5.3 Electric cells

Understanding

- Cells
- Primary and secondary cells
- Terminal potential difference
- Electromotive force emf
- Internal resistance

Applications and skills

- Investigating practical electric cells (primary and secondary)
- Describing the discharge characteristic of a simple cell (variation of terminal potential difference with time)
- Identifying the direction current flow required to recharge a cell
- Determining internal resistance experimentally
- Solving problems involving emf, internal resistance, and other electrical quantities

Equation

- emf of a cell: $\varepsilon = I(R + r)$

Nature of science

Scientists need to balance their research into more and more efficient electric cells with the long-term risks associated with the disposal of the cells. Some modern cells have extremely poisonous contents. There will be serious consequences if these chemicals are allowed to enter the water supply or the food chain. Can we afford the risk of using these toxic substances, and what steps should the scientists take when carrying forward the research?

Introduction

Electric currents can produce a **chemical effect**. This has great importance in chemical industries as it can be a method for extracting ores or purifying materials. However, in this course we do not investigate this aspect of the chemical effect. Our emphasis is on the use of an electric cell to store energy in a chemical form and then release it as electrical energy to perform work elsewhere.

Cells

Cells operate as direct-current (dc) devices meaning that the cell drives charge in one direction. The electron charge carriers leave the negative terminal of the cell. After passing around the circuit, the electrons re-enter the cell at the *positive* terminal. The positive terminal has a higher potential than the negative terminal – so electrons appear to gain energy (whereas positive charge carriers would appear to lose it).

The chemicals in the cell are reacting while current flows and as a result of this reaction the electrons gain energy and continue their journey around the circuit.

Nature of science

Anodes and cathodes

You will meet a naming system for anode and cathode which seems different for other cases in physics. In fact it is consistent, but you need to think carefully about it. For example, in a cathode-ray tube where the electrons in the tube are emitted from a hot metal filament, the filament is called the cathode and is at a negative voltage. This appears to be the opposite notation from that used for the electric cell. The reason is that the notation refers to what is happening inside the cell, not to the external circuit. The chemical reaction in the cell leads to positive ions being generated at one of the electrodes and then flowing away into the bulk of the liquid. So as far as the interior of the cell is concerned this is an anode, because it is an (internal) source of positive ions. Of course, as far as the external circuit is concerned, the movement of positive charges away from this anode leaves it negative and the electrode will repel electrons in the external circuit. As external observers, we call this the negative terminal even though (as far as the interior of the cell is concerned) it is an anode.

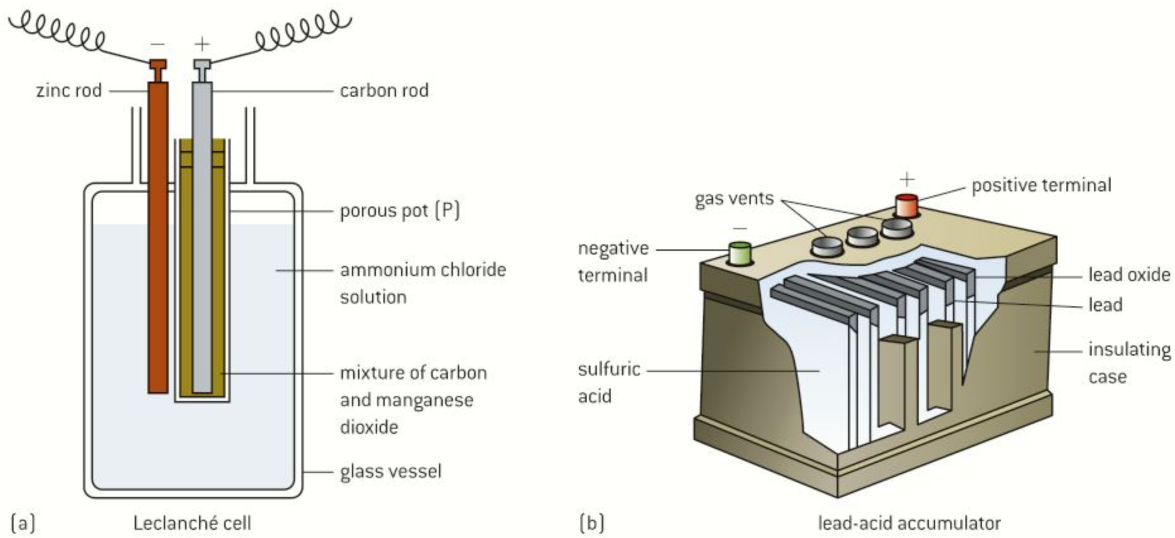
Primary and secondary cells

Many of the portable devices we use today: torches, music players, computers, can operate with internal cells, either singly or in batteries. In some cases, the cells are used until they are exhausted and then thrown away. These are called **primary cells**. The original chemicals have completely reacted and been used up, and they cannot be recharged. Examples include AA cells (properly called dry cells) and button mercury cells as used in clocks and other small low-current devices.

On the other hand, some devices use rechargeable cells so that when the chemical reactions have finished, the cells can be connected to a charger. Then the chemical reaction is reversed and the original chemicals form again. When as much of the re-conversion as is possible has been achieved, the cell is again available as a chemical energy store. Rechargeable cells are known as **secondary cells**.

There many varieties of cell, here are two examples of the chemistry of a primary cell and that of a secondary cell.

The **Leclanché cell** was invented by Georges Leclanché in 1886. It is a primary cell and is the basis of many domestic torch and radio batteries.



▲ Figure 1 Leclanché cell and lead-acid accumulator.

Figure 1(a) shows one practical arrangement of the cell. It consists of a zinc rod that forms the negative terminal. Inside the zinc is a paste of ammonium chloride separated from manganese dioxide (the cathode) by a porous membrane. In the centre of the manganese dioxide is a carbon rod that acts as the positive terminal for the cell.

Zinc atoms on the inside surface of the case oxidize to become positive ions. They then begin to move away from the inside of the case through the chloride paste leaving the case negatively charged. When the cell is connected to an external circuit, these electrons move around the circuit eventually reaching the carbon rod. A reaction inside the cell uses these electrons together with the components of the cell eventually forming the "waste products" of the cell, which include ammonia, manganese oxide, and manganese hydroxide.

Secondary cells are very important today. They include the lead–acid accumulator, together with more modern developments such as the nickel–cadmium (NiCd), nickel–metal-hydride (NiMH), and lithium ion cells. All these types can be recharged many times and even though they may have a high initial cost (compared to primary cells of an equivalent emf and capacity), the recharge is cheap so that, during the projected lifetime of the cell, the overall cost is lower than that of primary cells.

Although the lead-acid accumulator is one of the earliest examples of a secondary cell, it remains important ("accumulator" is an old word that implies the accumulation or collection of energy into a store). It is capable of delivering the high currents needed to start internal combustion and diesel engines, and it is reliable in the long term to maintain the current to important computer servers if the mains supply fails.

The **lead–acid cell** (figure 1(b)) is slightly older than the Leclanché cell, and was invented in 1859 by Gaston Planté.

In its charged state the cell consists of two plates, one of metallic lead, the other of lead(IV) oxide (PbO_2) immersed in a bath of dilute sulfuric acid. During discharge when the cell is supplying current to an external circuit, the lead plate reacts with the acid to form lead(II) sulfate and the production of two free electrons. The liquid surrounding the plates loses acid and becomes more dilute. At the oxide plate, electrons are gained (from the external circuit) and lead(II) sulfate is formed, also with the removal of acid from the liquid. So the net result of discharging is that the plates convert to identical lead sulfates and the liquid surrounding the plates becomes more dilute.

Recharging reverses these changes: electrons are forced from the positive plate by an external charging circuit and forced onto the negative plate. At the negative plate, atomic lead forms, at the positive, lead oxide is created, which restores the cell to its original state. The charge–recharge cycle can be carried out many times providing that the cell is treated carefully. However, if lead or lead oxide fall off the plates, they can no longer be used in the process and will collect at the bottom of the cell container. In the worst case the lead will short out the plates and the cell will stop operating. If the cell is overcharged (when no more sulfate can be converted into lead and lead oxide) the charging current will begin to split the water in the cell into hydrogen and oxygen gas which are given off from the cell. The total amount of liquid in the cell will decrease, meaning that the plates may not be fully covered by the acid. These parts of the plates will then not take part in the reaction and the ability of the cell to store energy will decrease.

Much industrial research effort is concentrated on the development of rechargeable cells. An important consideration for many manufacturers of electronic devices is the energy density for the battery (the energy stored per unit volume) as this often determines the overall design and mass of an electronic device. Also a larger energy density may well provide a longer lifetime for the device.

Capacity of a cell

Two cells with the same chemistry will generate the same electromotive force (emf) as each other. However if one of the cells has larger plates than the other and contains larger volumes of chemicals, then it will be able to supply energy for longer when both cells carry the same current.

The **capacity** of a cell is the quantity used to measure the ability of a cell to release charge. If a cell is discharged at a high rate then it will not be long before the cell is exhausted or needs recharging, if the discharge current is low then the cell will supply energy for longer times. The capacity of a cell or battery is the constant current that it can supply for a given discharge. So, if a cell can supply a constant current of 2 A for 20 hours then it said to have a capacity of 40 amp-hours (abbreviated as 40 Ah).

The implication is that this cell could supply 1 A for 40 hours, or 0.1 A for 400 hours, or 10 A for 4 hours. However, practical cells do not necessarily discharge in such a linear way and this cell may be able to provide a small discharge current of a few milliamps for much

Worked examples

1 Explain the difference between a primary and a secondary cell.

Solution

A primary cell is one that can convert chemical energy to electrical energy until the chemicals in the cell are exhausted. Recharging the cell is not possible.

A secondary cell can be recharged and the chemicals in it are converted back to their original form so that electrical energy can be supplied by the cell again.

2 A cell has a capacity of 1400 mA h. Calculate the number of hours for which it can supply a current of 1.8 mA.

Solution

Cell capacity = current × time and therefore $1400 = 1.8t$. In this case $t = 780$ hours.

