Cambridge

IGCSE

Physics

CODE: (9702)

Chapter 12 and Chapter 13

Practical circuits and waves

Chapter 12: Practical circuits

Internal resistance

The **internal resistance** of a power supply or other e.m.f. source is crucial for accurate voltage measurements, as it can be affected by factors such as supply precision and battery flatness.

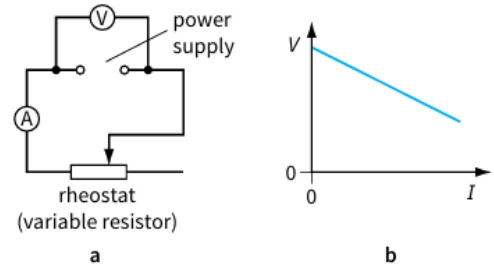


Figure 12.2 **a** A circuit for determining the e.m.f. and internal resistance of a supply; **b** typical form of results.

Figure 12.2 shows a circuit you can use to investigate this effect, and a sketch graph showing how the voltage across the terminals of a power supply might decrease as the supplied current increases.

he charges moving round a circuit have to pass through the external components **and** through the internal resistance of the power supply

It can often help to solve problems if we show the internal resistance r of a source of e.m.f. explicitly in circuit diagrams (Figure 12.3).

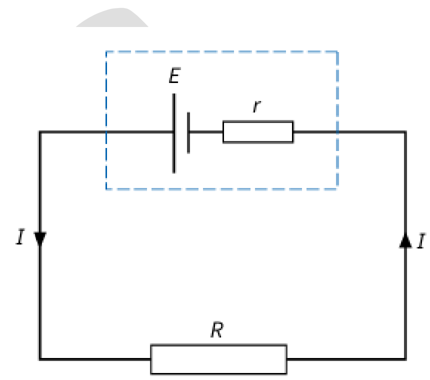


Figure 12.3 It can be helpful to show the internal resistance *r* of a cell (or a supply) in a circuit diagram.

The combined resistance of the circuit is thus R + r, and we can write:

$$E = I(R + r) \qquad \text{or} \qquad E = IR + Ir$$

We cannot measure the e.m.f. E of the cell directly, because we can only connect a voltmeter across its terminals. This terminal p.d. V across the cell is always the same as the p.d. across the external resistor. Therefore, we have:

$$V = IR$$

The quantity Ir is the potential difference across the internal resistor and is referred to as the lost volts. If we combine these two equations, we get:

$$V = E - Ir$$

or

$$\text{terminal p.d.} = \text{e.m.f.} - \text{'lost volts'}$$

The effects of internal resistance

The maximum current that can be drawn from this battery is when its terminals are shorted-out. (The external resistance R ≈ 0.) The maximum current is given by:

$$\text{maximum current} = \frac{E}{r} = \frac{3.0}{1.0} = 3.0\text{ A}$$

The **terminal p.**d. of a battery depends on the resistance of the external resistor, with a 1.0 Ω resistor resulting in 1.5 V. When the external resistance is much greater than the internal resistance, the terminal p.d. approaches the e.m.f. value, causing the battery's terminal p.d. to decrease.

Potential dividers

How can we get an output of 3.0 V from a battery of e.m.f. 6.0 V? Sometimes we want to use only part of the e.m.f. of a supply. To do this, we use an arrangement of resistors called a potential divider circuit.

Figure 12.6 shows two potential divider circuits, each connected across a battery of e.m.f. 6.0 V and of negligible

The output voltage V_{out} depends on the relative values of R_1 and R_2. You can calculate the value of V_{out} using the following **potential divider equation**:

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

In this equation, V_{in} is the total voltage across the two resistors.

