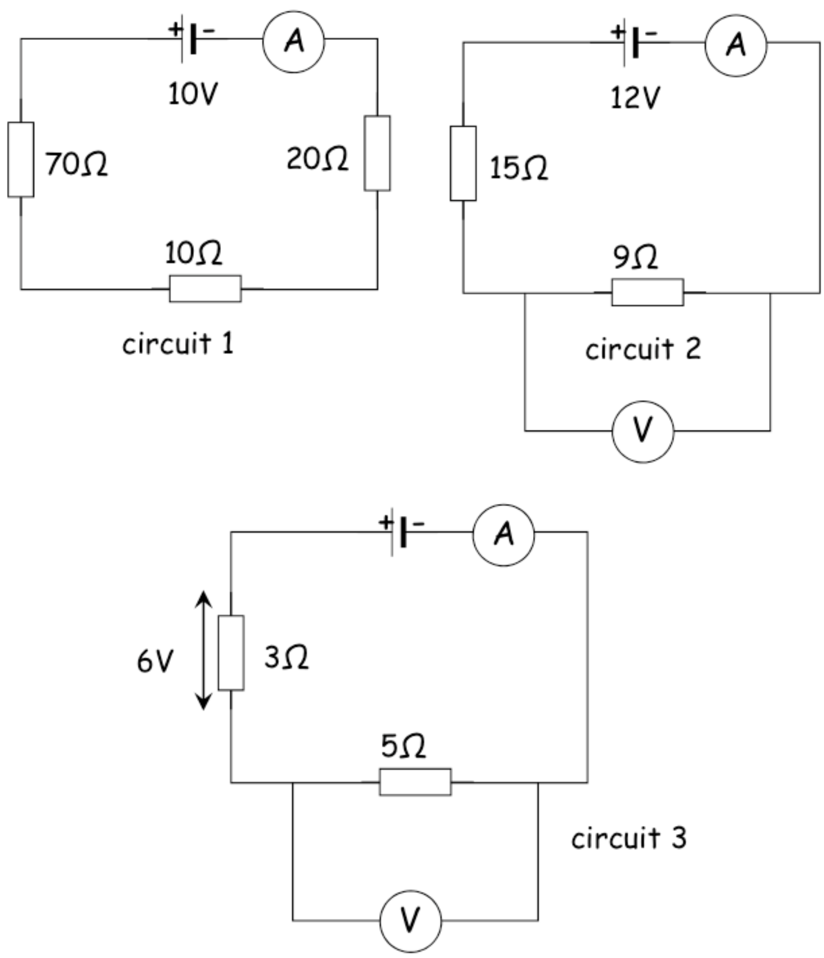
1. There is a current of 40 mA in a lamp for 16 s.
Calculate the quantity of charge that passes any point in the circuit in this time.

2. A flash of lightning lasts for 1 ms. The charge transferred between the cloud and the ground in this time is 5 C. Calculate the value of the average current in this flash of lightning.

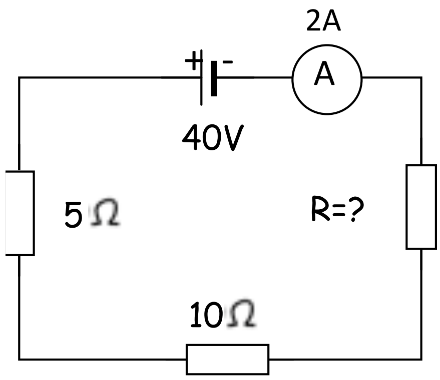
3. The current in a circuit is $2\ 5 \times 10^{-2}$ A. How long does it take for 500 C of charge to pass any given point in the circuit?

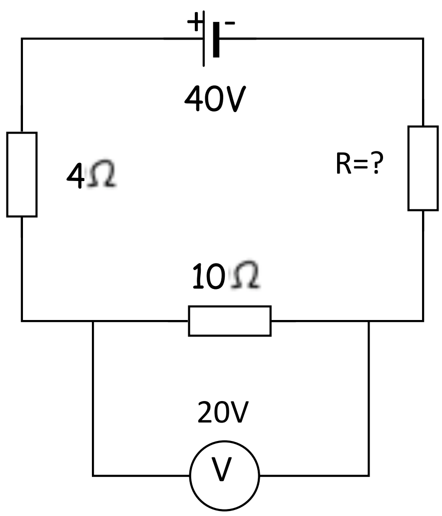
4. There is a current of 3 mA in a 2 kΩ resistor. Calculate the p.d. across the resistor.

5. Calculate the values of the readings on the meters in the following circuits



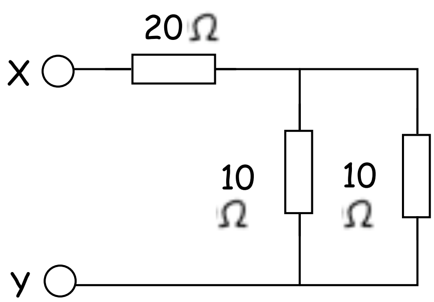
6. Calculate the unknown values R of the resistors in the following circuits.



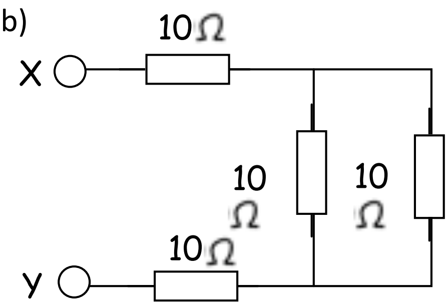


7. Calculate the total resistance between X and Y for the following combinations of resistors.

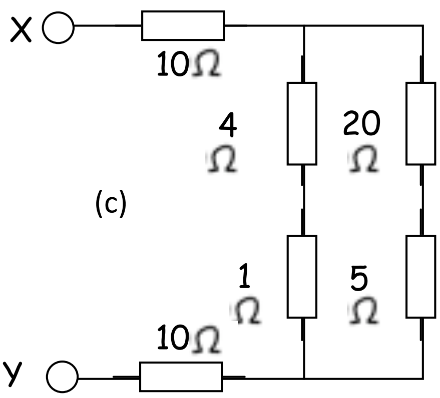
(a)



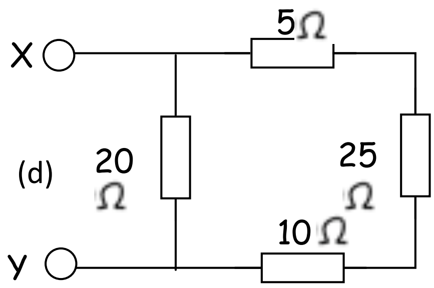
(b)