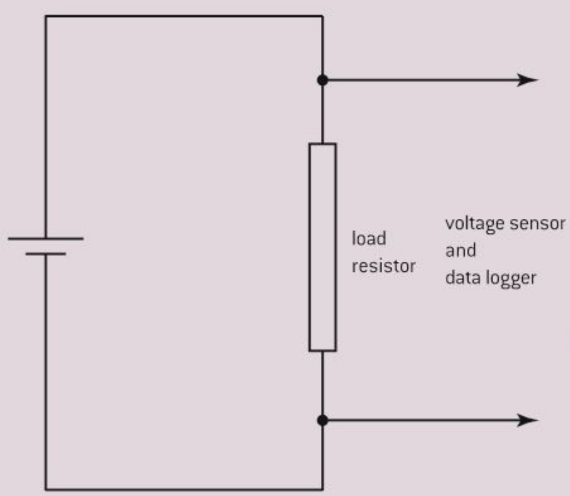
longer than expected from the value of its capacity. Conversely, the cell may be able to discharge at 10 A for much less than 4 hours. An extreme example of this is the lead–acid batteries used to start cars and commercial vehicles. A typical car battery may have a capacity of 100 A h. The current demand for starting the car on a cold winter's day can easily approach 150 A. But the battery will only be able to turn the engine for a few minutes rather than the two-thirds of an hour we might expect.

Discharging cells

Investigate!

Discharge of a cell

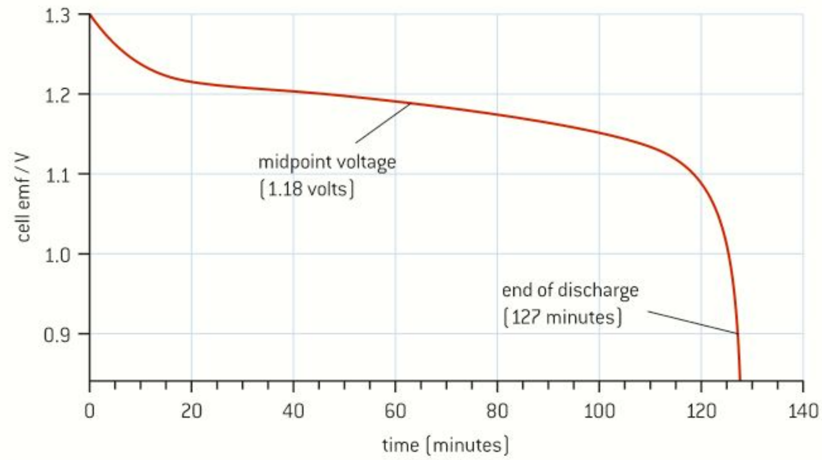
- Some cells have high capacity, and studying the discharge of such a cell can take a long time. This is a good example of how electronic data collection (data-logging) can help an experimenter.



▲ Figure 2

- The aim is to collect data to find how the terminal pd across the cell varies with time from the start of the discharge. The basic circuit is shown in figure 2. Use a new cell to provide the current so that the initial behaviour of the cell can be seen too.
- Many data loggers need to be "told" how often to take measurements (the sampling rate). You will need to make some judgements about the overall length of time for which the experiment is likely to operate. Suppose you have a 1.5 V cell rated at 1500 mA h (you can check the figure by checking the cell specification on the manufacturer's website). It would seem reasonable that if the cell is going to supply a current of 250 mA, then it would discharge in a time of between 4–10 hours. You will need to set up the data logger accordingly with a suitable time between readings (the sampling interval). Do not, however, exceed the maximum discharge current of the cell.
- When the computer is set up, turn on the current in the discharge circuit and start the logging. Eventually the cell will have discharged and you can display the data as a graph. What are the important features of your graph?
- Test other types of cell too, at least one primary and one secondary cell. Are there differences in the way in which they discharge?
- For at least one cell, towards the end of the discharge, switch off the discharge current while still continuing to monitor the terminal pd. Does the value of the pd stay the same or does it recover? When the discharge is resumed what happens to the pd?

The results you obtain will depend on the types and qualities of the cells you test. A typical discharge curve looks like that in figure 3 on p222 in which the terminal potential difference of the cell is plotted against time since the discharge current began.

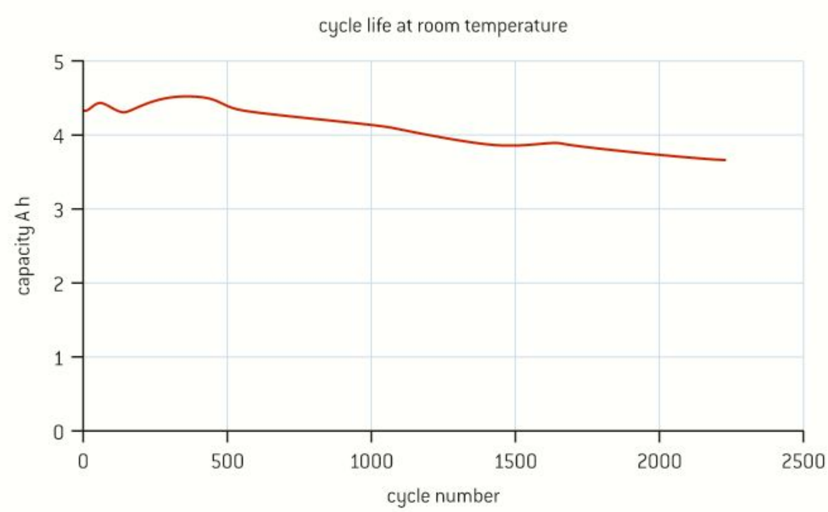


▲ Figure 3 Typical discharge–time graph for a cell.

Important features of this graph are that:

- The initial terminal pd is higher than the quoted emf (the value the manufacturer prints on the case), but the initial value quickly drops to the rated emf (approximately).
- For most of the discharge time the terminal pd remains more or less constant at or around the quoted emf. There is however sometimes a slow decline in the value of the terminal pd.
- As the cell approaches exhaustion, the terminal pd drops very rapidly to a low level.
- If the current is switched off, the terminal pd rises and can eventually reach the rated value again. However, when discharge is resumed, the terminal pd falls very quickly to the low value that it had before.

Other experiments are possible, particularly for rechargeable cells to see the effects of repeated discharge–charge cycles on the cell. Figure 4 shows how the capacity of a Ni–Cd cell changes as cell is taken through more and more cycles.



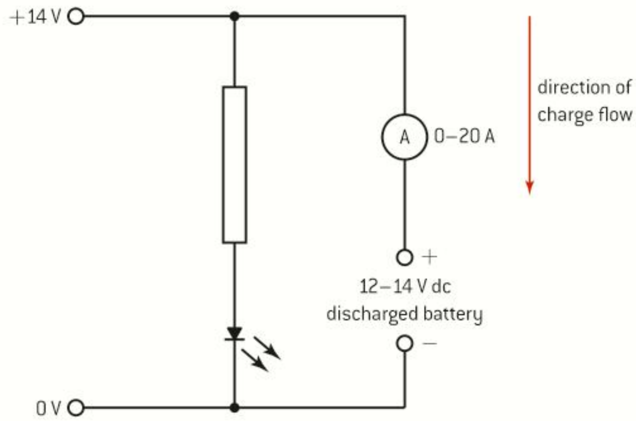
▲ Figure 4 Cycle life of a rechargeable cell.

Recharging secondary cells

The clue to recharging a secondary cell is in the earlier descriptions of cell chemistry. The chemicals produce an excess of electrons at the negative terminal. During discharge these electrons then move through the external circuit transferring their energy as they go. When the electron arrives at the positive terminal, all of its energy will have been transferred to other forms and it will need to gain more from the chemical store in the cell.

To reverse the chemical processes we need to return energy to the cell using electrons as the agents, so that the chemical action can be reversed. When charging, the electrons need to travel in the reverse direction to that of the discharge current and you can imagine that the charger has to force the electrons the "wrong" way through the cell.

Part of a possible circuit to charge a 6-cell lead–acid battery is shown in figure 5.

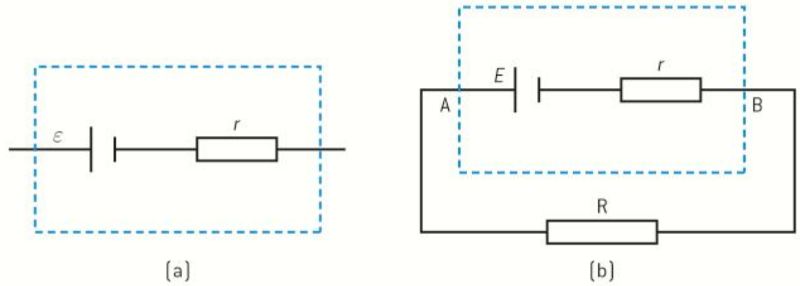


▲ Figure 5 Charging circuit for a cell.

The direction of the charging current is shown in the diagram. It is in the opposite direction to that of the cell when it is supplying energy. An input pd of 14 V is needed, notice the polarity of this input. The light-emitting diode (LED) and its series resistor indicate that the circuit is switched on. The ammeter shows the progress of charging. When the battery is completely discharged, the charging current will be high, but as the charging level (and therefore the emf) of the battery rises, this current gradually falls. During the charging process the terminal voltage will be greater than the emf of the cell. At full charge the emf of the battery is 13.8 V. When the current in the meter is zero, the battery is fully charged.

Internal resistance and emf of a cell

The materials from which the cells are made have electrical resistance in just the same way as the metals in the external circuit. This **internal resistance** has an important effect on the total resistance and current in the circuit.



▲ Figure 6

Figure 6(a) shows a simple model for a cell. Inside the dotted box is an "ideal" cell that has no resistance of its own. Also inside the box is a resistance symbol that represents the internal resistance of the cell. The two together make up our model for a real cell. The model assumes that the internal resistance is constant (for a practical cell it varies with the state of discharge) and that the emf is constant (which also varies with discharge current).

TOK

Simple assumptions

The model of a cell with a fixed internal resistance and a constant emf is an example of modelling. In this case the model is a simple one that cannot be realized in practice. Another model we used earlier was to suggest that there are ideal ammeters with zero resistance and ideal voltmeters with infinite resistance.

