b The magnitude of the decrease in kinetic energy of the proton is:

$$\Delta E_K = \tfrac{1}{2} \times 1.67 \times 10^{-27}\ [(4.4 \times 10^5)^2 - (2.2 \times 10^5)^2]$$

$$\Delta E_K = 1.2 \times 10^{-16}\,\mathrm{J}$$

Converting to electronvolts:

$$\Delta E_K = \frac{1.2 \times 10^{-16}\,\mathrm{J}}{1.6 \times 10^{-19}\,\mathrm{J\,eV^{-1}}}$$

$$= 750\,\mathrm{eV}$$

Hence $qV = 750\,\mathrm{eV}$, implying $V = 750$ volts.

T5-Electrici
& Magnétisme

Nature of science

The microscopic–macroscopic connection

If you are plumber, do you need to know the molecular structure of water? The flow of water in pipes is a macroscopic phenomenon whereas the detailed molecular structure of water is microscopic. We have a vast difference in scales of length in the two cases. In very many phenomena the presence of two different scales means that the detailed physics operating at one scale does not affect the physics at the other. This is also the case with current: it was possible to give detailed descriptions of the behaviour of current in circuits long before it was discovered that current is electrons moving in the same direction. (However, the most complicated problems in physics are those in which the physics at one length scale does affect the physics at the other scale.)

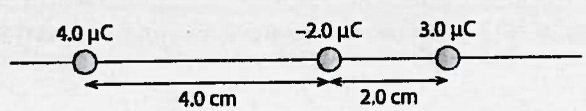
? Test yourself

1 a Calculate the force between two charges q_1 of $2.0\,\mu\mathrm{C}$ and q_2 $4.0\,\mu\mathrm{C}$ separated by $r = 5.0\,\mathrm{cm}$.

b Let the force calculated in **a** be F. In terms of F and without further calculations, state the force between these charges when:

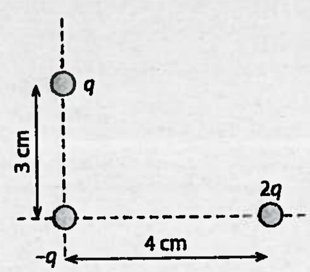
- **i** the separation r of the charges is doubled
- **ii** q_1 and r are both doubled
- **iii** q_1, q_2 and r are all doubled.

2 Three charges are placed on a straight line as shown in the diagram. Calculate the net force on the middle charge.



3 In the previous question, determine the position of the middle charge so that it is in equilibrium.

4 Calculate the force (magnitude and direction) on the charge q in the diagram where $q = 3.0\,\mu\mathrm{C}$.



5 Two plastic spheres each of mass 100.0 mg are suspended from very fine insulating strings of length 85.0 cm. When equal charges are placed on the spheres, the spheres repel and are in equilibrium when 10.0 cm apart.

a Determine the charge on each sphere.

b Estimate how many electron charges this corresponds to.

6 Consider two people, each of mass 60 kg, a distance of 10 m apart.

a Assuming that all the mass in each person is made out of water, estimate how many electrons there are in each person.

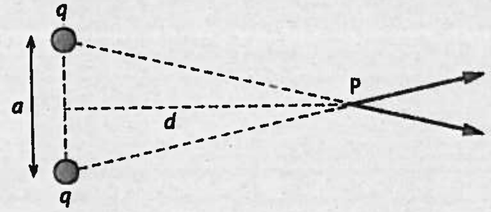
b Hence, estimate the electrostatic force of repulsion between the two people due to the electrons.

c List any other simplifying assumptions you have made to make your estimate possible.

d No such force is observed in practice. Suggest why this is so.

7 A charge of magnitude $+5.0\,\mu C$ experiences an electric force of magnitude 3.0×10^{-5} N when placed at a point in space. Determine the electric field at that point.

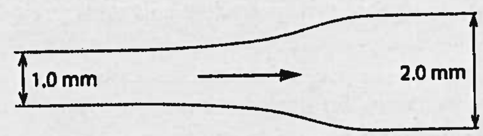
8 The electric field is a vector and so two electric fields at the same point in space must be added according to the laws of vector addition. Consider two equal positive charges q, each $2.00\,\mu C$, separated by $a = 10.0$ cm and a point P a distance of $d = 30.0$ cm, as shown in the diagram. The diagram shows the directions of the electric fields produced at P by each charge. Determine the magnitude and direction of the net electric field at P.



9 Repeat the calculation of question 8 where the top charge is $+2.00\,\mu C$ and the bottom charge is $-2.00\,\mu C$.

10 The electron drift speed in a copper wire of diameter 1.8 mm is $3.6 \times 10^{-4}\,m\,s^{-1}$. The number of free electrons per unit volume for copper is $8.5 \times 10^{28}\,m^{-3}$. Estimate the current in the wire.

11 In the diagram, the current through the 1.0 mm diameter part of the wire is 1.2 A and the drift speed is $2.2 \times 10^{-4}\,m\,s^{-1}$.



Calculate **a** the current and **b** the drift speed in the part of the wire with 2.0 mm diameter.

12 Silver has 5.8×10^{28} free electrons per m^3. If the current in a 2 mm radius silver wire is 5.0 A, find the velocity with which the electrons drift in the wire.