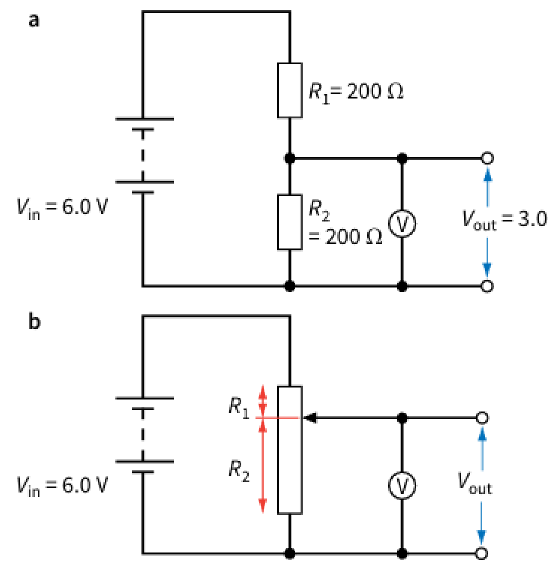


Figure 12.6 Two potential divider circuits.

Potentiometer circuits

A potentiometer is a device used for comparing potential differences. A driver cell is connected across the length of wire. Suppose this cell has an e.m.f. Eo of 2.0 V. We can then say that point A is at a voltage of 2.0 V, B is at 0 V, and the midpoint of the wire is at 1.0 V. In other words, the voltage decreases steadily along the length of the wire.

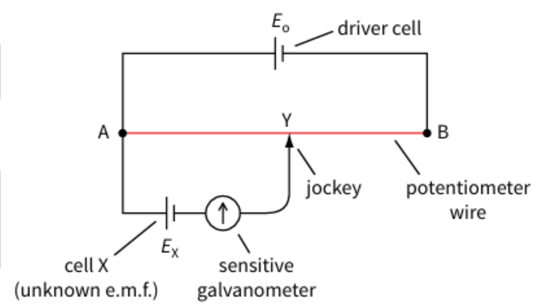


Figure 12.8 A potentiometer connected to measure the e.m.f. of cell X.

To measure the e.m.f. EX of cell X, connect the positive terminal to point A and a lead from the negative terminal to a sensitive galvanometer. A metal jockey is connected to the wire, allowing precise positioning. The galvanometer needle deflects in one direction near point A and the opposite direction near point B. Find a point Y along the wire with zero deflection, touching gently and briefly. The potentiometer is balanced if the potential difference across the wire is equal to the e.m.f. of cell X.

To calculate the unknown e.m.f. E_X we measure the length AY. Then we have:

$$E_X = \frac{AY}{AB} \times E_o$$

where E_o is the e.m.f. of the driver cell.

The potentiometer can be thought of as a potential divider because the point of contact Y divides the resistance wire into two parts, equivalent to the two resistors of a potential divider.

Comparing e.m.f.s with a potentiometer

A potentiometer balances without current flow, ensuring its terminal p.d. equals its e.m.f., eliminating 'lost volts'. However, the driver cell's internal resistance causes a lower p.d. between A and B, resulting in some volts lost. To overcome this issue, potentiometers can be used to compare p.d.s between cells, ensuring E_Y is greater than E_X.

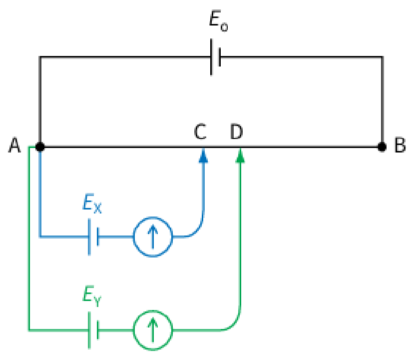


Figure 12.9 Comparing two e.m.f.s using a potentiometer.

The ratio of the e.m.f.s of the two cells will be equal to the ratio of the two lengths AC and AD:

$$\frac{E_X}{E_Y} = \frac{AC}{AD}$$

If one of the cells used has an accurately known e.m.f., the other can be calculated with the same degree of accuracy.

Comparing p.d.s

The same technique can be used to compare potential differences. For example, two resistors could be connected in series with a cell (Figure 12.10). The p.d. across one resistor is first connected to the potentiometer and the balance length found. This is repeated with the other resistor and the new balance point is found. The ratio of the lengths is the ratio of the p.d.s.