Scientists frequently begin with a very simple model of a system and then explore the possibilities that this model can offer in terms of analysis and behaviour. The next step is to make the model more complicated (but without being too intricate!) and to see how much complexity is needed before the model resembles the real system that is being modelled.

Do the simplifications and assumptions of ideal behaviour form a suitable basis for modelling?

The model cell has an emf ε and an internal resistance r in series with an external resistance R (figure 6(b)). The current in the circuit is I.

We can apply Kirchhoff's second law to this circuit:

the emf of the cell supplying energy to the circuit	$= \varepsilon$
the sum of the pds	$= IR + Ir$

So

$$\varepsilon = IR + Ir$$

If the pd across the external resistor is V, then

$$\varepsilon = V + Ir$$

or

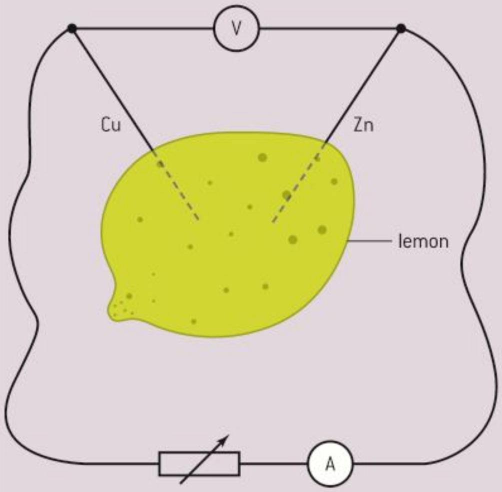
$$V = \varepsilon - Ir$$

It is important to realize that V, which is the pd across the external resistance, is equal to the terminal pd across the ideal cell and its internal resistance (in other words between A and B). **The emf is the open circuit pd across the terminals of a power source – in other words, the terminal pd when no current is supplied**. The pd between A and B is less than the emf unless the current in the circuit is zero. The difference between the emf and the **terminal pd** (the measured pd across the terminal of the cell) is sometimes referred to as the "lost pd" or the "lost volts". These lost volts represent the energy required to drive the electron charge carriers through the cell itself. Once the energy has been used in the cell in this way, it cannot be available for conversion in the external circuit. You may have noticed that when a secondary cell is being charged, or any cell is discharging at a high current, the cell becomes warm. The energy required to raise the temperature of the cell has been converted in the internal resistance.

Investigate!

Measuring the internal resistance of a fruit cell

The method given here works for any type of electric cell, but here we use a citrus fruit cell (orange, lemon, lime, etc.) or even a potato for the measurement. The ions in the flesh of the fruit or the potato react with two different metals to produce an emf. With an external circuit that only requires a small current, the fruit cell can discharge over surprisingly long times.



▲ Figure 7

- To make the cell, take a strip of copper foil and a strip of zinc foil, both about 1 cm by 5 cm and insert these, about 5 cm apart deep into the fruit. You may need to use a knife to make an incision unless the foil is stiff enough.
- Connect up the circuit shown in figure 7 using a suitable variable resistor.
- Measure the terminal pd across the fruit cell and the current in it for the largest range of pd you can manage.

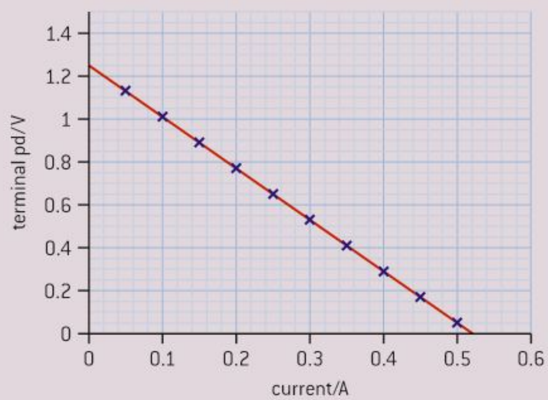
  Compare the equation

  $$V = \varepsilon - Ir$$

  with the equation for a straight line

  $$y = c + mx$$

  A plot of V on the y-axis against I on the x-axis should give a straight line with a gradient of $-r$ and an intercept on the V-axis of ε.
- A set of results for a cell (not a fruit cell in this case) is shown together with the corresponding graph of V against I. The intercept for this graph is 1.25 V and the gradient is $-2.4\ \text{V A}^{-1}$ giving an internal resistance value of 2.4 Ω.



Terminal pd / V	Current / A
1.13	0.05
1.01	0.10
0.89	0.15
0.77	0.20
0.65	0.25
0.53	0.30
0.41	0.35
0.29	0.40
0.17	0.45
0.05	0.50

▲ Figure 8

Worked example

1 A cell of emf 6.0 V and internal resistance 2.5 Ω is connected to a 7.5 Ω resistor.

Calculate:

a) the current in the cell

b) the terminal pd across the cell

c) the energy lost in the cell when charge flows for 10 s.

Solution

a) Total resistance in the circuit is 10 Ω, so current in circuit $= \frac{6}{10} = 0.60$ A

b) The terminal pd is the pd across cell $= IR =$

$0.6 \times 7.5 = 4.5$ V

c) In 10 s, 6 C flows through the cell and the energy lost in the cell is 1.5 J C^{-1}. The energy lost is 9.0 J.

2 A battery is connected in series with an ammeter and a variable resistor R. When $R = 6.0\ \Omega$, the current in the ammeter is 1.0 A. When $R = 3.0\ \Omega$, the current is 1.5 A. Calculate the emf and the internal resistance of the battery.

Solution

Using

$$V = \varepsilon - Ir$$

and knowing that $V = IR$ gives two equations:

$$6 \times 1 = \varepsilon - 1 \times r$$

and

$$3 \times 1.5 = \varepsilon - 1.5 \times r$$

These can be solved simultaneously to give $(6 - 4.5) = 0.5r$ or $r = 3.0\ \Omega$ and $\varepsilon = 9.0$ V.

Worked example

A battery of emf 9.0 V and internal resistance 3.0 Ω is connected to a load resistor of resistance 6.0 Ω. Calculate the power delivered to the external load.

Solution

Using the equation $\frac{\varepsilon^2}{(R+r)^2} R$ leads to $\frac{9^2}{(6+3)^2} 6 = 6.0$ W

Power supplied by a cell

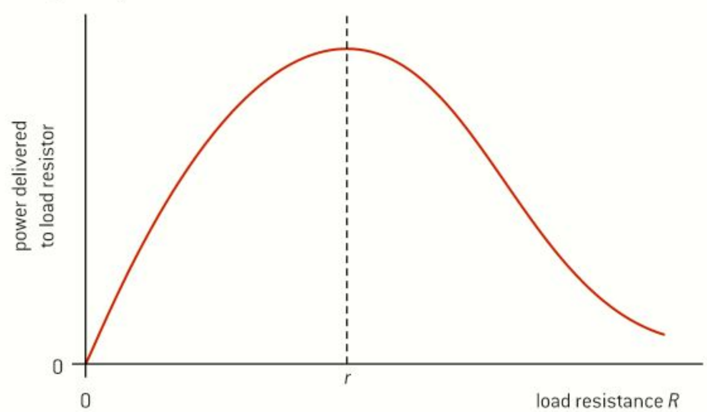
The total power supplied by a non-ideal cell is equal to the power delivered to the external circuit plus the power wasted in the cell. Algebraically,

$$P = I^2 R + I^2 r$$

using the notation used earlier.

The power delivered to the external resistance is

$$\frac{\varepsilon^2}{(R+r)^2} R$$



▲ Figure 9 Power delivered to a resistor.

Figure 9 shows how the power that is delivered to the external circuit varies with R. The peak of this curve is when $r = R$, in other words, when the internal resistance of the power supply is equal to the resistance of the external circuit. The load and the supply are "matched" when the resistances are equal in this way. This matching of supply and circuit is important in a number of areas of electronics.

5.4 Magnetic effects of electric currents

Understanding

- Magnetic fields
- Magnetic force

Applications and skills

- Sketching and interpreting magnetic field patterns
- Determining the direction of the magnetic field based on current direction
- Determining the direction of force on a charge moving in a magnetic field
- Determining the direction of force on a current-carrying conductor in a magnetic field
- Solving problems involving magnetic forces, fields, current and charges

Equations

- force on a charge moving in a magnetic field: $F = qvB \sin\theta$
- force on a current-carrying conductor in a magnetic field: $F = ILB \sin\theta$

Nature of science

Sometimes visualization aids our understanding. Magnetic field lines are one of the best examples of this. Scientists began by visualizing the shape and strength of a magnetic field through the position and direction of the fictitious lines of force (or field lines). The image proved to be so powerful that the technique was subsequently used with electric and gravitational fields too.

Introduction

Electromagnetism is the third effect observed when charge moves in a circuit – the electric current gives rise to a magnetic field. But it was not the observation of a magnetic effect arising from a current in a wire that began the ancient study of magnetism. Early navigators knew that some rocks are magnetic. As with the nature of electric charge, the true origins of magnetic effects remained obscure for many centuries. Only comparatively recently has an understanding of the microscopic aspects of materials allowed a full understanding of the origins of magnetism. As with electrostatics, scientists began by using the concept of the field to describe the behaviour of interacting magnets. However, magnetic fields differ fundamentally in character from electrostatic fields and are in some ways more complex.

Magnetic field patterns

The repulsion between the like poles of two bar magnets is familiar to us. The forces between magnets of even quite modest strength are impressive. Modern magnetic alloys can be used to produce tiny magnets (less than 1 cm in diameter and a few millimetres thick) that can easily attract another ferromagnetic material through significant thicknesses of a non-magnetic substance.

At the beginning of a study of magnetism, it is usual to describe the forces in terms of fields and field lines. You may have met this concept before. There is said to be a **magnetic field** at a point if a force acts on a magnetic pole (in practice, a pair of poles) at that point. Magnetic fields are visualized through the construction of field lines.