13 a If a current of 10.0 A flows through a heater, how much charge passes through the heater in 1 h?

b How many electrons does this charge correspond to?

14 A conducting sphere of radius 15.0 cm has a positive charge of $4.0\,\mu C$ deposited on its surface. Calculate the magnitude of the electric field produced by the charge at distances from the centre of the sphere of:

a 0.0 cm

b 5.0 cm

c 15.0 cm

d 20.0 cm.

Nature of science

In 1825 in England Peter Barlow proposed a law explaining how wires conducted electricity. His careful experiments using a constant voltage showed good agreement, and his theory was accepted. At about the same time in Germany, Georg Ohm proposed a different law backed up by experimental evidence using a range of voltages. The experimental approach to science was not popular in Germany, and Ohm's findings were rejected. It was not until 1841 that the value of his work was recognised, first in England and later in Germany. In modern science, before research findings are published they are reviewed by other scientists working in the same area (peer review). This would have shown the errors in Barlow's work and given Ohm recognition sooner.

Test yourself

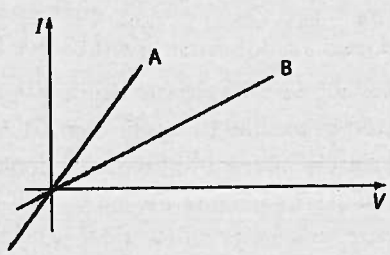
15 Outline the mechanism by which electric current heats up the material through which it flows.

16 Explain why doubling the length of a wire, at constant temperature, will double its resistance.

17 The graphs show the current as a function of voltage across the same piece of metal wire which is kept at two different temperatures.

a Discuss whether the wire obey Ohm's law.

b Suggest which of the two lines on the graph corresponds to the higher temperature.



18 The current in a device obeying Ohm's law is 1.5 A when connected to a source of potential difference 6.0 V. What will the potential difference across the same device be when a current of 3.5 A flows in it?

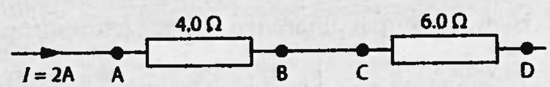
19 A resistor obeying Ohm's law is measured to have a resistance of 12 Ω when a current of 3.0 A flows in it. Determine the resistance when the current is 4.0 A.

20 The heating element of an electric kettle has a current of 15 A when connected to a source of potential difference 220 V. Calculate the resistance of the heating element.

21 The diagram shows two resistors with a current of 2.0 A flowing in the wire.

a Calculate the potential difference across each resistor.

b State the potential between points B and C.

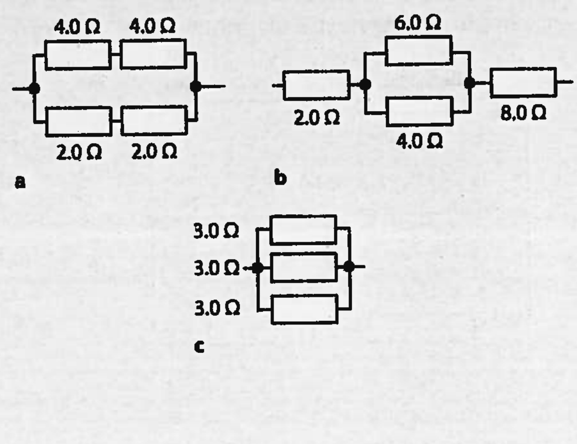


22 The filament of a lamp rated as 120 W at 220 V has resistivity $2.0 \times 10^{-6}\,\Omega\,m$.

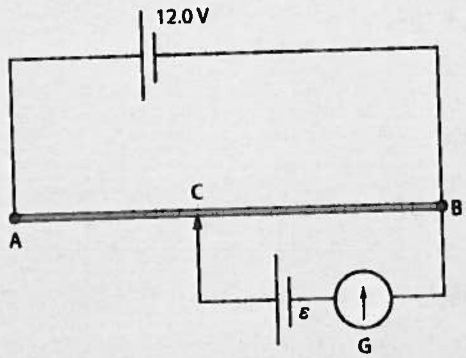
a Calculate the resistance of the lamp when it is connected to a source of 220 V.

b The radius of the filament is 0.030 mm. Determine its length.

23 Determine the total resistance for each of the circuit parts in the diagram.



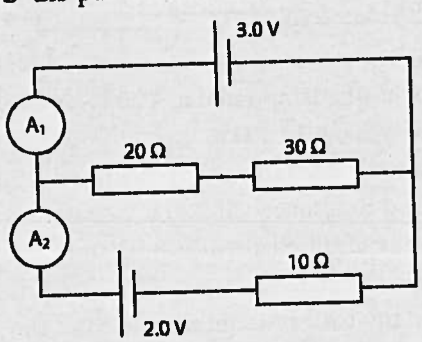
24 In the potentiometer in the diagram, wire AB is uniform and has a length of 1.00 m. When contact is made at C with BC = 54.0 cm, the galvanometer G shows zero current. Determine the emf of the second cell.