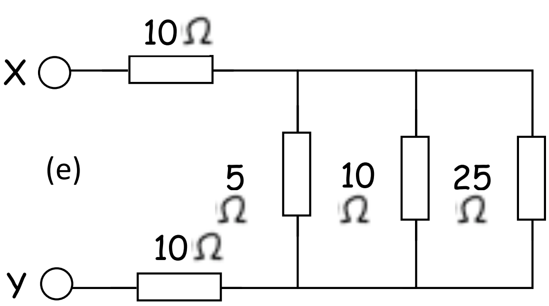
(c)



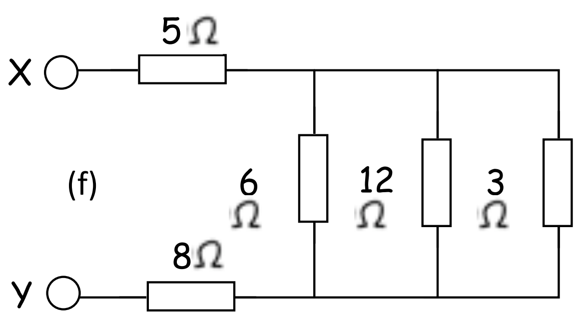
(d)



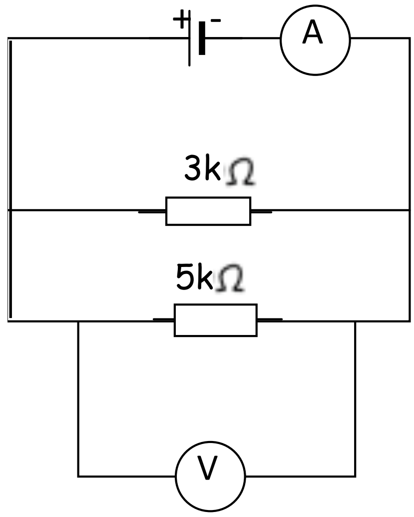
(e)



(f)



8. In the following circuit the reading on the ammeter is 2 mA. Calculate the reading on the voltmeter.



9. Calculate the power in each of the following situations.

(a) A 12 V battery is connected to a motor. There is a current of 5 A in the motor.

(b) A heater of resistance 60 Ω that is connected across a 140V supply.

(c) A current of 5 A in a heater coil of resistance 20 Ω.

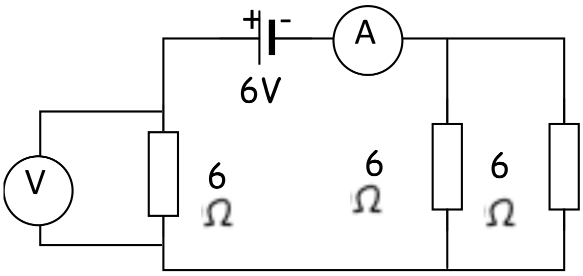
10. The heating element in an electric kettle has a resistance of 30 Ω.

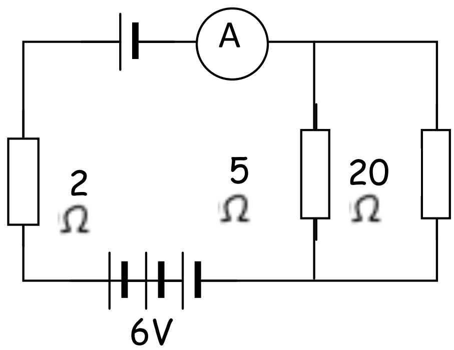
(a) What is the current in the heating element when it is connected to a 230 V supply?

(b) Calculate the power rating of the element in the kettle.

11. A 15 V supply produces a current of 2 A in a lamp for 5 minutes. Calculate the energy supplied in this time.

12. Calculate the readings on the ammeter and the voltmeter in the circuit shown below.





13. Each of the four cells in the circuit shown is identical. Calculate

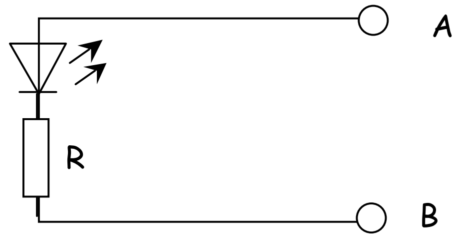
(a) the reading on the ammeter

(b) the current in the 20 Ω resistor

(c) the voltage across the 2 Ω resistor.

14. A voltage of 12 V is applied across a resistor. The current in the resistor is 50 mA. Calculate the resistance of the resistor.

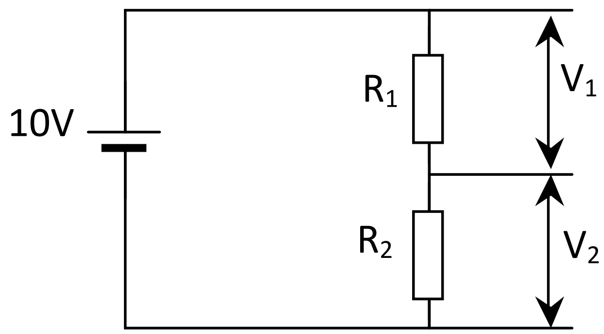
15. The LED in the circuit below is to emit light.



(a) What is the required polarity of A and B when connected to a 5 V supply so that the LED emits light?
(b) What is the purpose of the resistor R in the circuit?
(c) The LED rating is 20 mA at 1·5 V. Calculate the value of resistor R.

16. Write down the series and parallel circuit rules for
(a) potential differences (b) currents .

17. What is the name given to the circuit shown?



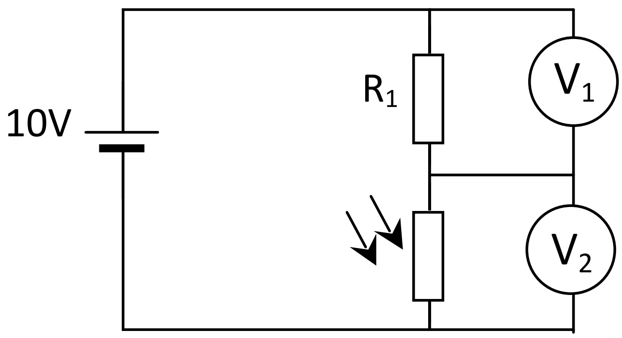
Write down the relationship between V_1, V_2, R_1 and R_2 .