Magnetic field lines have very similar (but not identical) properties to those of the electric field lines in Sub-topic 5.1. In summary these are:

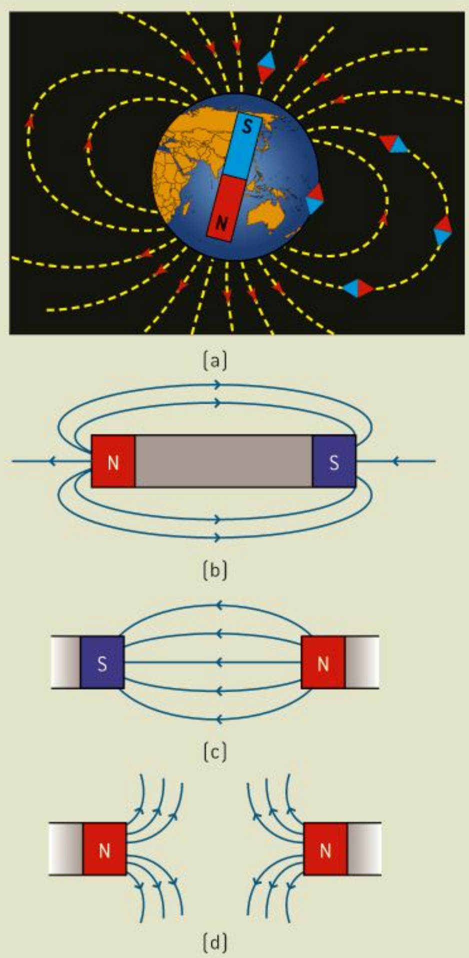
- Magnetic field lines are conventionally drawn from the north-seeking pole to the south-seeking pole, they represent the direction in which a north-seeking pole at that point would move.
- The strength of the field is shown by the density of the field lines, closer lines mean a stronger field.
- The field lines never cross.
- The field lines act as though made from an elastic thread, they tend to be as short as possible.

Nature of science

Talking about poles

A word about notation: there is a real possibility of confusion when talking about magnetic poles. This partly arises from the origin of our observations of magnetism. When we write "magnetic north pole" what we really mean is "the magnetic pole that seeks the geographic north pole" (figure 1(a)). We often talk loosely about a magnetic north pole pointing to the north pole. Misunderstandings can occur here because we also know that like poles repel and unlike poles attract. So we end up with the situation that a magnetic north pole is attracted to the "geographic north pole" – which seems wrong in the context of two poles repelling. In this book we will talk about north-seeking poles meaning "geographic north-seeking" and south-seeking poles meaning "geographic south seeking". On the diagrams, N will mean geographic north seeking, S will mean geographic south seeking.

Figure 1(b) shows the patterns for a single bar magnet and (c) and (d) two arrangements of a pair of bar magnets of equal strength.



▲ Figure 1 Magnetic field patterns.

In the pairs, notice the characteristic field pattern when the two opposite poles are close (figure 1(b)) and when the two north-seeking poles are close (figure 1(c)). When two north-seeking poles are close (or two south-seeking poles), there is a position where the field is zero between the magnets (called a null point). When two opposite poles are close, the field lines connect the two magnets. In this situation the magnets will be attracted, so this particular field pattern implies an attraction between poles.

Investigate!

Observing field patterns of permanent magnets and electric currents

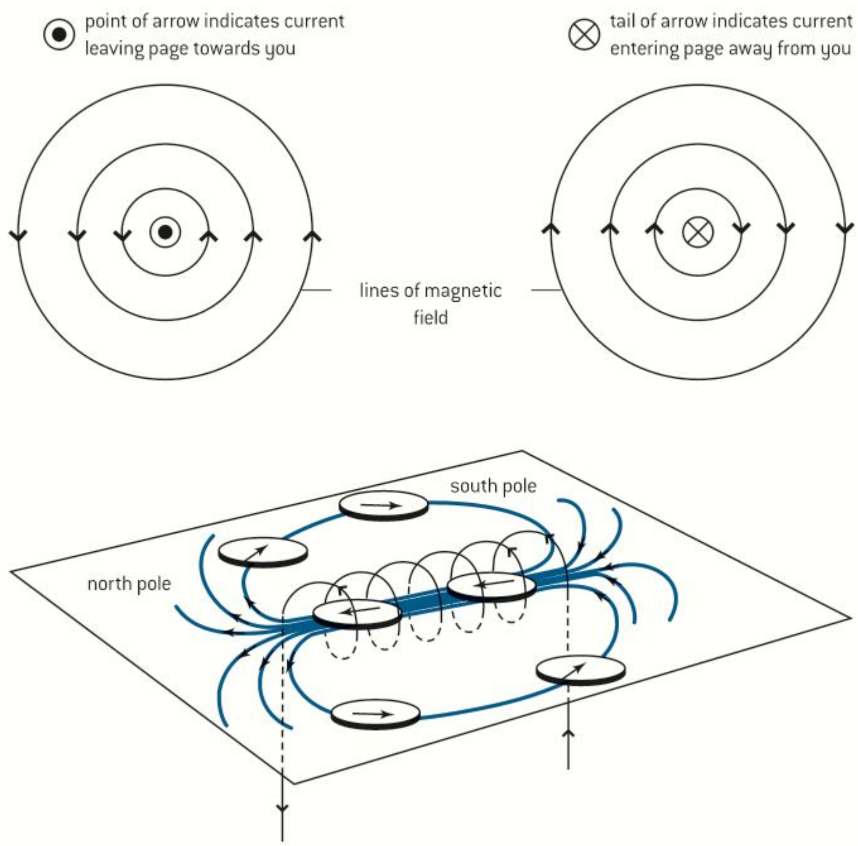
- There are a number of ways to carry out this experiment. They can involve the scattering of small iron filings, observation of suspensions of magnetized particles in a special liquid, or other techniques. This *Investigate!* is based on the iron-filing experiment but the details will be similar if you have access to other methods.
- Take a bar magnet and place a piece of rigid white card on top of it. You may need to support the card along its sides. Choose a non-magnetic material for the support.
- Take some iron filings in a shaker (a pepper pot is ideal) and, from a height above the card of about 20 cm sprinkle filings onto the card. It is helpful to tap the card gently as the filings fall onto it.
- You should see the field pattern forming as the magnetic filings fall through the air and come under the influence of the magnetic field. Sketch or photograph the arrangement.
- The iron filings give no indication of field direction. The way to observe this is to use a plotting compass – a small magnetic compass a few centimetres in diameter – that indicates the direction to which a north-seeking pole sets itself. Place one or more of these compasses on the card and note the direction in which the north-seeking pole points.
- Repeat with two magnets in a number of configurations; try at least the two in figure 1.
- Electric currents also give rise to a magnetic field. However, currents small enough to be safe will only give weak fields, not strong enough to affect the filings as they fall.

▲ Figure 2

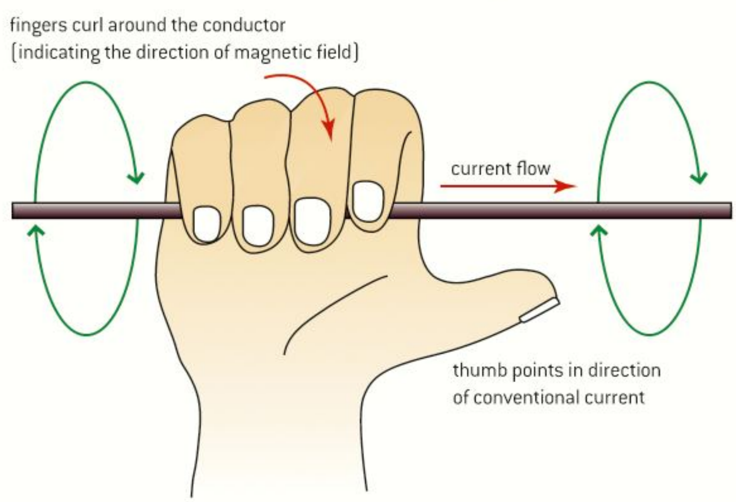
- To improve the effect: cut a small hole in the centre of the card and run a long lead through it (the lead will need to be a few metres long). Loop the lead in the same direction through a number of times (about ten turns if possible). This trick enables one current to contribute many times to the same field pattern. You may need at least 25 A in total (2.5 A in the lead) to see an effect.

Magnetic field due to a current in conductors

The magnetic field pattern due to a current in a long straight wire is a circular pattern centred on the wire. This seems odd to anyone only used to the bar magnet pattern. Measurements show that the field is strong close to the wire but becomes weaker further away from it. This should be clear in your drawings of the long wire field pattern when the lines of force are drawn at increased spacing as you move further from the wire.



▲ Figure 3 Magnetic field patterns around current-carrying conductors.



▲ Figure 4 Right-hand corkscrew rule.

Your observations using the plotting compasses should have shown that the direction of the field depends on the direction of the current.

Using the conventional current (i.e. the direction that positive charges are moving in the wire) the relationship between the current and the magnetic field direction obeys a **right-hand corkscrew rule relationship**.

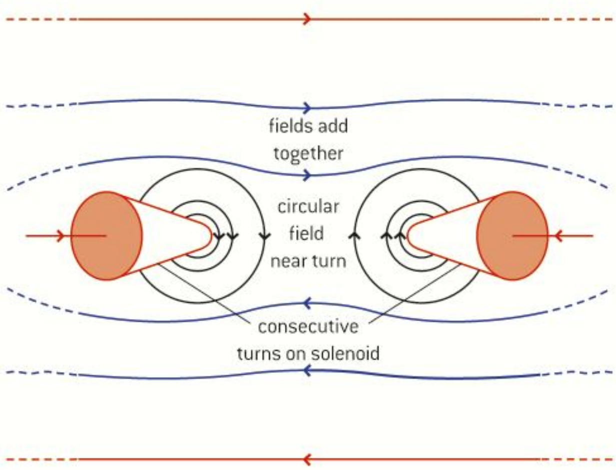
To remember this, hold your right hand with the fingers curled into the palm and the thumb extended away from the fingers (see figure 4). The thumb represents the direction of the conventional current and the fingers represent the direction of the field. Another way to think of the current–field relationship is in terms of a

screwdriver being used to insert a screw. The screwdriver has to turn a right-handed screw clockwise to insert it and drive the screw forwards. The direction in which the imaginary screw moves is that of the conventional current, and the direction in which the screwdriver turns is that of the field.

Use whichever **direction rule** you prefer, but use it consistently and remember that the rule works for conventional current.

The strength of the magnetic field can be increased by increasing the current in the conductor.