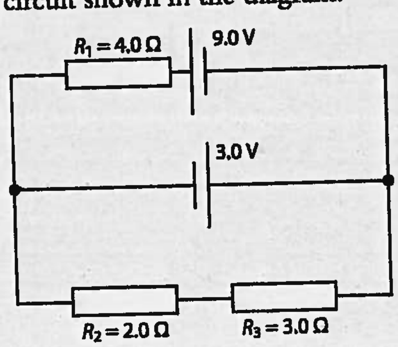
25 In the circuit shown the top cell has emf 3.0V and the lower cell has emf 2.0V. Both cells have negligible internal resistance.
Calculate:

a the readings of the two ammeters

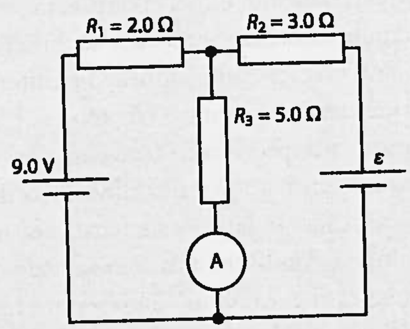
b the potential difference across each resistor.



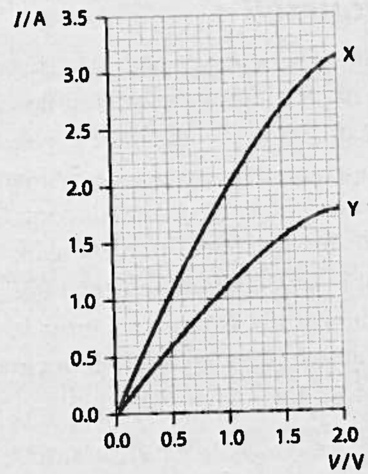
26 Calculate the current in each resistor in the circuit shown in the diagram.



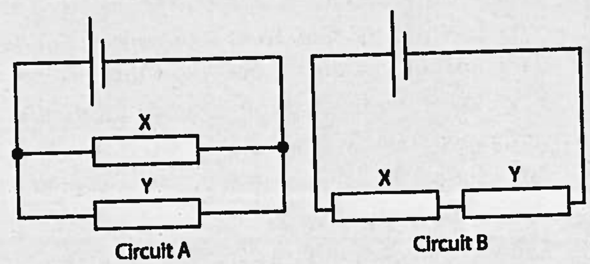
27 In the circuit in the diagram the ammeter reads 7.0 A. Determine the unknown emf ε.



28 Two resistors, X and Y, have I–V characteristics given by the graph

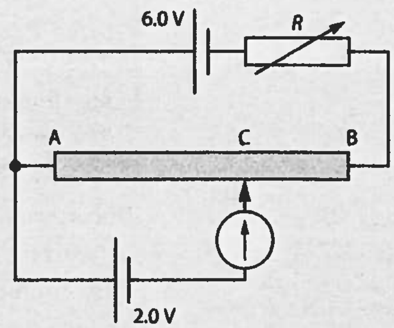


a Circuit A shows the resistors X and Y connected in parallel to a cell of emf 1.5 V and negligible internal resistance. Calculate the total current leaving the cell.



b In circuit B the resistors X and Y are connected in series to the same cell. Estimate the total current leaving the cell in this circuit.

29 The top cell in the circuit in the diagram has emf 6.0 V. The emf of the cell in the lower part of the circuit is 2.0 V. Both cells have negligible internal resistance. AB is a uniform wire of length 1.0 m and resistance 4.0 Ω.
When the variable resistor is set at 3.2 Ω the galvanometer shows zero current. Determine the length AC.



5.3 Electric cells

Batteries are now used to power watches, laptops, cars and entire submarines. Substantial advances in battery technology have resulted in batteries that store more energy, recharge faster and pose smaller environmental dangers.

Learning objectives

- Distinguish between primary and secondary cells.
- Understand the presence of an internal resistance.
- Distinguish between emf and terminal potential difference.

Emf

We have already discussed that electric charges will not drift in the same direction inside a conductor unless a potential difference is established at the ends of the conductor. In a circuit we therefore need a source of potential difference. The most common is the connection of a **battery** in the circuit. (Others include a generator, a thermocouple or a solar cell.) What these sources do is to convert various forms of energy into **electrical energy**.

To understand the function of the battery, we can compare a battery to a pump that forces water through pipes up to a certain height and down again (Figure **5.42**). The pump provides the gravitational potential energy *mgh* of the water that is raised. The water, descending, converts its gravitational potential energy into thermal energy (frictional losses) and mechanical work. Once the water reaches the pump, its gravitational potential energy has been exhausted and the pump must again perform work to raise the water so that the cycle repeats.

In an electric circuit a battery performs a role similar to the pump's. A battery connected to an outside circuit will force current in the circuit. Thus, the chemical energy of the battery is eventually converted into thermal energy (the current heats up the wires), into mechanical work (the circuit may contain a motor that may be used to raise a load) and into chemical energy again if it is used to charge another battery in the external circuit. Within the battery itself, negative ions are pushed from the negative to the positive terminal and positive ions in the opposite direction. This requires work that must be done on the ions (Figure **5.43**). This work is provided by the **chemical energy** stored in the battery and is released by chemical reactions taking place inside the battery.