Chapter 13: Waves

Describing waves

When you pluck the string of a guitar, it vibrates. The vibrations create a wave in the air which we call sound. In fact, all vibrations produce waves of one type or another (Figure 13.2). Waves that move through a material (or a vacuum) are called progressive waves

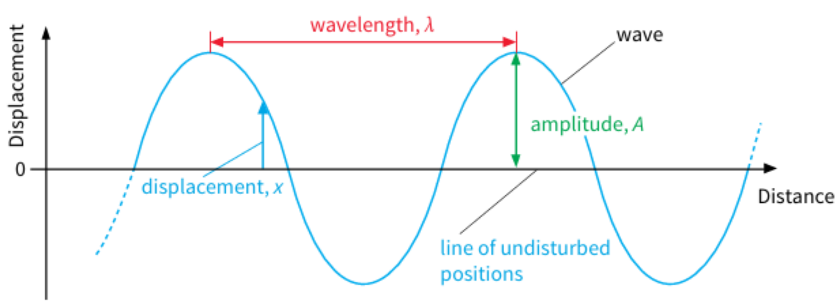


Figure 13.3 A displacement–distance graph illustrating the terms displacement, amplitude and wavelength.

Figure 13.3 or a similar graph of displacement against time illustrates the following important definitions about waves and wave motion:

■ ■ The distance of a point on the wave from its undisturbed position or equilibrium position is called the displacement x.

■ ■ The maximum displacement of any point on the wave from its undisturbed position is called the amplitude A. The amplitude of a wave on the sea is measured in units of distance, e.g. metres. The greater the amplitude of the wave, the louder the sound or the rougher the sea!

Figure 13.2 Radio telescopes detect radio waves from distant stars and galaxies; a rainbow is an effect caused by the reflection and refraction of light waves by water droplets in the atmosphere.

■ ■ The distance from any point on a wave to the next exactly similar point (e.g. crest to crest) is called the wavelength λ (the Greek letter lambda). The wavelength of a wave on the sea is measured in units of distance, e.g. metres.

■ ■ The time taken for one complete oscillation of a point in a wave is called the period T. It is the time taken for a point to move from one particular position and return to that same position, moving in the same direction. It is measured in units of time, e.g. seconds..

■■ The number of oscillations per unit time of a point in a wave is called its frequency f. For sound waves, the higher the frequency of a musical note, the higher is its pitch. Frequency is measured in hertz (Hz), where 1 Hz = one oscillation per second (1 kHz = 10^3 Hz and 1 MHz = 10^6 Hz). The frequency f of a wave is the reciprocal of the period T:

$$f = \frac{1}{T}$$

Figure 13.4 The impact of a droplet on the surface of a liquid creates a vibration, which in turn gives rise to waves on the surface.

Waves are called mechanical waves if they need a substance (medium) through which to travel. Sound is one example of such a wave. Other cases are waves on strings, seismic waves and water waves (Figure 13.4). Some properties of typical waves are given on Table 13.1

Longitudinal and transverse waves

There are two distinct types of wave, longitudinal and transverse.
Waggle the end of the slinky spring from side to side. T he segments of the spring move from side to side as the wave travels along the spring. These are transverse waves. So the distinction between longitudinal and transverse waves is as follows:

■ ■ In longitudinal waves, the particles of the medium vibrate parallel to the direction of the wave velocity.

■ ■ In transverse waves, the particles of the medium vibrate at right angles to the direction of the wave velocity.

Representing waves

Figure 13.8 shows how we can represent longitudinal and transverse waves. The longitudinal wave shows how the material through which it is travelling is alternately compressed and expanded. This gives rise to high and low pressure regions, respectively.

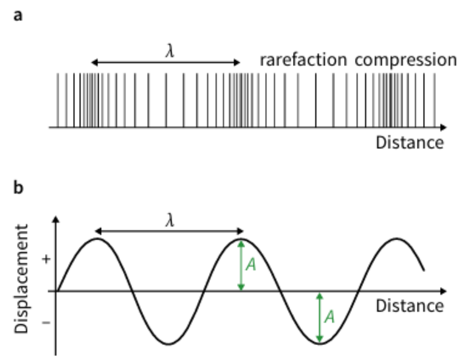


Figure 13.8 **a** Longitudinal waves and **b** transverse waves. A = amplitude, λ = wavelength.