The magnetic field due to the solenoid is familiar to you already. To understand how it arises, you need to imagine the long straight wire being coiled up into the solenoid shape taking its circular field with it as the coiling takes place. With current in the wire, the circular field is set up in each wire. This circular field adds together with fields from neighbouring turns in the solenoid. Figure 5 shows this; look closely at what happens close to the individual wires. The black lines show the field near the wires, the blue lines show how the fields begin to combine, the red line shows the combined field in the centre of the solenoid.

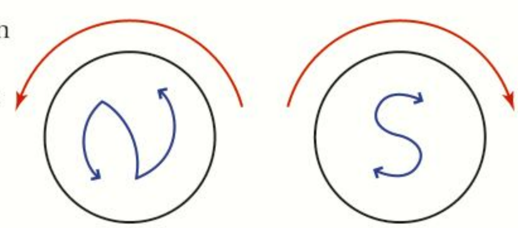


▲ Figure 5 Building up the field pattern.

A field runs along the hollow centre of the solenoid and then outside around the solenoid (figure 3). Outside it is identical to the bar magnet pattern to the extent that we can assign north- and south-seeking poles to the solenoid. Again there is an easy way to remember this using an N and S to show the north-seeking and south-seeking poles. The arrows on the N and S show the current direction when looking into the solenoid from outside. If you look into the solenoid and the conventional current is anticlockwise at the end of the solenoid closer to you then that is the end that is north-seeking. If the current is clockwise then that is the south-seeking end.

The strength of the magnetic field in a solenoid can be increased by:

- increasing the current in the wire
- increasing the number of turns per unit length of the solenoid
- adding an iron core inside the solenoid.

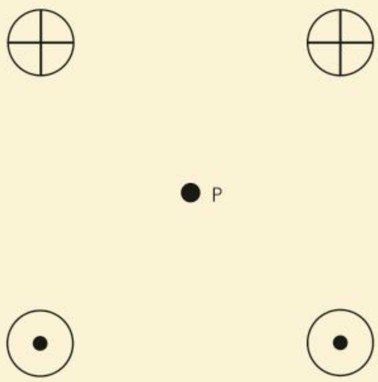


▲ Figure 6 Right hand corkscrew rule and pole direction.

Worked example

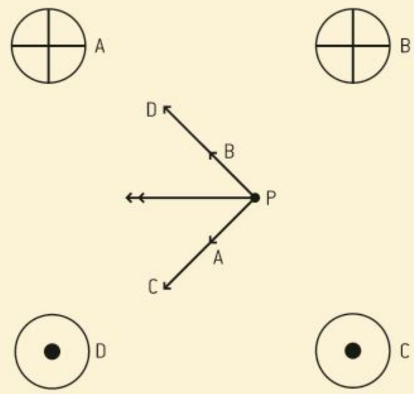
Four long straight wires are placed perpendicular to the plane of the paper at the edges of a square.

The same current is in each wire in the direction shown in the diagram. Deduce the direction of the magnetic field at point P in the centre of the square.



Solution

The four field directions are shown in the diagram. The sum of these four vectors is another vector directed from point P to the left.



Nature of science

But why permanent magnets?

We have said nothing about the puzzle of permanent magnets or the magnetism of the Earth (Figure 1(a)). The suggestion is that magnetism arises between charges when the charges move relative to each other. Can this idea be extended to help explain the reasons for permanent magnetism (known as ferromagnetism)? In fact, permanent magnetism is comparatively rare in the periodic table, only iron, nickel, and cobalt and alloys of these metals show it.

The reason is due to the arrangement of the electrons in the atoms of these substances. Electrons are now known to have the property of *spin* which can be imagined as an orbiting motion around the atom. In iron, cobalt and nickel, there is a particular arrangement that involves an unpaired electron. This is the atomic origin of the moving charge that is needed for a magnetic field to appear.

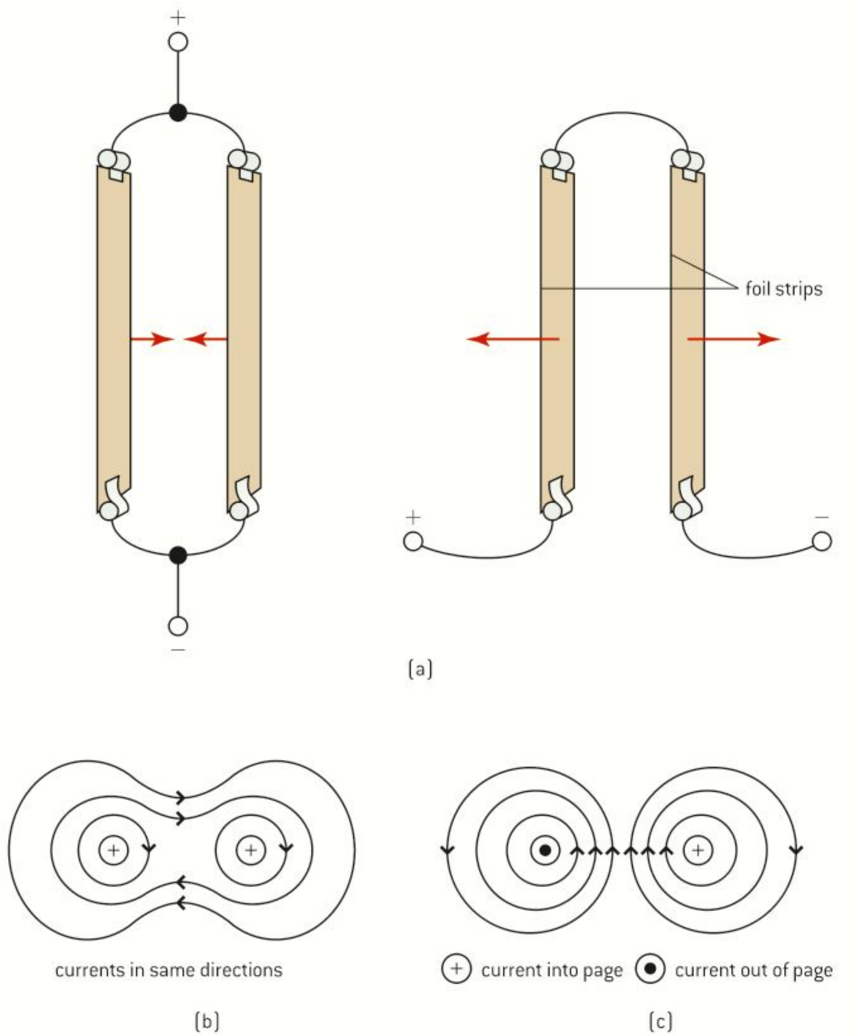
The second reason why iron, nickel, and cobalt are strong permanent magnets is that neighbouring atoms can co-operate and line up the spins of their unpaired electrons in the same direction. So, many electrons are all spinning in the same direction and giving rise to a strong magnetic field.

Deep in the centre of the Earth it is thought that a liquid-like metallic core containing free electrons is rotating relative to the rest of the planet. Again, these are conditions that can lead to a magnetic field. In which direction do you predict that the electrons are moving? However, this phenomenon is not well understood and is still the subject of research interest. Why, for example, does the magnetic field of the Earth flip every few thousand years? There is much evidence for this including the magnetic "striping" in the undersea rocks of the mid-Atlantic ridge and in the anomalous magnetism found in some ancient cooking hearths of the aboriginal peoples of Australia.

Forces on moving charges

Force between two current-carrying wires

We have used field ideas to begin our study of magnetic effects, but these conceal from us the underlying physics of magnetism. To begin this study we look at the interactions that arise between conductors when they are carrying electric current.



▲ Figure 7

Figure 7(a) shows two foil strips hanging vertically. The current directions in the foils can be the same or opposite directions. When the currents are in the same direction, the strips move together due to the force on one foil strip as it sits in the magnetic field of the other strip. When the currents are in opposing directions, the strips are seen to move apart.

You can set this experiment up for yourself by using two pieces of aluminium foil about 3 cm wide and about 70 cm long for each conductor. The power supply should be capable of providing up to 25 A so take care! Connections are made to the foils using crocodile (alligator) clips.

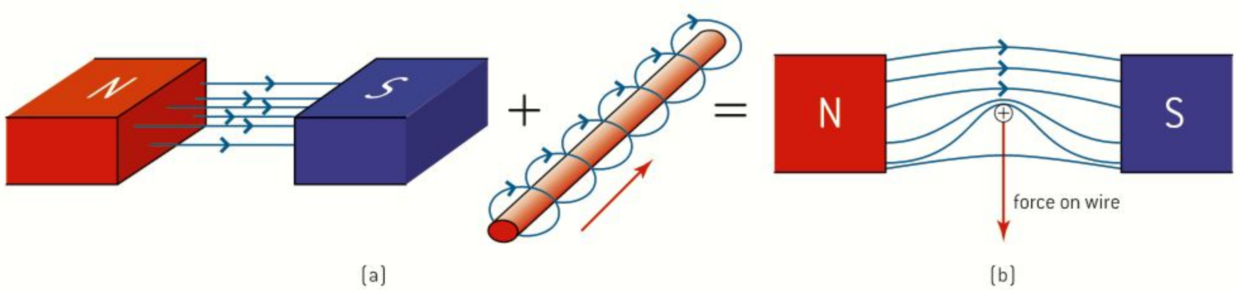
The forces on the foil can be explained in terms of the interactions between the fields as shown in the figure 7(b). When the currents are in the same direction, the field lines from the foils combine to give a pattern in which field lines loop around both foils. The notation used to show the direction of conventional current in the foil is explained on the diagram. Look back at figure 1(d) which shows the field pattern for two bar magnets with the opposite poles close. You know that the bar magnets are attracted to each other in this situation. The field pattern for the foils is similar and also leads to attraction. Think of the field lines as trying to be as short as possible. They become shorter if the foils are able to move closer together.

When the currents are in opposite directions, the field pattern changes (figure 7(c)). Now the field lines between the foils are close together and in the same direction thus representing a strong field. It seems reasonable that a strong magnetic field (like a strong electrostatic field) represents a large amount of stored energy. This energy can be reduced if the foils move apart allowing the field lines to separate too. Again, this has similarities to the bar magnet case but this time with like poles close together.