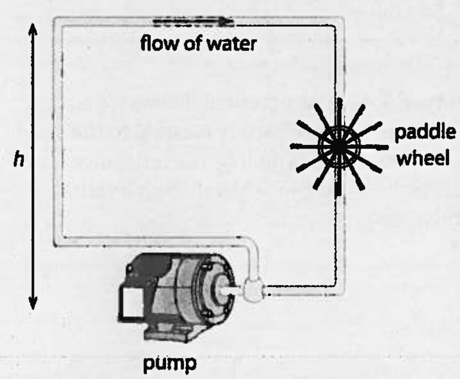


Figure 5.42 In the absence of the pump, the water flow would stop. The work done by the pump equals the work done to overcome frictional forces plus work done to operate devices, such as, for example, a paddle wheel.

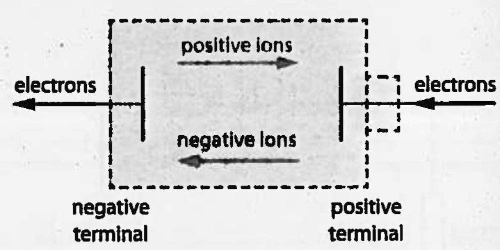


Figure 5.43 Inside the battery, negative ions move from the negative to the positive terminal of the battery. Positive ions move in the opposite direction. In the external circuit, electrons leave the negative battery terminal, travel through the circuit and return to the battery at the positive terminal.

Let us now calculate the power generated by the 12 V battery:

$$P = \varepsilon I = 12 \times 0.625 = 7.5\text{ W}$$

The total resistance of the circuit is 16 Ω and so the total power dissipated in the resistors is $16 \times 0.625^2 = 6.25$ W. The remaining 1.25 W is stored in the 2.0V battery that is being charged. This is the same as the power 'dissipated' by the battery: $2.0 \times (-0.625) = -1.25$ W. We give the current a negative sign because it flows the 'wrong' way in the battery. The negative sign for the power means that this is power being stored, not being dissipated.

Discharging a cell

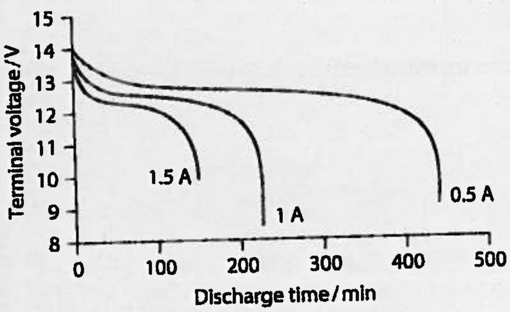


Figure 5.47 Discharge time for a cell for different currents.

A characteristic of a cell is the amount of charge it can deliver to an external circuit in its lifetime. This is known as the **capacity** of the cell. Suppose we connect a cell to an external resistor and monitor the potential difference across the cell, the terminal voltage. The general features are shown in Figure **5.47**.

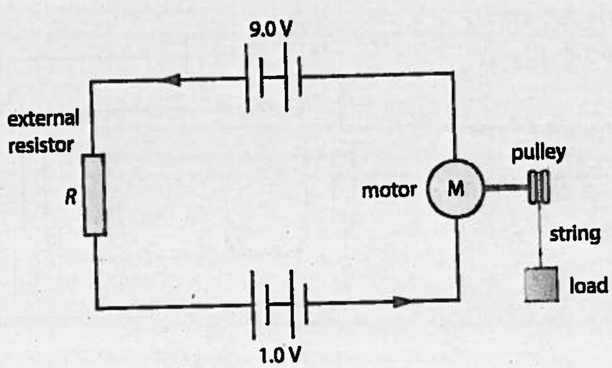
The bigger the current, the faster the cell discharges. After an initial sudden drop, the terminal voltage remains almost constant until the capacity of the cell is exhausted at the end if its lifetime, when there is again a sudden drop. The gentle drop in voltage for the majority of the cell's lifetime is explained partly by an increasing internal resistance.

Nature of science

Consumers look for longer battery life in their electronic equipment, which drives research into electric cells. Mercury and cadmium are toxic components of some cells, and other cells contain flammable or otherwise dangerous materials. Scientists working to increase the storage capacity of cells need to balance the benefits (for example electric cars, which aim to be 'greener' than cars running on gasoline) with the long-term risks associated with the disposal of the chemical components when the batteries are discarded.

? Test yourself

30 Describe the energy changes taking place in the circuit shown in the diagram.



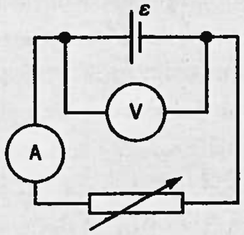
31 A battery has emf = 10.0 V and internal resistance 2.0 Ω. The battery is connected in series to a resistance R. Make a table of the power dissipated in R for various values of R and then use your table to plot the power as a function of R. For what value of R is the power dissipated maximum?

32 A battery of emf ε and internal resistance r sends a current I into a circuit.

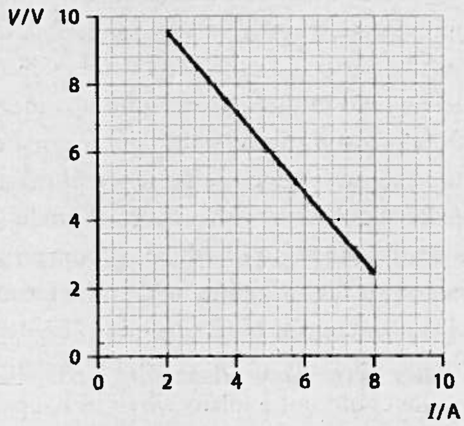
a Sketch the potential difference across the battery as a function of the current.

b What is the significance of **i** the slope and **ii** the vertical intercept of the graph?