18. Calculate the values of V_1 and V_2 of the circuit in question 17 when:

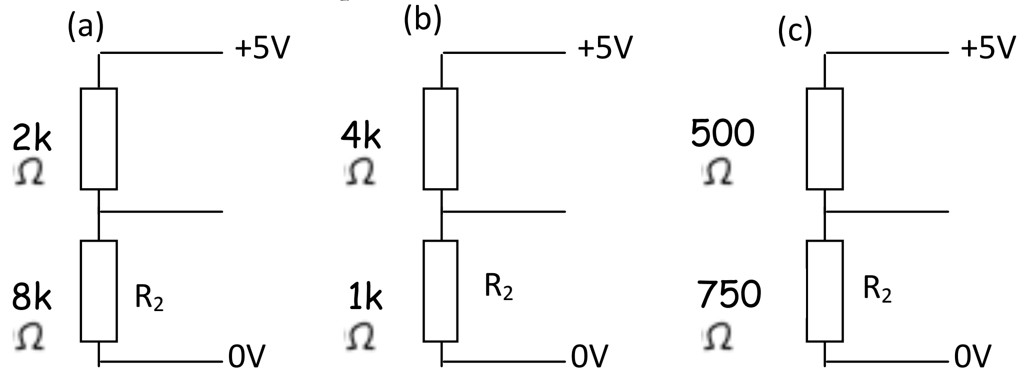
(a) $R_1 = 1\ k\Omega$ $R_2 = 49\ k\Omega$
(b) $R_1 = 5\ k\Omega$ $R_2 = 15\ k\Omega$

19. The light dependent resistor in the circuit is in darkness.

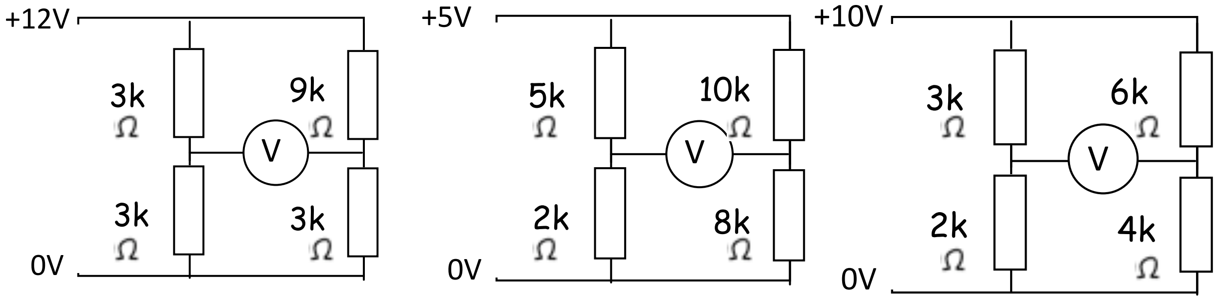
Light is now shone on the LDR.
Explain what happens to the readings on V_1 and V_2



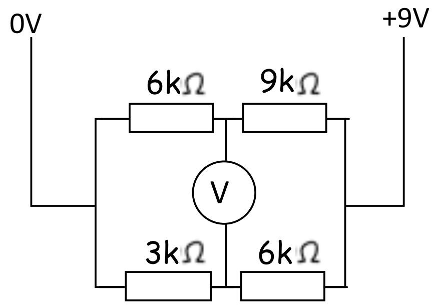
20. Calculate the p.d. across resistor R_2 in each of the following circuits.



21. Calculate the p.d. across AB (voltmeter reading) in each of the following circuits



22. A circuit consisting of two potential dividers is set up as shown.

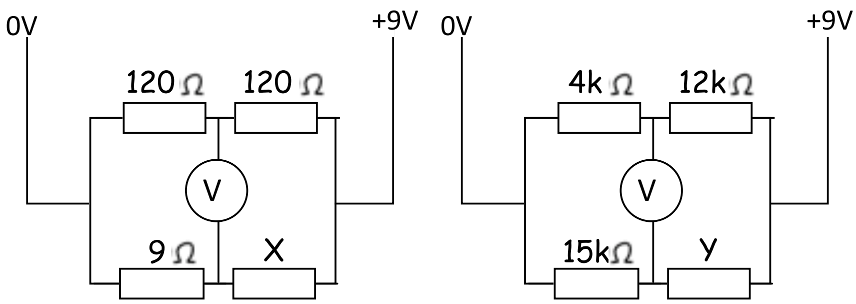


(a) Calculate the reading on the voltmeter.

(b) (i) Suggest a value of a resistor to replace the 9 kΩ resistor that would give a reading of 0 V on the voltmeter.

(ii) Suggest a value of resistor to replace the 3 kΩ resistor that would give a reading of 0 V on the voltmeter.

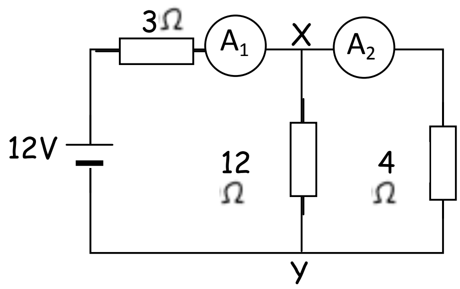
23. In the circuits shown the reading on the voltmeters is zero. Calculate the value of the unknown resistors X and Y in each of the circuits



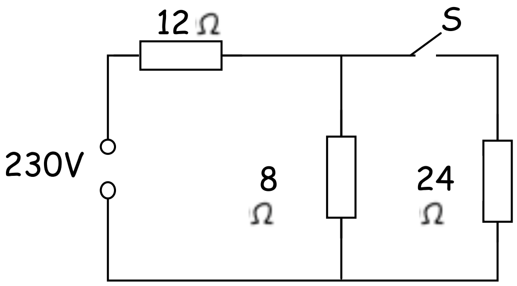
Electrical sources and internal resistance

1. State what is meant by:
   (a) the e.m.f. of a cell
   (b) the p.d. between two points in a circuit.

2. A circuit is set up as shown.



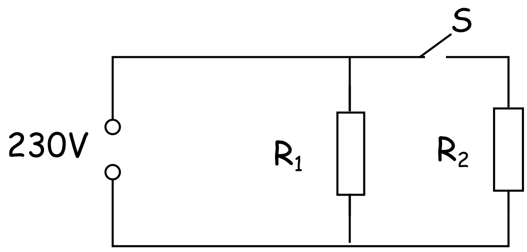
   (a) Calculate the total resistance of the circuit.
   (b) Calculate the readings on the ammeters.
   (c) What is the value of the p.d. between X and Y?
   (d) Calculate the power supplied by the battery.



3. The circuit shown uses a 230 V alternating mains supply.

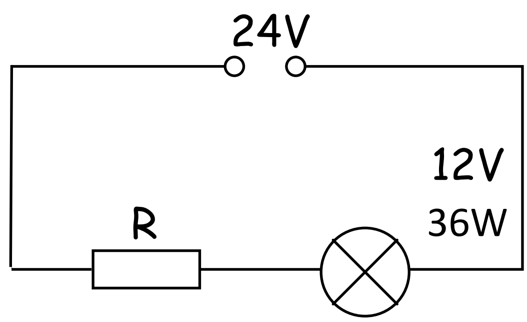
Calculate the current in each resistor when:
   (a) switch S is open
   (b) switch S is closed

4. An electric cooker has two settings, high and low. This involves two heating elements, R_1 and R_2. On the low setting the current from the supply is 1 A. On the high setting the current from the supply is 3 A.