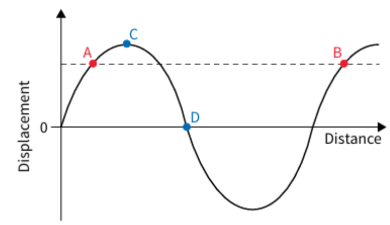
We can compare the **compressions and rarefactions** (or expansions) of the longitudinal wave with the peaks and troughs of the transverse wave.

Phase and phase difference

As one point on a wave vibrates, the point next to it vibrates slightly out-of-step with it. We say that they vibrate out of phase with each other – there is a **phase difference between them.**

Wave energy

It is energy that is transmitted by the wave. Each particle vibrates; as it does so, it pushes its neighbour, transferring energy to it. Then that particle pushes its neighbour, which pushes its neighbour. In this way, energy is transmitted from one particle to the next, to the next, and so on down the line.



Points A and B are vibrating; they have a phase difference of 360° or 0°. They are 'in phase'

Points C and D have a phase difference of 90°.

Figure 13.9 Different points along a wave have different phases.

Intensity

The term intensity has a very precise meaning in physics. The intensity of a wave is defined as the rate of energy transmitted (i.e. power) per unit area at right angles to the wave velocity.

$$\text{intensity} = \frac{\text{power}}{\text{cross-sectional area}}$$

Intensity and amplitude

The intensity of a wave generally decreases as it travels along. There are two reasons for this:

■ ■ The wave may 'spread out'

■ ■ The wave may be absorbed or scattered (as when light passes through the Earth's atmosphere).

In fact, intensity is proportional to the square of the amplitude:

$$\text{intensity} \propto \text{amplitude}^2 \quad (I \propto A^2)$$

The relationship also implies that, for a particular wave:

$$\frac{\text{intensity}}{\text{amplitude}^2} = \text{constant}$$

So, if one wave has **twice** the amplitude of another, it has **four** times the intensity. This means that it is carrying energy at four times the rate.

Wave speed

The speed with which energy is transmitted by a wave is known as the wave speed v. This is measured in m s−1.

The wave equation

An important equation connecting the speed v of a wave with its frequency f and wavelength λ can be determined as follows. We can find the speed of the wave using:

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

But a wave will travel a distance of one whole wavelength in a time equal to one period T. So:

$$\text{wave speed} = \frac{\text{wavelength}}{\text{period}}$$

or

$$v = \frac{\lambda}{T}$$

$$v = \left(\frac{1}{T}\right) \times \lambda$$

However, $f = \frac{1}{T}$ and so:

wave speed = frequency × wavelength

$$v = f \times \lambda$$

	Water waves in a ripple tank	Sound waves in air	Waves on a slinky spring
Speed / m s^{-1}	about 0.12	about 300	about 1
Frequency / Hz	about 6	20 to 20 000 (limits of human hearing)	about 2
Wavelength / m	about 0.2	15 to 0.015	about 0.5

Table 13.1 Speed (v), frequency (f) and wavelength (λ) data for some mechanical waves readily investigated in the laboratory.

Table 13.1 gives typical values of speed (v), frequency (f) and wavelength (λ) for some mechanical waves. You can check for yourself that v = f λ is satisfied.

This is an example of the Doppler effect; you can hear the same thing if a train passes at speed while sounding its whistle. Figure 13.11 shows why this change in frequency is observed. It shows a source of sound emitting waves with a constant frequency fs, together with two observers A and B.

The Doppler effec

■ ■ If the source is stationary (Figure 13.11a), waves arrive at A and B at the same rate, and so both observers hear sounds of the same frequency fs.