33 In an experiment, a voltmeter was connected across the terminals of a battery as shown in the diagram.



The current in the circuit is varied using the variable resistor. The graph shows the variation with current of the reading of the voltmeter.

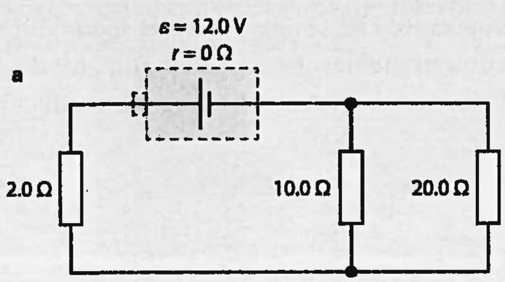


a Calculate the internal resistance of the battery.

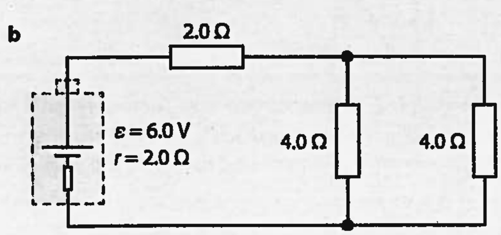
b Calculate the emf of the battery.

34 Calculate the current in, and potential difference across, each resistor in the circuits shown in the diagram.

a



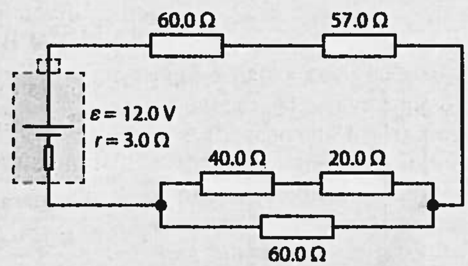
b



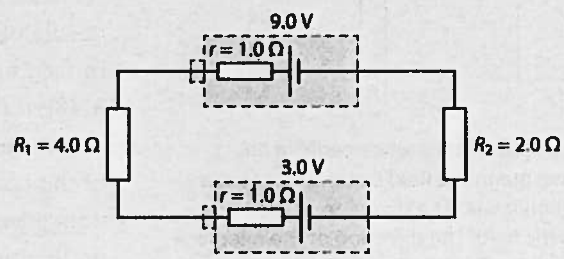
35 When two resistors, each of resistance $4.0\,\Omega$, are connected in parallel with a battery, the current leaving the battery is 3.0 A. When the same two resistors are connected in series with the battery, the total current in the circuit is 1.4 A. Calculate:

a the emf of the battery

b the internal resistance of the battery.



36 In the circuit shown in the diagram each of the cells has an internal resistance of $1.0\,\Omega$.



a Determine the current in the circuit.

b Calculate the power dissipated in each cell.

c Comment on your answer to **b**.

The ampere is defined through the magnetic force between two parallel wires. If the force on a 1 m length of two wires that are 1 m apart and carrying equal currents is 2×10^{-7} N, then the current in each wire is defined to be 1 A.

The coulomb is defined in terms of the ampere as the amount of charge that flows past a certain point in a wire when a current of 1 A flows for 1 s.

The ampere is equal to a coulomb divided by a second; but it is defined as above.

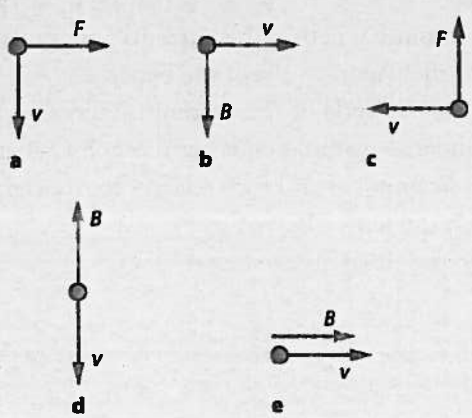
Nature of science

Introduced in the 19th century by Michael Faraday as 'lines of force', the concept of magnetic field lines allowed scientists to visualise the magnetic field around a magnet, and the magnetic field around a moving charge. A few years later, in one of the greatest unifications in physics, James Clerk Maxwell showed that all magnetic phenomena and electric phenomena are different sides of the same general phenomenon, electromagnetism, and that light is a combination of electric and magnetic fields. In the early 20th century, Albert Einstein showed that viewing electric and magnetic phenomena from different frames of reference leads naturally to the theory of relativity. At about the same time, trying to understand magnetism in different materials required the introduction of quantum theory.

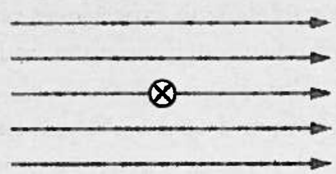
? Test yourself

37 Draw the magnetic field lines for two parallel wires carrying equal currents into the page. Repeat for anti-parallel currents.