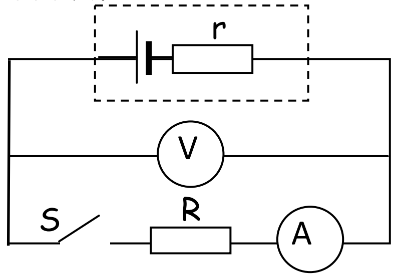
   (a) Calculate the resistance of R_1 and R_2.
   (b) What is the power consumption at each setting?

5. A lamp is rated at 12 V, 36 W. It is connected in a circuit as shown.



   (a) Calculate the value of the resistor R that allows the lamp to operate at its normal rating.
   (b) Calculate the power dissipated in the resistor.

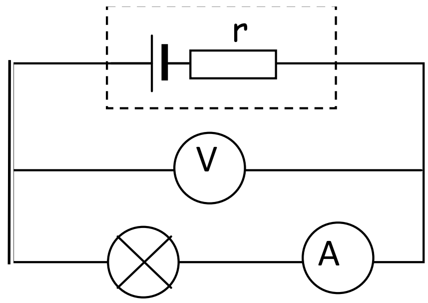
6. In the circuit shown, r represents the internal resistance of the cell and R represents the external resistance (or load resistance) of the circuit.



When S is open, the reading on the voltmeter is 2 0 V.
When S is closed, the reading on the voltmeter is 1 6 V and the reading on the ammeter is 0 8 A.

(a) What is the value of the e.m.f. of the cell?
(b) When S is closed what is the terminal potential difference across the cell?
(c) Calculate the values of r and R.
(d) The resistance R is now halved in value. Calculate the new readings on the ammeter and voltmeter.

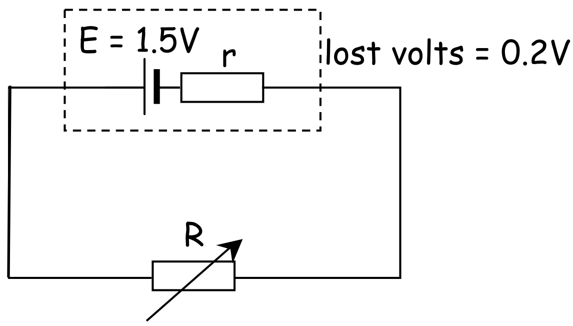
7. The battery in the circuit shown has an e.m.f. of 5 0 V. The current in the lamp is 0 20 A and the reading on the voltmeter is 3 0 V. Calculate the internal resistance of the battery.



8. A battery of e.m.f. 4 0 V is connected to a load resistor with a resistance of 15 Ω. There is a current of 0 2 A in the load resistor. Calculate the internal resistance of the battery.

9. A signal generator has an e.m.f. of 8 0 V and an internal resistance of 4 0 Ω. A load resistor is connected across the terminals of the generator. The current in the load resistor is 0. 50 A. Calculate the resistance of the load resistor.

10. A cell is connected in a circuit as shown.



(a) Calculate the terminal p.d. across the cell.

(b) The resistance of the variable resistor R is now increased.
   (i) Describe and explain what happens to the current in the circuit.
   (ii) Describe and explain what happens to the p.d. across the terminals of the cell.

11. A cell has an e.m.f. 1·5 V and an internal resistance of 2·0 Ω. A 3·0 Ω resistor is connected across the terminals of the cell. Calculate the current in the circuit.

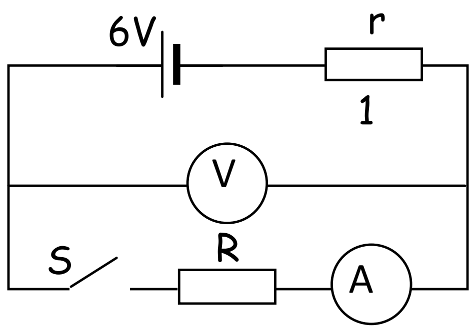
12. A student is given a voltmeter and a torch battery. When the voltmeter is connected across the terminals of the battery the reading on the voltmeter is 4·5 V.

When the battery is connected across a 6·0 Ω resistor the reading on the voltmeter decreases to 3·0 V.

(a) Calculate the internal resistance of the battery.

(b) What value of resistor when connected across the battery reduces the reading on the voltmeter to 2·5 V?

13. In the circuit shown, the battery has an e.m.f. of 6·0 V and an internal resistance of 1·0 Ω.



When the switch is closed, the reading on the ammeter is 2·0 A. What is the corresponding reading on the voltmeter?

14. To find the internal resistance of a cell a load resistor is connected across the terminals of the cell. A voltmeter is used to measure V_{tpd}, the voltage measured across the terminals of the cell. An ammeter is used to measure I, the current in the variable resistor. The table below shows the results obtained as the resistance of the variable resistor is changed.

$V_{t.p.d.}$ (V)	1·02	0·94	0·85	0·78	0·69	0·60
I (A)	0·02	0·04	0·06	0·08	0·10	0·12

(a) Draw a diagram of the circuit used to produce these results.

(b) Plot a graph of the results and from it determine:

(i) the e.m.f. of the cell

(ii) the internal resistance of the cell

(iii) the short circuit current of the cell.

15. A variable resistor is connected across a power supply. A voltmeter is used to measure $V_{t.p.d.}$, the voltage measured across the terminals of the supply. An ammeter is used to measure I, the current in the variable resistor. The table below shows the results obtained as the resistance of the variable resistor is changed.

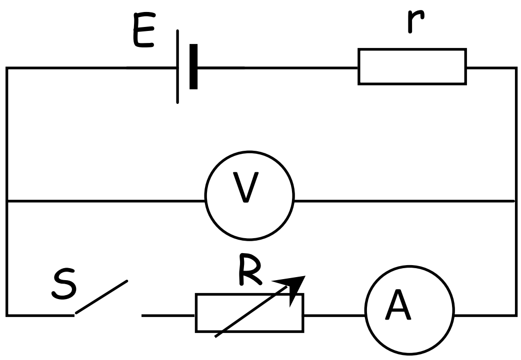
$V_{t.p.d.}$(V)	5·5	5·6	5·7	5·8	5·9
I (A)	5·0	4·0	3·0	2·0	1·0

Plot a graph of $V_{t.p.d}$. against I.

(a) What is the value of the open circuit p.d.?
(b) Calculate the internal resistance of the power supply.
(c) Calculate the short circuit current of the power supply.
(d) The variable resistor is now removed from the circuit and a lamp of resistance 1·5 Ω is connected across the terminals of the supply. Calculate:
(i) the terminal p.d.
(ii) the power delivered to the lamp.

16. A circuit is set up as shown to investigate the properties of a battery.

The variable resistor provides known values of resistance R.For each value of resistance R, the switch is closed and the current I noted. The table shows the results obtained.