■ ■ If the source is moving towards A and away from B (Figure 13.11b), the situation is different. From the diagram you can see that the waves are squashed together in the direction of A and spread apart in the direction of B

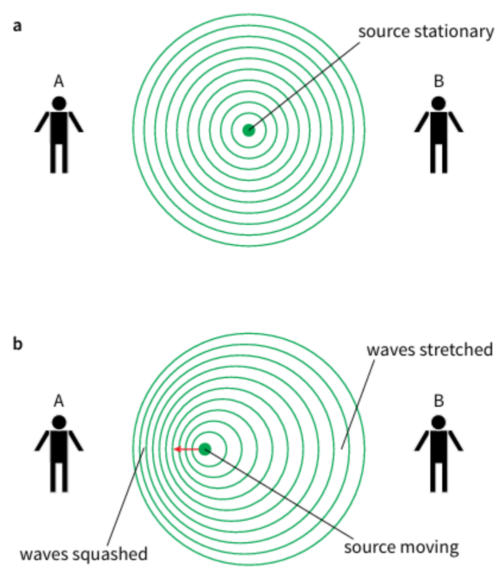


Figure 13.11 Sound waves, represented by wavefronts, emitted at constant frequency by **a** a stationary source, and **b** a source moving with speed v_s.

An equation for observed frequency

The speed of sound waves depends on the source's speed, while the speed of sound waves travels through the air. The frequency and wavelength of sound waves change with the source's speed, and the length of the wave train, which represents the first wave's distance from the source, is equal to the wave speed.

The observed wavelength is now given by $\lambda_o = \frac{(v+v_s)}{f_s}$.
The observed frequency is given by:

$$f_o = \frac{v}{\lambda_o} = \frac{f_s \times v}{(v+v_s)}$$

This tells us how to calculate the observed frequency when the source is moving away from the observer. If the source is moving towards the observer, the train of f_s waves will be compressed into a shorter length equal to $v - v_s$, and the observed frequency will be given by:

$$f_o = \frac{v}{\lambda_o} = \frac{f_s \times v}{(v-v_s)}$$

We can combine these two equations to give a single equation for the Doppler shift in frequency due to a moving source:

$$\text{observed frequency } f_o = \frac{f_s \times v}{(v \pm v_s)}$$

where the plus sign applies to a receding source and the minus sign to an approaching source. Note these important points:

- The frequency f_s of the source is not affected by the movement of the source – it still emits f_s waves per second.
- The speed v of the waves as they travel through the air (or other medium) is also unaffected by the movement of the source.

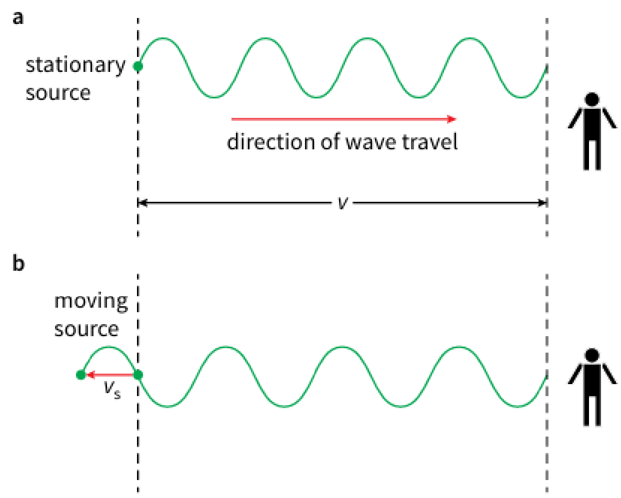


Figure 13.12 Sound waves, emitted at constant frequency by **a** a stationary source, and **b** a source moving with speed v_s away from the observer.

Electromagnetic waves You should be familiar with the idea that light is a region of the electromagnetic spectrum

An electric current always gives rise to a magnetic field (this is known as electromagnetism). A magnetic field is created by any moving charged particles such as electrons.

Physicists continue to strive to unify the big ideas of physics; you may occasionally hear talk of a **theory of everything**. This would not truly explain **everything**, but it would explain all known forces, as well as the existence of the various fundamental particles of matter.