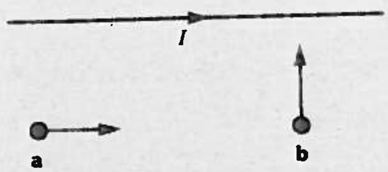
38 Determine the direction of the missing quantity from B, v and F in each of the cases shown in the diagram. The circle represents a positive charge.



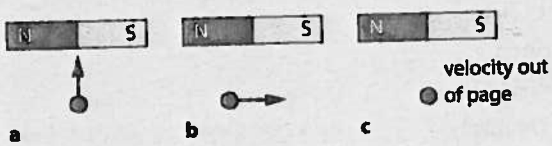
39 Draw the magnetic field lines that result when the magnetic field of a long straight wire carrying current into the page is superimposed on a uniform magnetic field pointing to the right that lies on the page.



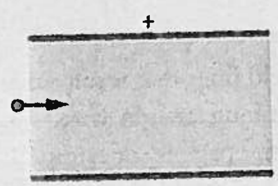
40 A long straight wire carries current as shown in the diagram. Two electrons move with velocities that are parallel and perpendicular to the current. Determine the direction of the magnetic force experienced by each electron.



41 A proton moves past a bar magnet as shown in the diagram. Find the direction of the force it experiences in each case.



42 The diagram shows two parallel plates. The electric field is directed from top to bottom and has magnitude $2.4 \times 10^3\,\mathrm{N\,C^{-1}}$. The shaded region is a region of magnetic field normal to the page.

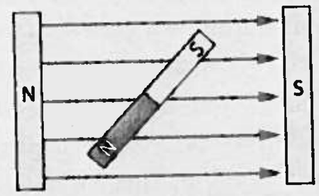


a Deduce the magnetic field magnitude and direction so that an electron experiences zero net force when shot through the plates with a speed of $2.0 \times 10^5\,\mathrm{m\,s^{-1}}$.

b Suggest whether a proton shot with the same speed through the plates experiences zero net force.

c The electron's speed is doubled. Suggest whether the electron would it still be undeflected for the same magnetic field found in **a**.

43 A bar magnet is placed in a uniform magnetic field as shown in the diagram.



a Suggest whether there is a net force on the bar magnet.

b Determine how it will move.

44 A high-tension electricity wire running along a north–south line carries a current of 3000 A. The magnetic field of the Earth at the position of the wire has a magnitude of 5.00×10^{-5} T and makes an angle of 30° below the horizontal. Calculate the force experienced by a length of 30.0 m of the wire.

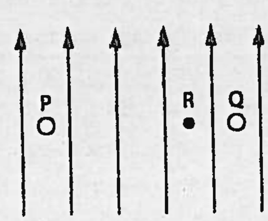
45 **a** An electron of speed v enters a region of magnetic field B directed normally to its velocity and is deflected into a circular path. Deduce an expression for the number of revolutions per second the electron will make.

b The electron is replaced by a proton. Suggest whether the answer to **a** changes.

46 A uniform magnetic field is established in the plane of the paper as shown in the diagram. Two wires carry **parallel** currents of equal magnitudes normally to the plane of the paper at P and Q. Point R is on the line joining P to Q and closer to Q. The magnetic field at position R is zero.

a Determine whether the currents are going into the paper or out of the paper.

b The magnitude of the current is increased slightly. Determine whether the point where the magnetic field is zero moves to the right or to the left of R.

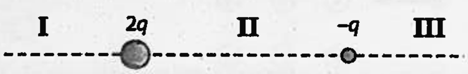


Exam-style questions

1 A small charge q is placed near a large spherical charge Q. The force experienced by both charges is F. The electric field created by Q at the position of q is:

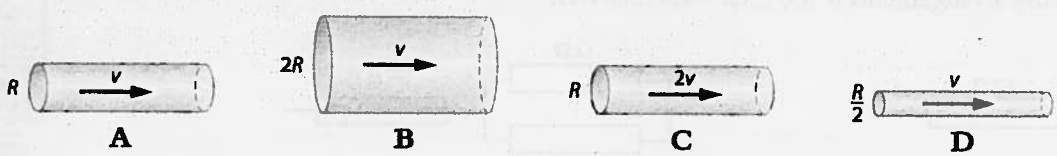
A $\frac{F}{Q}$ **B** $\frac{F}{q}$ **C** $\frac{F}{Qq}$ **D** $\frac{FQ}{q}$

2 Two charges are fixed as shown. The charges are $2q$ and $-q$. In which regions can the electric field strength due to the two particles be zero?

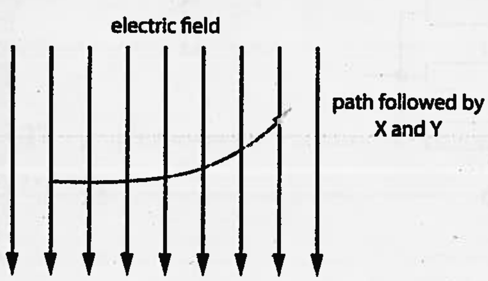


A I only **B** II only **C** III only **D** I and III

3 The diagrams show equal lengths of wires made of the same material and various cross-sectional radii. The drift speed of electrons is indicated. In which wire is the current the greatest?



4 Two charged particles X and Y are projected horizontally with the same speed from the same point in a region of uniform electric field. Gravity is not negligible.