Force between a bar magnet field and a current-carrying wire

One extremely important case is the interaction between a uniform magnetic field and that produced by a current in a wire.

Again we can start with the field between two bar magnets with unlike poles close. In the centre of the region between the magnets, the field is uniform because the field lines are parallel and equally spaced.



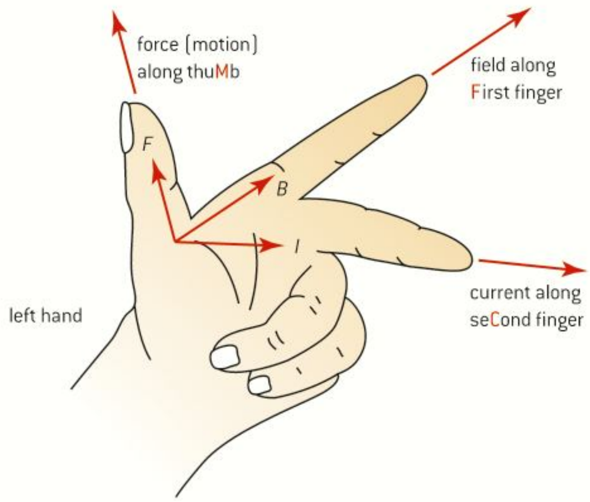
▲ Figure 8 The catapult field.

Suppose a wire carrying a current sits in this field. Figure 8(a) shows the arrangement and the directions of the uniform magnetic field and the field due to the current. A force acts downwards on the wire.

The effect can again be explained in terms of the interaction between the two magnetic fields. The circular field due to the wire adds to the uniform field due to the magnets to produce a more complicated field. This is shown in figure 8(b). Overall, the field is weaker below the wire than above it. Using our ideas of the field lines, it is clear that the system (the wire and the uniform field) can overcome this difference in field strength, either by attempting to move the wire downwards or by moving the magnets that cause the uniform field upwards. This effect is sometimes called the **catapult field** because the field lines above the wire resemble the stretched elastic cord of a catapult just before the object in the catapult is fired.

This effect is of great importance to us. It is the basis for the conversion of electrical energy into kinetic energy. It is used in electric motors, loudspeakers, and other devices where we need to produce movement from an electrical power source. It is called the **motor effect**.

It is possible to predict the direction of motion of the wire by drawing the field lines on each occasion when required but this is tedious. There are a number of direction rules that are used to remember the direction of the force easily. One of the best known of these is due to the English physicist Fleming and is known as **Fleming's left-hand rule**.



▲ Figure 9 Fleming's left-hand rule.

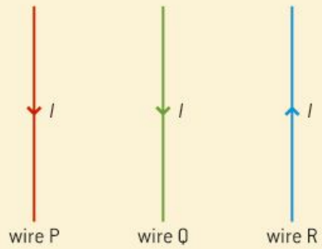
To use the rule, extend your left hand as shown in figure 9. Your first (index) finger points in the direction of the uniform magnetic field and your second finger points in the direction of the conventional current in the wire, then your thumb gives the direction of the force acting on the wire.

The motor effect

The explanation for the motor effect has been given so far in terms of field lines. This is, of course, not the complete story. We should be looking for explanations that involve interactions between individual charges, both those that produce the uniform magnetic field and those that arise from the current in the wire. Electrostatic effects (as their name implies) arise between charges that are not moving. Magnetic effects arise because the sets of charges that produce the fields are moving relative to each other and are said to be in different frames of reference. There have been no electrostatic effects because we have dealt with conductors in which there is an exact balance of positive and negative charges. Magnetism can be thought of as the residual effect that arises when charges are moving with respect to each other.

Worked example

Wires P and R are equidistant from wire Q.



Each wire carries a current of the same magnitude and the currents are in the directions shown.

Describe the direction of the force acting on wire Q due to wires P and R.

Solution

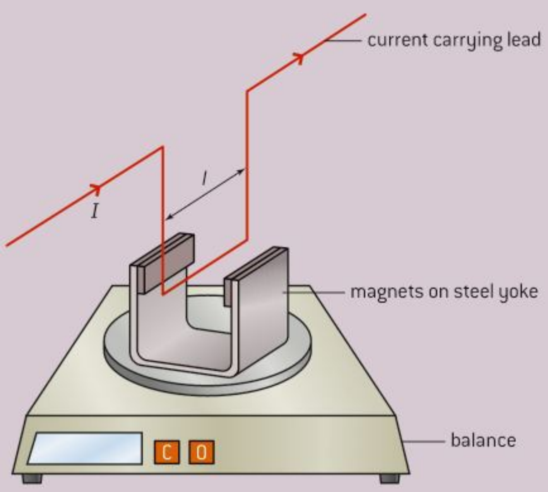
Using the right-hand corkscrew rule, the field due to wire P at wire Q is out of the plane of the paper, and the field due to wire R at wire Q is also out of the plane of the paper.

Using Fleming's left-hand rule, the force on wire Q is in the plane of the paper and to the left.

The magnitude of the magnetic force

Investigate!

Force on a current-carrying conductor



▲ Figure 10

- This is an experiment that will give you an idea of the size of the magnetic force that acts on typical laboratory currents. If carried out carefully it will also allow you to see how the force varies with the length of the conductor and the size of the current.
- You will need some pairs of flat magnets (known as "magnadur" magnets, a sensitive top-pan balance, a power supply and a suitable long straight lead to carry the current.
- Arrange the apparatus as shown in the diagram.
- Zero the balance so that the weight of the magnets is removed from the balance reading.
- The experiment is in two parts:
  - First, vary the current in the wire and collect data for the force acting on the magnets, and therefore the balance, as a result. A trick to improve precision is to reverse the current in the wire and take balance readings for both directions. Then add the two together (ignoring the negative sign of one reading) to give double the answer. Draw a graph to display your data.
  - Second, use two pairs of magnets side-by-side to double the length of the field. Take care that the poles match, otherwise the forces will cancel out. This is not likely to work so well as you need to assume that the magnet pairs have the same strength. This will probably not be true. But, roughly speaking, does doubling the length of wire in the field double the force?

The result of experiments like the one above is that the force acting on the wire due to the field is proportional to:

- the length (l) of the wire
- the current (I) in the wire.

This leads us to a definition of magnetic field strength rather different from that of electric field strength and gravitational field strength.

We cannot define the magnetic field strength in terms of

$$\frac{\text{force}}{\text{a single quantity}}$$

because the force depends on two quantities: current and length.

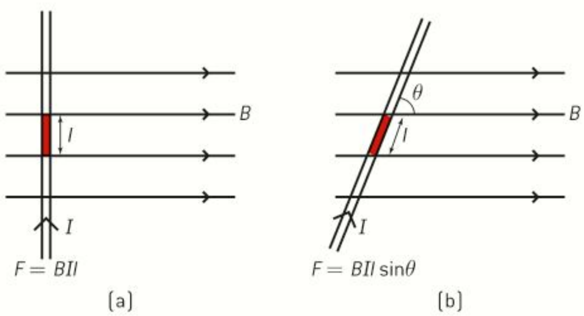
Instead we define

magnetic field strength

$$= \frac{\text{force acting on a current element}}{\text{current in the element} \times \text{length of the element}}$$

By "element" we mean a short section of a wire that carries a current. If a force F acts on the element of length l when the current in it is I, then the magnetic field strength B is defined by

$$B = \frac{F}{Il}$$



▲ Figure 11

The unit of magnetic field strength is the **tesla**, abbreviated T and the tesla is equivalent to the fundamental units kg s^{-2} A^{-1}. When a 1 metre long current element is in a magnetic field and has a current of 1 A in it, if a magnetic force of 1 N acts on it, then the magnetic field strength is defined to be 1 T. The tesla can also be thought of as a shortened form of N A^{-1} m^{-1}. The tesla turns out to be a very large unit indeed. The largest magnetic field strengths created in a laboratory are a few kT and the magnetic field of the Earth is roughly 10^{-4} T. The very largest fields are associated with some neutron stars. The field strength can be order of 100 GT in such stars.

Having defined B we can go on to rearrange the equation to give the force that acts on a wire:

$$F = BIl$$

This applies when the field lines, the current and the wire are all at 90° to each other as they are when you use the Fleming left-hand rule. If this is not the case (see figure 11(b)) and the wire is at an angle θ to the lines then we need to take the appropriate component of I or l that is at 90° to the field.

In terms of the way the angle is defined in figure 11(b), the equation becomes

$$F = BIl \sin\theta$$

This equation is written in terms of the current in the wire. Of course, the current is, as usual, the result of moving charge carriers. The equation can be changed to reflect this.

From Sub-topic 5.1 we know that the current I is given by

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

where Q is the charge that flows through the current element taking a time t to do it.

Substituting

$$F = B\left(\frac{Q}{t}\right) l \sin\theta$$

$$= BQ\left(\frac{l}{t}\right) \sin\theta$$

The term $\left(\frac{l}{t}\right)$ is the **drift speed *v*** of the charge carriers and making this substitution gives the expression

$$F = BQv \sin\theta$$

for the force acting on a charge Q moving at speed v at an angle θ to a magnetic field of strength B.

Notice the way that the angle θ is defined in the diagrams. It is the angle between the direction in which the charge is moving (or the current direction – the same thing) and the field lines. Don't get this wrong and use cosine instead of sine in your calculations.

TOK

Why direction rules?

During this sub-topic we have introduced two direction rules: the corkscrew rule for magnetic fields around wires and Fleming's rule for the motor effect. What is the status of these rules? Are they implicit in the way the universe operates, or are they simply indications that depend on the way we define current direction and other fundamental quantities in physics? To begin to answer this, consider what would have happened if Franklin had known that charge carriers in metals were electrons with a negative charge. What would this have changed (if anything)?

Nature of science

The definition of the ampere

In Topic 1 you learnt that the ampere was defined in terms of the force between two current-carrying wires. You may have thought this odd both then and when the relationship between current and charge was developed earlier in this topic. Perhaps it is clearer now.

A precise measurement of charge is quite difficult. At one time it could only be achieved through chemical measurements of electrolysis – and the levels of precision were not great enough to give a good value at that time.