R(Ω)	0	2	4	6	8	10	12
I(A)	6.80	3.78	2.62	2.00	1.62	1.36	1.17
1/I(A^{-1})							

(a) Show that the relationship E = I(R + r) can be put in the form: $R = \frac{E}{I} - r$

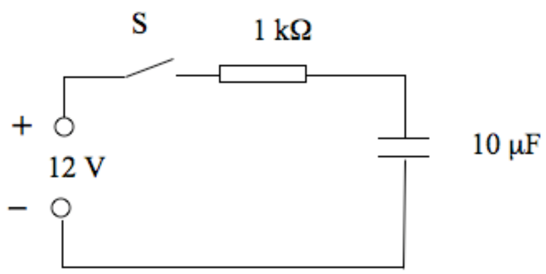
(b) Complete the third row in the table.

(c) Use the values of R and 1/I to plot a graph.

(d) Use the information in the graph to find:
(i) the internal resistance of the battery
(ii) the e.m.f. of the battery.

(e) The battery is now short circuited. Calculate the current in the battery when this happens.

17. A student uses the following circuit to investigate the conditions for transferring the maximum power into a load resistor.

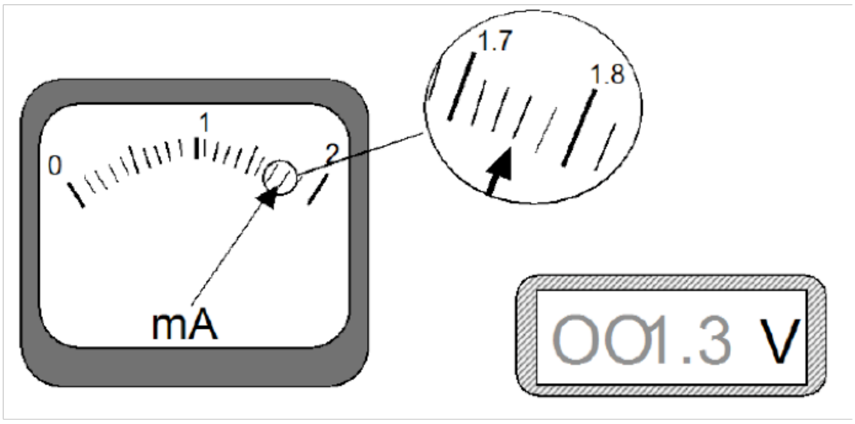


For each setting of the variable resistor the current in the circuit is recorded.
The table below shows the results obtained.

R (Ω)	1	2	3	4	5	6
I (A)	2·40	2·00	1·71	1·50	1·33	1·20

(a) Complete the table by calculating the power in the load for each value of R.
(b) Sketch a graph to show how the power in the load resistor R varies with R.
(c) In order to achieve maximum transfer of power, what is the relationship between the internal resistance of the power source and the resistance of the load resistor?

18. An automotive electrician needed to accurately measure the resistance of a resistor.
She set up a circuit using an analogue milliammeter and a digital voltmeter.



(a) What are the readings on the ammeter and the voltmeter?
(b) What is the nominal resistance calculated from these readings?
(c) What is the smallest division on the milliammeter?
(d) What is the absolute uncertainty on the milliammeter?
(e) What is the absolute uncertainty on the voltmeter?
(f) What is the percentage uncertainty on the milliammeter?
(g) What is the percentage uncertainty on the voltmeter?
(h) Which is the greatest percentage uncertainty?
(i) What is the percentage uncertainty in the resistance?
(j) What is the absolute uncertainty in the resistance?
(k) Express the final result as (resistance ± uncertainty) Ω
(l) Round both the result and the uncertainty to the relevant number of significant figures or decimal places.

Capacitors

1. A 50 μF capacitor is charged until the p.d. across it is 100 V.

   (a) Calculate the charge on the capacitor when the p.d. across it is 100 V.

   (b) The capacitor is now 'fully' discharged in a time of 4·0 milliseconds.

      (i) Calculate the average current during this time.

      (ii) Why is this average current?

2. A capacitor stores a charge of $3{\cdot}0 \times 10^{-4}$ C when the p.d. across its terminals is 600 V. What is the capacitance of the capacitor?

3. A 30 μF capacitor stores a charge of 12×10^{-4} C.

   (a) What is the p.d. across its terminals?

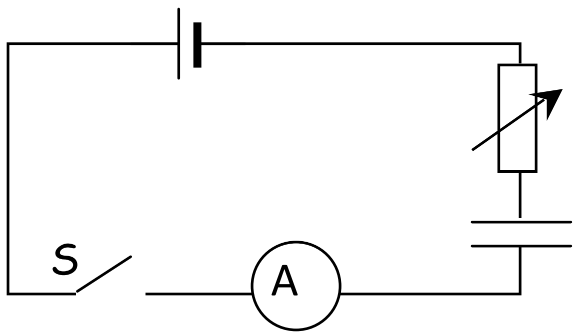
   (b) The tolerance of the capacitor is ± 0·5 μF. Express this uncertainty as a percentage.

4. A 15 μF capacitor is charged using a 1·5 V battery. Calculate the charge stored on the capacitor when it is fully charged.

5. (a) A capacitor stores a charge of $1{\cdot}2 \times 10^{-5}$ C when there is a p.d. of 12 V across it. Calculate the capacitance of the capacitor.

   (b) A 0·10 μF capacitor is connected to an 8·0 V d.c. supply. Calculate the charge stored on the capacitor when it is fully charged.

6. A circuit is set up as shown.
The capacitor is initially uncharged.
The switch is now closed. The capacitor is charged with a constant charging current of $2{\cdot}0 \times 10^{-5}$ A for 30 s. At the end of this time the p.d. across the capacitor is 12 V.



   (a) What has to be done to the value of the variable resistor in order to maintain a current constant for the 30 s?

   (b) Calculate the capacitance of the capacitor.

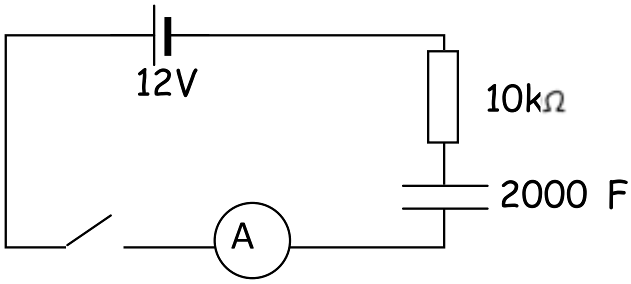
7. A 100 μF capacitor is charged using a 20 V supply.

   (a) How much charge is stored on the capacitor when it is fully charged?

   (b) Calculate the energy is stored in the capacitor when it is fully charged.

8. A 30 μF capacitor stores $6{\cdot}0 \times 10^{-3}$ C of charge. How much energy is stored in the capacitor?

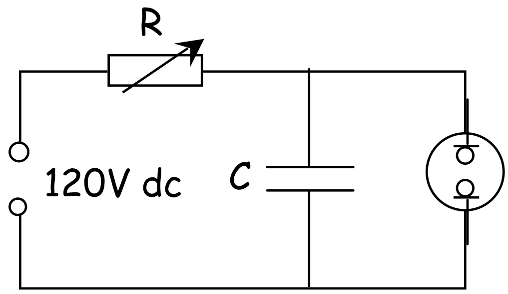
9. The circuit below is used to investigate the charging of a capacitor.