Electromagnetic radiation By the end of the 19th century, several types of electromagnetic wave had been discovered:

■ ■ radio waves – these were discovered by Heinrich Hertz when he was investigating electrical sparks

■ ■ infrared and ultraviolet waves – these lie beyond either end of the visible spectrum

Figure 13.13 These telecommunications masts are situated 4500 metres above sea level in Ecuador. They transmit microwaves, a form of electromagnetic radiation, across the mountain range of the Andes.

Figure 13.14 Abdus Salam, the Pakistani physicist, won the 1979 Nobel Prize for Physics for his work on unification of the fundamental forces.

■ ■ X-rays – these were discovered by Wilhelm Röntgen and were produced when a beam of electrons collided with a metal target such as tungsten

■ ■ γ-rays – these were discovered by Henri Becquerel when he was investigating radioactive substances.

The speed of light

James Clerk Maxwell showed that the speed c of electromagnetic radiation in a vacuum (free space) was independent of the frequency of the waves

In other words, all types of electromagnetic wave travel at the same speed in a vacuum. In the SI system of units, c has the value:

$$c = 299\,792\,458\ \mathrm{m\,s^{-1}}$$

The approximate value for the speed of light in a vacuum (often used in calculations) is $3.0 \times 10^8\ \mathrm{m\,s^{-1}}$.

The wavelength λ and frequency f of the radiation are related by the equation:

$$c = f\lambda$$

When light travels from a vacuum into a material medium such as glass, its speed **decreases** but its frequency **remains the same**, and so we conclude that its wavelength must decrease.

The observed frequency of light from a moving source can be calculated using the same equation as for sound, $f_{\text{obs}} = \frac{f \times c}{(c \pm v_s)}$ but there is an important condition. The speed of the source v_s must be small compared to the speed of light c. For speeds approaching c, the equation must be altered to take account of the theory of relativity.

Radiation	Wavelength range / m
radio waves	$>10^{6}$ to 10^{-1}
microwaves	10^{-1} to 10^{-3}
infrared	10^{-3} to 7×10^{-7}
visible	7×10^{-7} (red) to 4×10^{-7} (violet)
ultraviolet	4×10^{-7} to 10^{-8}
X-rays	10^{-8} to 10^{-13}
γ-rays	10^{-10} to 10^{-16}

Table 13.3 Wavelengths (in a vacuum) of the electromagnetic spectrum.

Orders of magnitude

Table 13.3 shows the approximate ranges of wavelengths in a vacuum of the principal bands which make up the electromagnetic spectrum. This information is shown as a diagram in Figure 13.15. Here are some points to note:

■ ■ There are no clear divisions between the different ranges or bands in the spectrum. The divisions shown in Table 13.3 are somewhat arbitrary.

■ ■ The naming of subdivisions is also arbitrary. For example, microwaves are sometimes regarded as a subdivision of radio waves.

■ The ranges of X-rays and γ-rays overlap. The distinction is that X-rays are produced when electrons decelerate rapidly or when they hit a target metal at high speeds. γ-rays are produced by nuclear reactions such as radioactive decay

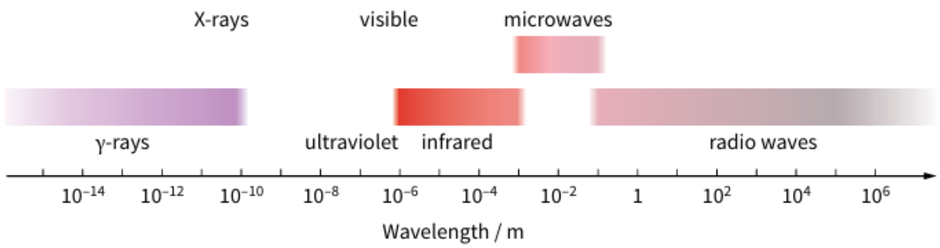


Figure 13.15 Wavelengths of the electromagnetic spectrum. The boundaries between some regions are fuzzy.

The nature of electromagnetic waves

An electromagnetic wave is a disturbance in the electric and magnetic fields in space. Figure 13.16 shows how we can represent such a wave. In this diagram, the wave is travelling from left to right.