It is much easier to set up an experiment that measures the force between two wires. The experiment can be done to a high precision using a device called a **current balance** (as in the force *Investigate!* above) in which the magnetic force can be measured in terms of the gravitational force needed to cancel it out. This is rather like old-fashioned kitchen scales where the quantity being measured is judged against a standard mass acted on by gravity.

Worked example

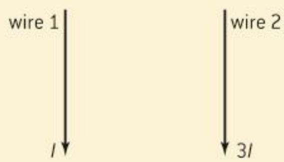
1 When a charged particle of mass m, charge q moves at speed v in a uniform magnetic field then a magnetic force F acts on it. Deduce the force acting on a particle mass m of charge $2q$ and speed $2v$ travelling in the same direction in the same magnetic field.

Solution

The equation for the force is $F = BQv \sin \theta$

In the equation, $\sin \theta$ and B do not change but every other quantity does, so the force is $4F$.

2 Electric currents of magnitude I and $3I$ are in wires 1 and 2 as shown.



A force F acts on wire 2 due to the current in wire 1. Deduce the magnitude of the force on wire 1 due to the current in wire 2.

Solution

This problem can be solved by reference to Newton's laws of motion, but an alternative is to consider the changes in magnetic field. If the magnetic field at wire 2 due to wire 1 is B then the magnetic field at wire 1 due to wire 2 is $3B$. However, the current in wire 1 is one-third of that in wire 2.

So force at wire 1 due to wire 2 is

$F = 3B \times \frac{I}{3} \times l =$ force in wire 2 due to wire 1.

The forces are the same.

Nature of science

Vectors and their products

You may have formed the view that vectors are just used for scale diagrams in physics. This is not the case, vectors come into their own in mathematical descriptions of magnetic force.

There is only one way to multiply scalars together: run a relay with four stages each of distance 100 m and the total distance travelled by the athletes is 400 m. Multiplying two scalars only gives another scalar.

Vectors, because of the added direction, can be multiplied together in two ways:

- to form a scalar product (sometimes called "dot" product) where, for example, force and displacement are multiplied together to give work done (a scalar) that has no direction. In vector notation this is written as $\boldsymbol{F} \cdot \boldsymbol{s} = W$. The multiplication sign is the dot (hence the name) the vectors are written with a bold font, the scalar in ordinary font.
- to form a vector product (sometimes called "cross" product) where two vectors are multiplied together to give a third vector, thus $\boldsymbol{a} \times \boldsymbol{b} = \boldsymbol{c}$

  The multiplication of qv and B to form the vector force F is a vector product. The charge q is a scalar but everything else in the equation is a vector. A mathematician would write

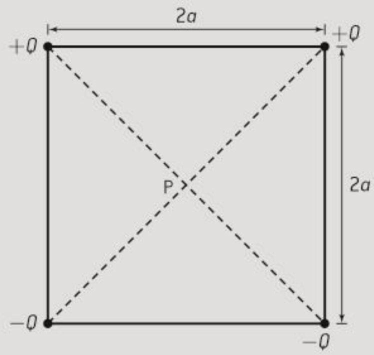
  $$\boldsymbol{F} = q\ (\boldsymbol{v} \times \boldsymbol{B})$$

  to show that the vector velocity and the vector magnetic field strength are multiplied together. The order of $\boldsymbol{v}$ and $\boldsymbol{B}$ is important. There is a vector rule for the direction of $\boldsymbol{F}$ that is consistent with our observations earlier and the $\sin \theta$ appears when the vector multiplication is worked out in terms of the separate components of the vector.

Vector notation turns out to be an essential language of physics, because it allows a concise notation and because it contains all the direction information within the equations rather than forcing us to use direction rules. However we do not pursue the full theory of vectors in IB Physics.

Questions

1 (*IB*) Four point charges of equal magnitude, are held at the corners of a square as shown below.



The length of each side of the square is $2a$ and the sign of the charges is as shown. The point P is at the centre of the square.

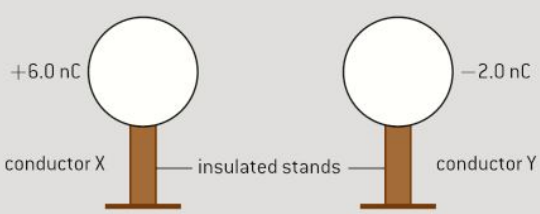
a) (i) Determine the magnitude of the electric field strength at point P due to one of the point charges.

(ii) On a copy of the diagram above, draw an arrow to represent the direction of the resultant electric field at point P.

(iii) Determine, in terms of Q, a and k, the magnitude of the electric field strength at point P. (7 marks)

2 (*IB*) Two point charges of magnitude $+2Q$ and $-Q$ are fixed at the positions shown below. Discuss the direction of the electric field due to the two charges between A and B. Suggest at which point the electric field is most likely to be zero. (3 marks)

3 (*IB*) Two identical spherical conductors X and Y are mounted on insulated stands. X carries a charge of +6.0 nC and Y carries a charge of –2.0 nC.

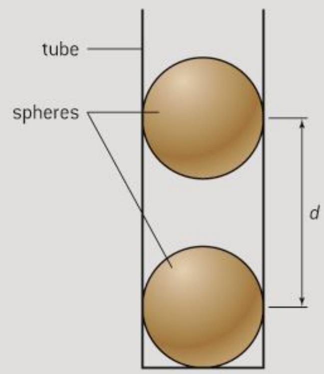


The electric force between them is $+F$ (i.e. attractive). The spheres are touched together and are then returned to their original separation.

a) Calculate the charge on X and the charge on Y.

b) Calculate the value of the electric force between them after being returned to their original separation. (7 marks)

4 (*IB*) Two charged plastic spheres are separated by a distance d in a vertical insulating tube, as shown.



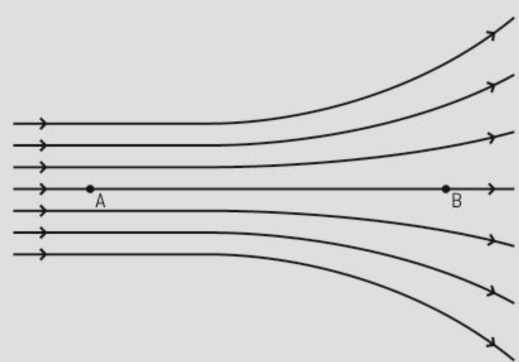
The charge on each sphere is doubled. Friction with the walls of the tube is negligible.

Deduce the new separation of the spheres.

(5 marks)

5 (*IB*)

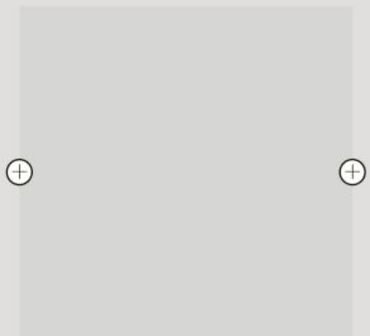
a) Electric fields may be represented by lines of force. The diagram below shows some lines of force.



(i) State whether the field strength at A and at B is constant, increasing or decreasing, when measured in the direction from A towards B.

(ii) Explain why field lines can never touch or cross.

b) The diagram below shows two insulated metal spheres. Each sphere has the same positive charge.



Copy the diagram and in the shaded area between the spheres, draw the electric field pattern due to the two spheres. (8 marks)

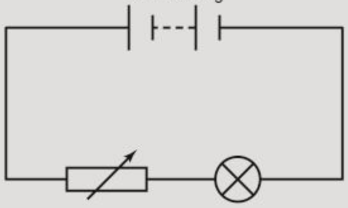
6 (*IB*) A lamp is at normal brightness when there is a potential difference of 12 V across its filament and a current in the filament of 0.50 A.

a) For the lamp at normal brightness, calculate:

(i) the power dissipated in the filament

(ii) the resistance of the filament.

b) In order to measure the voltage–current (*V–I*) characteristics of the lamp, a student sets up the following electrical circuit.



State the correct positions of an ideal ammeter and an ideal voltmeter for the characteristics of the lamp to be measured.

c) The voltmeter and the ammeter are connected correctly in the previous circuit. Explain why the potential difference across the lamp

(i) cannot be increased to 12 V

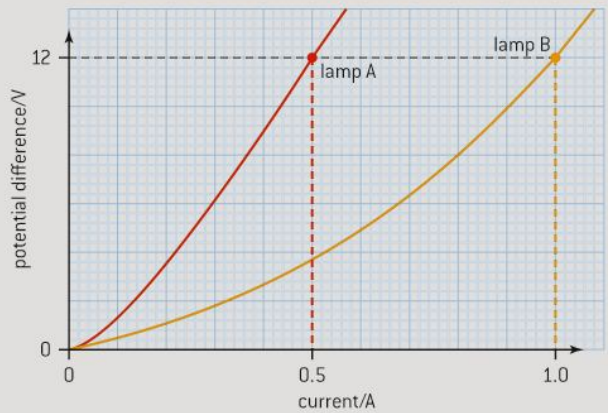
(ii) cannot be reduced to zero.

d) An alternative circuit for measuring the *V–I* characteristic uses a *potential divider*.

(i) Draw a circuit that uses a potential divider to enable the *V–I* characteristics of the filament to be found.

(ii) Explain why this circuit enables the potential difference across the lamp to be reduced to 0 V. (13 marks)

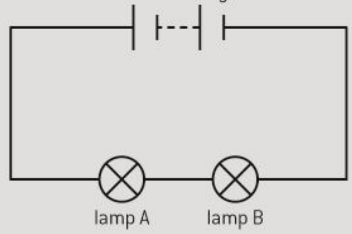
7 (*IB*) The graph below shows the *V–I* characteristic for two 12 V filament lamps A and B.



a) (i) Explain why the graphs indicate that these lamps do not obey Ohm's law.

(ii) State and explain which lamp has the greater power dissipation for a potential difference of 12 V.

The two lamps are now connected in series with a 12 V battery as shown below.



b) (i) State how the current in lamp A compares with that in lamp B.

(ii) Use the *V–I* characteristics of the lamps to deduce the total current from the battery.