The battery has negligible internal resistance.
The capacitor is initially uncharged. The switch is now closed.

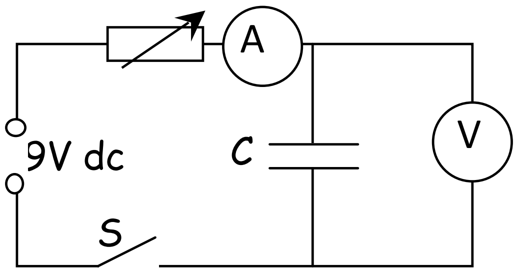
(a) Describe what happens to the reading on the ammeter from the instant the switch is closed.
(b) How can you tell when the capacitor is fully charged?
(c) What would be a suitable range for the ammeter?
(d) The 10 k Ω resistor is now replaced by a larger resistor and the investigation repeated. What is the maximum voltage across the capacitor now?

10. In the circuit below the neon lamp flashes at regular intervals. The neon lamp requires a potential difference of 100 V across it before it conducts and flashes. It continues to glow until the potential difference across it drops to 80 V. While lit, its resistance is very small compared with the resistance of R.



(a) Explain why the neon bulb flashes.
(b) Suggest two methods of decreasing the flash rate.

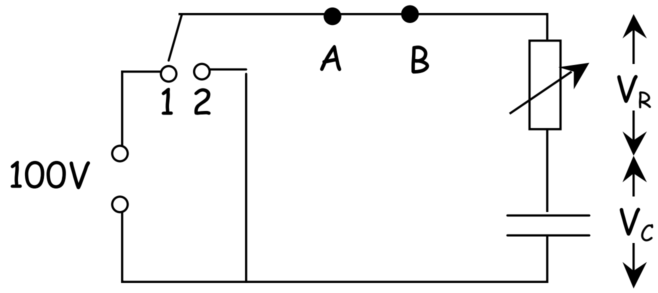
11. In the circuit below the capacitor C is initially uncharged. Switch S is now closed. By carefully adjusting the variable resistor R a constant charging current of 1·0 mA is maintained. The voltmeter reading is recorded every 10 seconds. The results are shown in the table below.



Time (s)	0	10	20	30	40
V (V)	0	1·9	4·0	6·2	8·1

(a) Plot a graph of the charge on the capacitor against the p.d. across the capacitor.
(b) Use the graph to calculate the capacitance of the capacitor.

12. The circuit below is used to charge and discharge a capacitor.



The battery has negligible internal resistance. The capacitor is initially uncharged. V_R is the p.d. across the resistor and V_C is the p.d. across the capacitor.

(a) What is the position of the switch:
(i) to charge the capacitor
(ii) to discharge the capacitor?

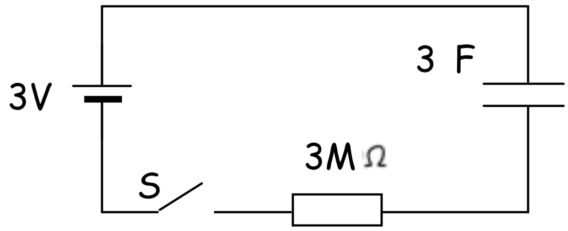
(b) Sketch graphs of V_R against time for the capacitor charging and discharging. Show numerical values for the maximum and minimum values of V_R.

(c) Sketch graphs of V_C against time for the capacitor charging and discharging. Show numerical values for the maximum and minimum values of V_C.

(d) (i) When the capacitor is charging what is the direction of the electrons between points A and B in the wire?
(ii) When the capacitor is discharging what is the direction of the electrons between points A and B in the wire?

(e) The capacitor has a capacitance of 4·0 μF. The resistor has resistance of 2·5 MΩ. Calculate:
(i) the maximum value of the charging current
(ii) the charge stored by the capacitor when the capacitor is fully charged.

13. A capacitor is connected in a circuit as shown.



The power supply has negligible internal resistance. The capacitor is initially uncharged.
V_R is the p.d. across the resistor and V_C is the p.d. across the capacitor. The switch S is now closed.

(a) Sketch graphs of:

(i) V_C against time during charging. Show numerical values for the maximum and minimum values of V_C.

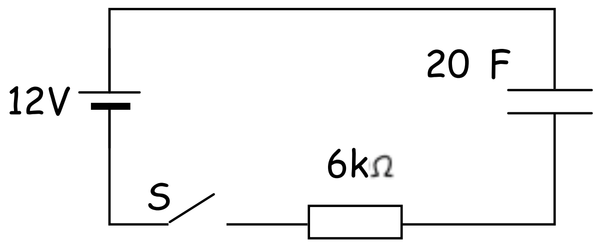
(ii) V_R against time during charging. Show numerical values for the maximum and minimum values of V_R.

(b) (i) What is the p.d. across the capacitor when it is fully charged?

(ii) Calculate the charge stored by the capacitor when it is fully charged.

(c) Calculate the maximum energy stored by the capacitor.

14. A capacitor is connected in a circuit as shown.

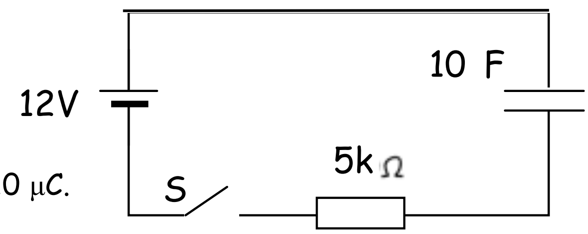


The power supply has negligible internal resistance.
The capacitor is initially uncharged. The switch S is now closed.

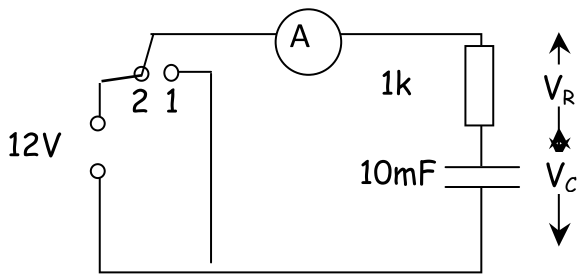
(a) Calculate the value of the initial current in the circuit.

(b) At a certain instant in time during charging the p.d. across the capacitor is 3 V. Calculate the current in the resistor at this time.