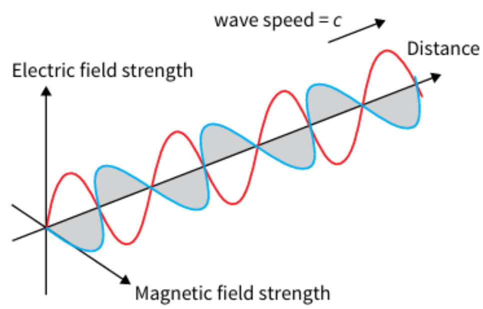


Figure 13.16 An electromagnetic wave is a periodic variation in electric and magnetic fields.

Revision questions

1.

A uniform electric field is produced between two parallel metal plates. The electric field strength is $1.4 \times 10^{4} NC^{-1}$. The potential difference between the plates is 350V.

(a) Calculate the separation of the plates.

separation = ... m

(b) A nucleus of mass 8.3×10^{-27} kg is now placed in the electric field. The electric force acting on the nucleus is 6.7×10^{-15}N.

(i) Calculate the charge on the nucleus in terms of e, where e is the elementary charge.

charge = ... e

(ii) Calculate the mass, in u, of the nucleus.

mass = ... u

(iii) Use your answers in (b)(i) and (b)(ii) to determine the number of neutrons in the nucleus.

number = ...

2. (a)Define electric field strength.

b) Two parallel metal plates in a vacuum are separated by a distance of 15mm, as shown in Fig. 6.1.

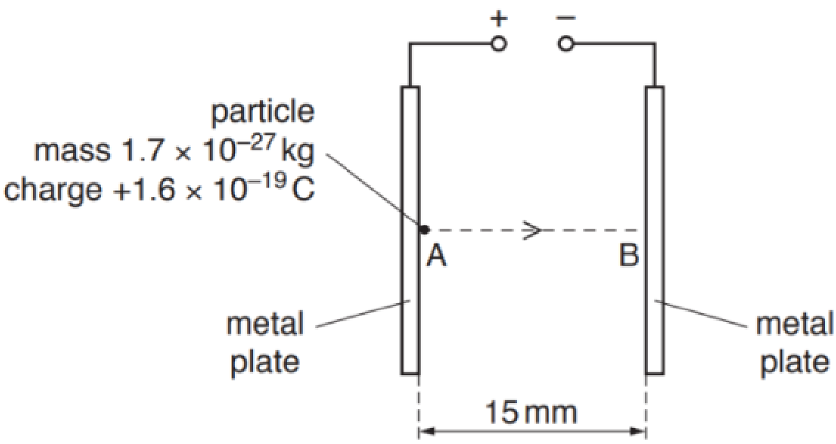


Fig. 6.1

A uniform electric field is produced between the plates by applying a potential difference between them.
A particle of mass 1.7×10^{-27} kg and charge $+1.6 \times 10^{-19}$C is initially at rest at point A on one plate. The particle is moved by the electric field to point B on the other plate. The particle reaches point B with kinetic energy 2.4×10^{-16} J.

(i)Calculate the speed of the particle at point B.

speed = ... ms^{-1}

(ii) State the work done by the electric field to move the particle from A to B.

work done = ... J

(iii) Use your answer in (ii) to determine the force on the particle.

force = ... N

(iv) Determine the potential difference between the plates.

potential difference = ... V

(v) On Fig. 6.2, sketch a graph to show the variation of the kinetic energy of the particle with the distance x from point A along the line AB. Numerical values for the kinetic energy are not required.

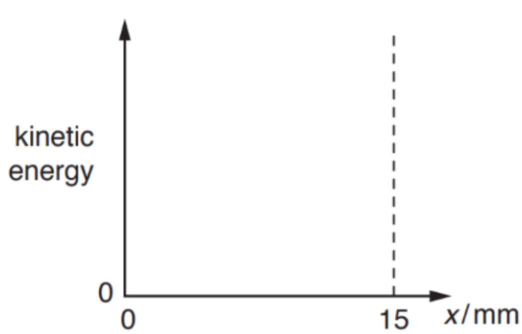


Fig. 6.2

3. (a) State Kirchhoff's second law.