The two particles follow identical paths. What conclusion about X and Y can one draw from this?

A They have the same mass.
B They have the same charge.
C They have the same acceleration.
D They have the same momentum.

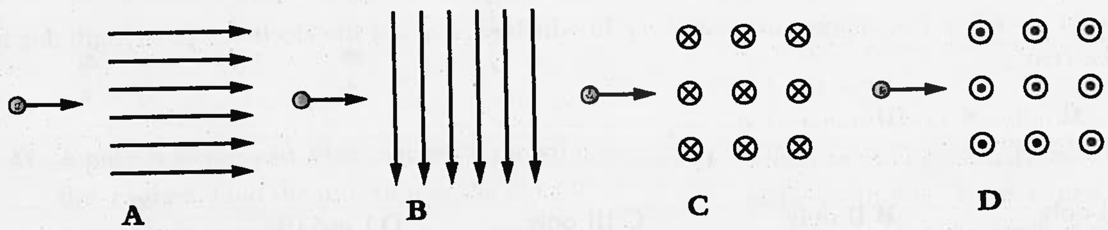
5 A charged particle moves in a circle of radius R in a region of uniform magnetic field. The magnetic field is at right angles to the velocity of the particle and exerts a force F on the particle. After half a revolution the change in the particle's kinetic energy is:

A 0 **B** πRF **C** $2\pi RF$ **D** RF

6 A negatively charged particle is at rest in a magnetic field B. The force on the particle is:

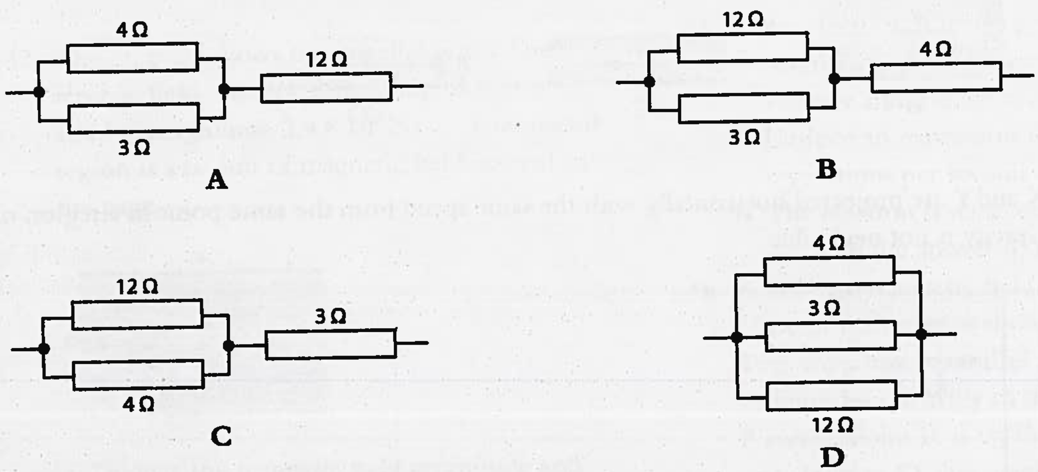
- **A** parallel to B
- **B** opposite to B
- **C** at right angles to B
- **D** zero.

7 An electron enters a region of magnetic field.

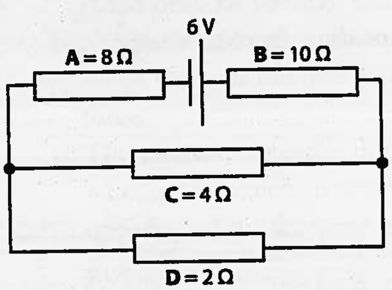


In which case is the initial force on the electron directed towards the bottom of the page?

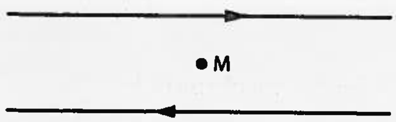
8 In which of the following arrangements is the total resistance 6 Ω?



9 In which of the resistors in the circuit below is the power dissipated the least?

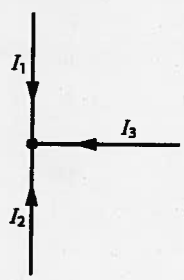


10 Two long parallel wires carry equal currents in opposite directions. What field do the two wires produce at point M, which is midway between the wires and on the plane of the paper?



A a magnetic field parallel to the wires
B an electric field parallel to the wires
C a magnetic field at right angles to the plane of the page
D an electric field at right angles to the plane of the page

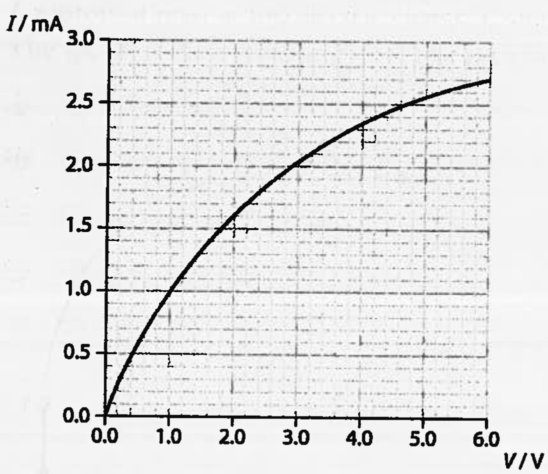
11 A student assigns currents at a junction in a circuit as shown in the diagram.