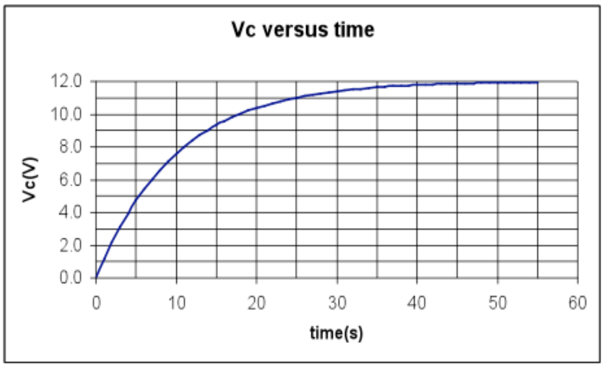
15. The circuit shown is used to charge a capacitor.
The power supply has negligible internal resistance.
The capacitor is initially uncharged. The switch S is now closed.
At a certain instant in time the charge on the capacitor is 20 μC.
Calculate the current in the circuit at this time.

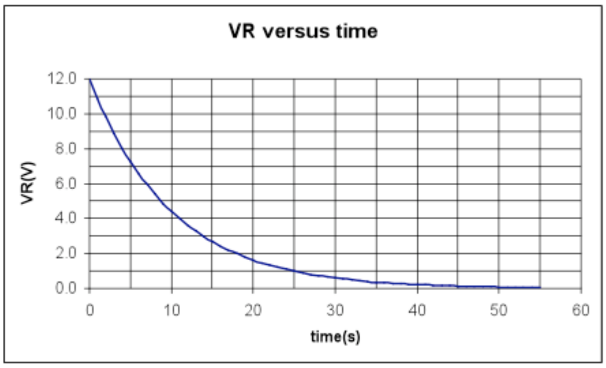


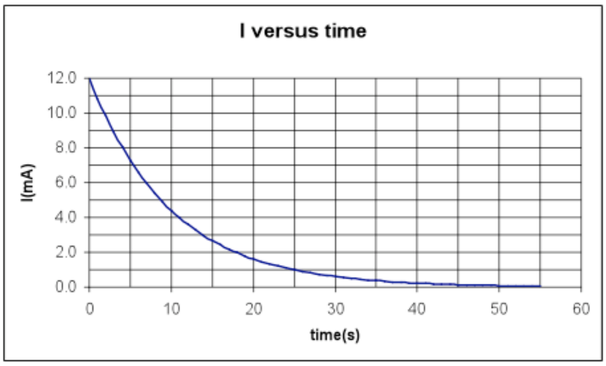
16. The circuit shown is used to investigate the charge and discharge of a capacitor.



The switch is in position 1 and the capacitor is uncharged.
The switch is now moved to position 2 and the capacitor charges.
The graphs show how V_C, the p.d. across the capacitor, V_R, the p.d. across the resistor, and I, the current in the circuit, vary with time.







(a)The experiment is repeated with the resistance changed to 2 kΩ. Sketch the original graphs again and on each graph sketch the new lines which show how V_C, V_R and I vary with time.

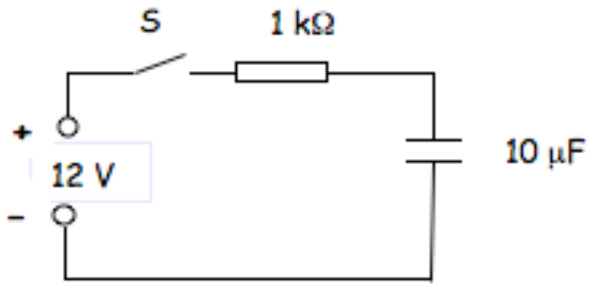
(b)The experiment is repeated with the resistance again at 1 kΩ but the capacitor replaced with one of capacitance 20 mF. Sketch the original graphs again and on each graph sketch the new lines which show how V_C, V_R and I vary with time.

(c) (i) What does the area under the current against time graph represent?
(ii)Compare the areas under the current versus time graphs in the original graphs and in your answers to (a) and (b). Give reasons for any differences in these areas.

(d) At any instant in time during the charging what should be the value of (V_C + V_R)?

(e)The original values of resistance and capacitance are now used again and the capacitor fully charged. The switch is now moved to position 1 and the capacitor discharges. Sketch graphs of V_C, V_R and I from the instant the switch is moved until the capacitor is fully discharged.

17. A student uses the circuit shown to investigate the charging of a capacitor.



The capacitor is initially uncharged.
The student makes the following statements:

(a) When switch S is closed the initial current in the circuit does not depend on the internal resistance of the power supply.
(b) When the capacitor has been fully charged the p.d. across the capacitor does not depend on the internal resistance of the power supply.

Use your knowledge of capacitors to comment on the truth or otherwise of these two statements.

Section 2: Electrons at work

1. In the following descriptions of energy levels in metals, insulators and semiconductors some words and phrases have been replaced by the letters A to N. From the table below choose the correct words or phrases to replace the letters.

In a metal the **_A_** band is completely filled and the **_B_** band is partially filled. The electrons in the **_C_** band are free to move under the action of **_D_** so the metal has a **_E_** conductivity.

In an insulator there are no free electrons in the **_F_** band. The energy gap between the two bands is large and there is not enough energy at room temperature to move electrons from the **_G_** band into the **_H_** band.
Insulators have a very **_I_** conductivity.

In a pure semiconductor the energy gap between the valence and conduction bands is **_J_** than in a metal. At room temperature there is enough energy to move some electrons from the **_K_** band into the **_L_** band. As the temperature is increased the number of electrons in the conduction band **_M_** so the conductivity of the semiconductor **_N_**.

Letter	List of replacement word or phrase
A, B, C, F, G, H, K, L	conduction, valence
D	an electric field, a magnetic field
E, I	low, high
J	bigger, smaller
M, N	decreases, increases

2. The conductivity of a semiconductor material can be increased by 'doping'.

(a) Explain what is meant by the 'conductivity' of a material.
(b) Explain, giving an example, what is meant by 'doping' a semiconductor.
(c) Why does 'doping' decrease the resistance of a semiconductor material?

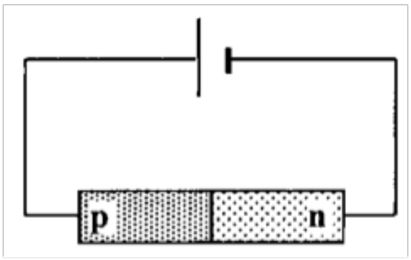
3. (a) A sample of pure germanium (four electrons in the outer shell) is doped with phosphorus (five electrons in the outer shell). What kind of semiconductor is formed?

(b) Why does a sample of n-type semiconductor still have a neutral overall charge?

4. Describe the movement of the majority charge carriers when a current flows in:

(a) an n-type semiconductor material
(b) a p-type semiconductor material.

5. A p-n junction diode is connected across a d.c. supply as shown.



(a) Is the diode connected in forward or reverse bias mode
(b) Describe the movement of the majority charge carriers across the p-n junction.
(c) What kind of charge is the only one that actually moves across the junction?

6. When positive and negative charge carriers recombine at the junction of ordinary diodes and LEDs, quanta of radiation are emitted from the junction.