(b) A battery has electromotive force (e.m.f.) 4.0V and internal resistance 0.35Ω. The battery is connected to a uniform resistance wire XY and a fixed resistor of resistance R, as shown in Fig. 5.1.

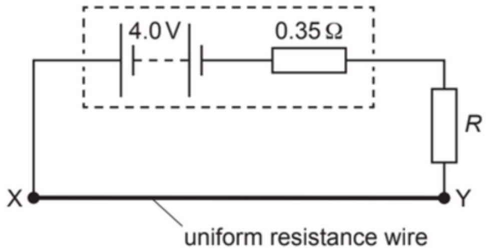


Fig. 5.1

Wire XY has resistance 0.90Ω. The potential difference across wire XY is 1.8V.

Calculate:

(i) the current in wire XY

current = ... A [1]

(ii) the number of free electrons that pass a point in the battery in a time of 45s

number = ...

(iii) resistance R.

R = ... Ω

(c) A cell of e.m.f. 1.2V is connected to the circuit in (b), as shown in Fig. 5.2.

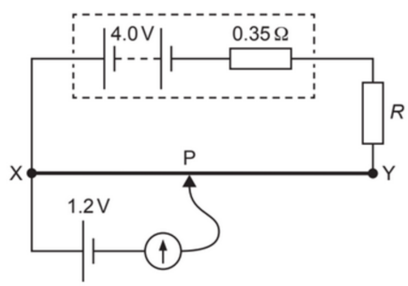


Fig. 5.2

The connection P is moved along the wire XY. The galvanometer reading is zero when distance XP is 0.30m.

(i) Calculate the total length L of wire XY.

L = ... m [2]

(ii) The fixed resistor is replaced by a different fixed resistor of resistance greater than R.

State and explain the change, if any, that must be made to the position of P on wire XY so that the galvanometer reading is zero.

4.

(a) Metal wire is used to connect a power supply to a lamp. The wire has a total resistance of 3.4Ω and the metal has a resistivity of $2.6\times10^{-8}\Omega m$. The total length of the wire is 59m.

(i) Show that the wire has a cross-sectional area of $4.5\times10^{-7}m^2$.

(ii) The potential difference across the total length of wire is 1.8V.
Calculate the current in the wire.
current = ...

(iii) The number density of the free electrons in the wire is $6.1\times10^{28}m^{-3}$.
Calculate the average drift speed of the free electrons in the wire.
average drift speed = ... ms^{-1}

(b) A different wire carries a current. This wire has a part that is thinner than the rest of the wire, as shown in Fig. 5.1.

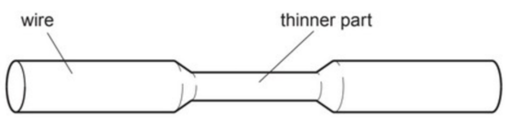


Fig. 5.1

(i) State and explain qualitatively how the average drift speed of the free electrons in the thinner part compares with that in the rest of the wire.

(ii) State and explain whether the power dissipated in the thinner part is the same, less or more than the power dissipated in an equal length of the rest of the wire.

(ii) A potential divider circuit is produced by connecting the three resistors to a battery of electromotive force (e.m.f.) 12V and negligible internal resistance. The potential divider circuit provides an output potential difference V_{OUT} of 8.0V.

Fig. 5.2 shows the circuit diagram.

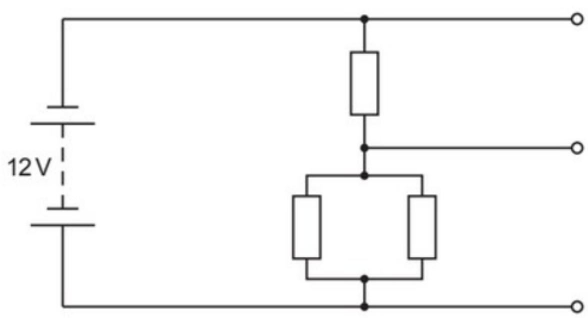


Fig. 5.2

On Fig. 5.2, label the resistances of all three resistors and the potential difference V_{OUT}.