(iii) Compare the power dissipated by the two lamps. (11 marks)

8 (*IB*)

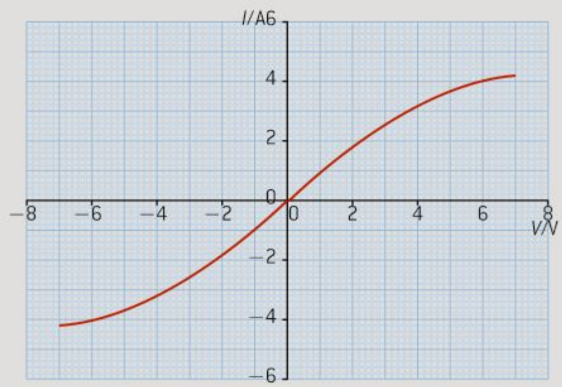
a) Explain how the resistance of the filament in a filament lamp can be determined from the *V–I* characteristic of the lamp.

b) A filament lamp operates at maximum brightness when connected to a 6.0 V supply. At maximum brightness, the current in the filament is 120 mA.

(i) Calculate the resistance of the filament when it is operating at maximum brightness.

(ii) You have available a 24 V supply and a collection of resistors of a suitable power rating and with different values of resistance. Calculate the resistance of the resistor that is required to be connected in series with the supply such that the voltage across the filament lamp will be 6.0 V. (4 marks)

9 (*IB*) The graph below shows the *I–V* characteristics for component X.



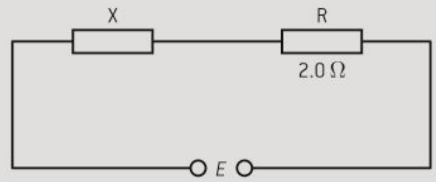
The component X is now connected across the terminals of a battery of emf 6.0 *V* and negligible internal resistance.

a) Use the graph to determine:

(i) the current in component X

(ii) the resistance of component X.

b) A resistor R of constant resistance 2.0 Ω is now connected in series with component X as shown below.



(i) Copy the graph in (a), and draw the *I–V* characteristics for the resistor R.

(ii) Determine the total potential difference *E* that must be applied across component X and across resistor R such that the current through X and R is 3.0 A. (7 marks)

10 (*IB*) A student is to measure the current–voltage (*I–V*) characteristics of a filament lamp. The following equipment and information are available.

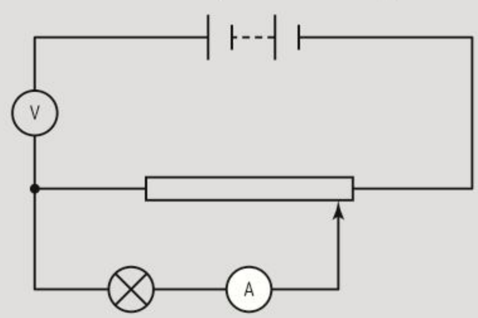
	Information
Battery	emf = 3.0 V, negligible internal resistance
Filament lamp	marked "3 V, 0.2 A"
Voltmeter	resistance = 30 kΩ, reads values between 0.0 and 3.0 V
Ammeter	resistance = 0.1 Ω, reads values between 0.0 and 0.5 A
Potentiometer	resistance = 100 Ω

a) For the filament lamp operating at normal brightness, calculate:

(i) its resistance

(ii) its power dissipation.

The student sets up the following *incorrect* circuit.



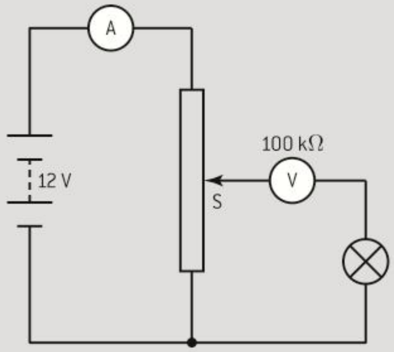
b) (i) Explain why the lamp will not light.

(ii) State the approximate reading on the voltmeter. Explain your answer.

(6 marks)

11 (*IB*) A particular filament lamp is rated at 12 V, 6.0 mA. It just lights when the potential difference across the filament is 6.0 V.

A student sets up an electric circuit to measure the *I*–*V* characteristics of the filament lamp.



In the circuit, shown below, the student has connected the voltmeter and the ammeter into the circuit *incorrectly*.

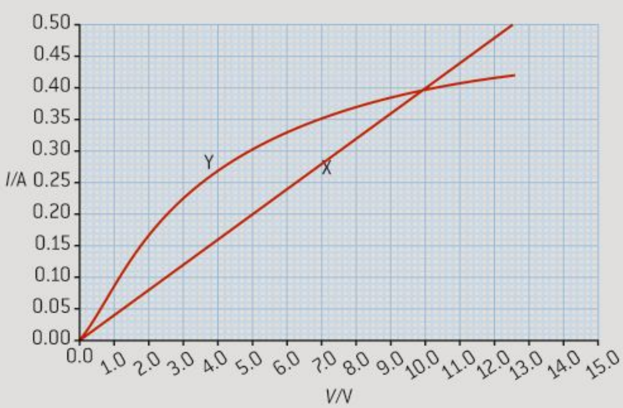
The battery has emf 12 V and negligible internal resistance. The ammeter has negligible resistance and the resistance of the voltmeter is 100 kΩ.

The maximum resistance of the variable resistor is 15 Ω.

a) Explain, without doing any calculations, whether there is a position of the slider S at which the lamp will be lit.

b) Estimate the maximum reading of the ammeter. (5 marks)

12 (*IB*) The graph below shows the current–voltage (*I*–*V*) characteristics of two different conductors X and Y.



a) (i) State the value of the current for which the resistance of X is the same as the resistance of Y and determine the value of this resistance.

(ii) Describe and suggest an explanation for the *I*–*V* characteristic of conductor Y.

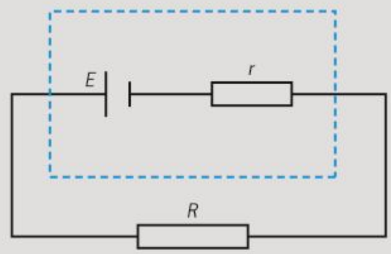
b) The two conductors X and Y are connected in series with a cell of negligible internal resistance. The current in the conductors is 0.20 A.

Use the graph to determine:

(i) the resistance of Y for this value of current

(ii) the emf of the cell. (8 marks)

13 (*IB*) A cell of electromotive force (emf) *E* and internal resistance *r* is connected in series with a resistor *R*, as shown below.



The cell supplies 8.1×10^3 J of energy when 5.8×10^3 C of charge moves completely round the circuit. The current in the circuit is constant.

a) Calculate the emf *E* of the cell.

b) The resistor *R* has resistance 6.0 Ω. The potential difference between its terminals is 1.2 V. Determine the internal resistance *r* of the cell.

c) Calculate the total energy transfer in *R*.

d) Describe, in terms of a simple model of electrical conduction, the mechanism by which the energy transfer in *R* takes place. (12 marks)

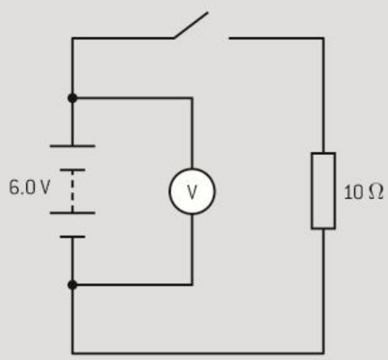
14 (*IB*) A battery is connected in series with a resistor R. The battery transfers 2000 C of charge completely round the circuit. During this process, 2500 J of energy is dissipated R and 1500 J is expended in the battery. Calculate the emf of the battery. (3 marks)

15 (*IB*) A student connects a cell in series with a variable resistor and measures the terminal pd V of the cell for a series of currents I in the circuit. The data are shown in the table.

V/V	I/mA
1.50	120
1.10	280
0.85	380
0.75	420
0.60	480
0.50	520

Use the data to determine the emf and internal resistance of the cell. (5 marks)

16 (*IB*) A battery is connected to a resistor as shown.



When the switch is open the voltmeter reads 12 V, when the switch is closed it reads 11.6 V.

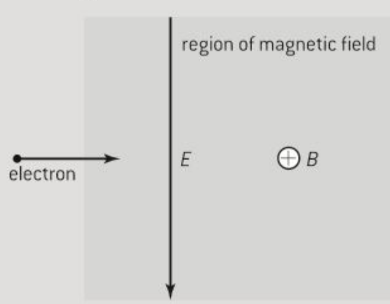
a) Explain why the readings differ.

b) (i) State the emf of the battery.

(ii) Calculate the internal resistance of the battery.

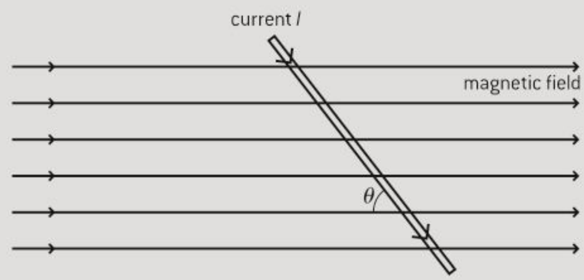
c) Calculate the power dissipated in the battery. (6 marks)

17 (*IB*) An electron enters a pair of electric and magnetic fields in a vacuum as shown in the diagram.



The electric field strength is 3.8×10^5 V m^{-1} and the magnetic field strength is 2.5×10^{-2} T. Calculate the speed of the electron if the net force acting on it due to the fields is zero. (3 marks)

18 (*IB*) A straight wire lies in a uniform magnetic field as shown.



The current in the wire is I and the wire is at an angle of θ to the magnetic field. The force per unit length on the conductor is F. Determine the magnetic field strength. (2 marks)

19 (*IB*) A straight wire of length 0.75 m carries a current of 35 A. The wire is at right angles to a magnetic field of strength 0.058 T. Calculate the force on the wire. (2 marks)

20 (*IB*) An ion with a charge of $+3.2 \times 10^{-19}$ C and a mass of 2.7×10^{-26} kg is moving due south at a speed of 4.8×10^3 m s^{-1}. It enters a uniform magnetic field of strength 4.6×10^{-4} T directed downwards towards the ground. Determine the force acting on the ion. (4 marks)