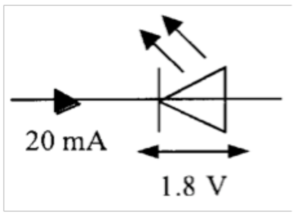
(a) Does the junction have to be forward biased or reverse biased for radiation to be emitted?
(b) What form does this emitted energy take when emitted by:
   (i) an LED
   (ii) an ordinary junction diode?

7. A particular LED is measured as having a recombination energy of $3{\cdot}12 \times 10^{-19}$ J.

(a) Calculate the wavelength of the light emitted by the LED.
(b) What colour of light is emitted by the LED?
(c)What factor about the construction of the LED determines the colour of the emitted light?

8. (a) State two advantages of an LED over an ordinary filament lamp.
   (b) An LED is rated as follows: operating p.d. 1·8 V, forward current 20 mA

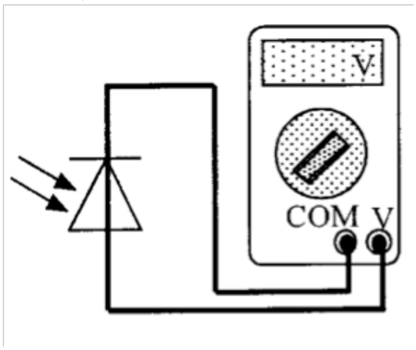
The LED is to be operated from a 6 V d.c. power supply.



(i) Draw a diagram of the circuit, including a protective resistor, which allows the LED to operate at its rated voltage.

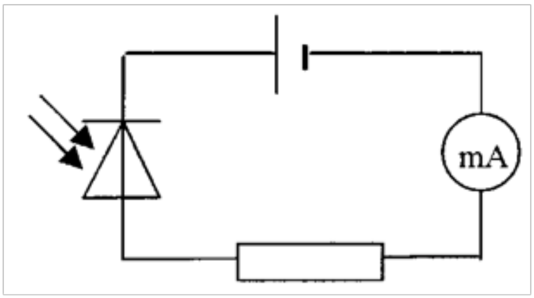
(ii) Calculate the resistance of the protective resistor that allows the LED to operate at its rated voltage.

9. The diagram shows a photodiode connected to a voltmeter.



(a) In which mode is the photodiode operating?
(b) Light is now incident on the photodiode.
(i) Explain how an e.m.f. is created across the photodiode.
(ii) The irradiance of the light incident on the photodiode is now increased. Explain why this increases the e.m.f. of the photodiode.

10. A photodiode is connected in reverse bias in a series circuit as shown.



(a) In which mode is the photodiode is operating?

(b) Why is the photodiode connected in reverse bias?

(c) What is the current in the circuit when the photodiode is in darkness? Explain your answer.

(d) The irradiance of the light on the photodiode is now increased.
(i) What is the effect on the current in the circuit?
(ii) What happens to the effective 'resistance' of the photodiode? Explain why this happens.

Solutions

Section 1: Electrons and energy
Monitoring and measuring a.c.

1. (a) 325 V (b) 100 times

2 (c) $V_{r.m.s.} = 0.71\ V_{peak}$

3. (a) 14 V

4. (a) 8.5 V (b) (i) 60 V (ii) 42 V

5. (a) (i) 100 Hz (ii) ±2 Hz

6. 5 cm

Current, voltage, power and resistance

1. 0.64 C

2. 5×10^3 A

3. $2{\cdot}0 \times 10^4$ s

4. 6 V

5. (a) I = 0·1 A (b) I = 0·5 A, V = 4·5 V (c) I = 2 A, V = 10 V

6. (a) 5 W
   (b) 6 W

7. (a) 25 W (b) 25 W (c) 24·2 W (d) 13·3 W (e) 22·9 W (f) 14·7 W.

8. $3{\cdot}75 \times 10^{-3}$ V

9. (a) 60 W (b) 327 W (c) 500 W

10. (a) 7·7 A (b) 1763 W

11. 9000 J

12. I = 0·67 A, V = 4 V

13. (a) 0·67 A (b) 0·13 A (c) 1·34 V

14. 240 W

15. (c) 175 W

18. (a) V_1 = 0·2 V, V_2 = 9·8 V (b) V_1 = 2·5 V, V_2 = 7·5 V

20. (a) 4 V (b) 1 V (c) 3 V

21. (a) 3 V (b) -0·8 V (c) 0 V

22. (a) 0·6 V (b) (i) 12 kW (ii) 4 kW

23. X = 9 W Y = 45 W

Electrical sources and internal resistance

2. (a) 6 W (b) A_1 = 2 A, A_2 = 1·5 A (c) 6 V (d) 24 W

4. (a) R_1 = 230 W R_2 = 115 W (b) Low 230 Ω high 690 Ω

5. (a) 4 W (b) 36 W

6. (a) 2·0 V (b) 1·6 V (c) r = 0·5 W R = 2 W (d) 1·3 A, 1·3 V

7. 10 W

8. 5 W

9. 12 W

10. (a) 1·3 V

11. 0·30 A

12. (a) 3·0 W (b) 3·75 W

13. 4·0 V

14. (b) (i) 1·1 V, the intercept on the y-axis
(ii) 4·2 W, the gradient of the line
(iii) 0·26 A

15 (a) 6 V (b) 0·1 W (c) 60 A

16. (b) 0·147, 0·264, 0·382, 0·.500, 0·617, 0·735, 0·855
(d) (i) 2·5 W (ii) 17 V
(e) 6·8 A

18. (a) Ammeter 1·76 mA, voltmeter 1·3 V
(b) 740 W (c) 0·02 mA (d) ±0·01 mA
(e) ± 0 1 V (f) 0·6 % (g) 8%
(h) 8% (i) 8% (j) 59 W
(k) (740± 59) W (j) (740 ± 60) Ω

Capacitors

1. (a) $5{\cdot}0 \times 10^{-3}$ C (b) (i) 1·25 A

2. 0·5 mF

3 (a) 40 V (b) 1·7%

4. $2{\cdot}25 \times 10^{-5}$ C

5. (a) 1·0 mF (b) 0·8 mC

6. (b) 50 mF

7. (a) $2{\cdot}0 \times 10^{-3}$ C (b) 0·020 J

8. 0·60 J

9. (b) Reading on ammeter is 0 A
(c) 0 to 2 mA (max. current 1·2 mA)
(d) 12 V

11. (b) 4·9 mF

12. (e) (i) 40 mA (ii) $4{\cdot}0 \times 10^{2}$ mC

13. (b) (i) 3 V (ii) 9 mC
(c) $1{\cdot}35 \times 10^{-5}$ J

14. (a) 2 mA (b) 1·5 mA

15. 2 mA

Section 2: Electrons at work

1. A = valence; B = conduction; C = conduction; D = an electric field; E = high; F = conduction; G = valence; H = conduction; I = low; J = smaller; K = valence; L = conduction; M = increases; N = increases.

7. (a) 638 nm (b) Red

8. (b) (ii) 210 Ω