The student's calculations correctly give that $I_1 = 3$ A and $I_2 = -2$ A. The value of I_3 is:

A 1 A
B −1 A
C 5 A
D −5 A

12 The graph shows the variation with voltage V across a filament lamp with the current I though the lamp.



a Suggest whether the resistor obeys Ohm's law. [1]
b Calculate the resistance of the lamp when $V = 4.0$ V. [2]
c The resistivity of the filament of the lamp at a voltage of 4.0 V is 3.0×10^{-7} Ωm. The radius of the filament is 0.25 mm. Calculate the length of the filament. [2]

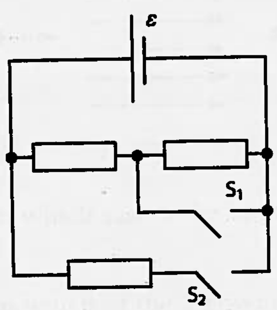
d Two lamps whose I–V characteristics are given by the graph above are connected in parallel to a battery of negligible internal resistance. The current leaving the battery is 2.0 mA. Estimate:

i the emf of the battery [1]

ii the power dissipated in each lamp. [1]

e Thermal energy is generated in a filament lamp when it is operating. Describe the mechanism by which this energy is generated. [3]

13 The three devices in the circuit shown are identical and may be assumed to have constant resistance. Each device is rated as 1500 W at 230 V. The emf of the source is 230 V and its internal resistance is negligible.



a Calculate the resistance of **one** of the devices. [2]

b Calculate the total power dissipated in the circuit when:

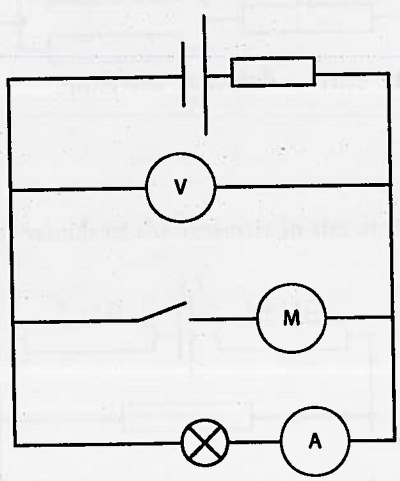
i S_1 is closed and S_2 is open [1]

ii S_1 is closed and S_2 is closed [1]

iii S_1 is open and S_2 is open [1]

iv S_1 is open and S_2 is closed. [1]

c In the circuit below the cell has internal resistance 0.0500 Ω. When the switch in series with a motor of resistance of 25.0 Ω is open, the voltmeter reads 11.5 V and the current in the ammeter is 9.80 A.



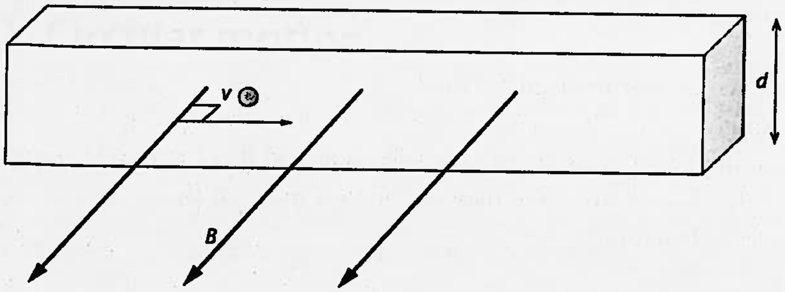
The switch is closed.

i Determine the emf of the cell. [2]

ii State and explain the effect, if any, of closing the switch on the brightness of the lamp. [2]

iii Calculate the current through the motor. [2]

4 A current I is established in the conductor. The diagram shows one of the electrons making up the current moving with drift speed v. The conductor is exposed to a magnetic field B at right angles to the direction of motion of the electron.



a On a copy of the diagram, draw an arrow to indicate the direction:

i of the conventional current in the conductor **[1]**

ii the magnetic force on the electron. **[1]**

b Show that the current in the conductor is given by $I = qnAv$, where q is the charge of the electron, A the cross-sectional area of the conductor, v the drift speed of the electrons and n is the number of free electrons per unit volume. **[3]**

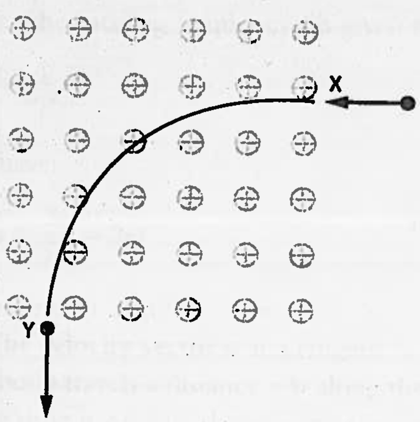
c Explain why a potential difference will be established between the top (T) and bottom (B) faces of the conductor. **[3]**

d **i** The electric field between T and B is given by $E = \frac{V}{d}$ where V is the potential difference between T and B and d is their separation. Show that the voltage between T and B (the Hall voltage) is given by $V = vBd$. **[2]**

ii The current in the conductor is 0.50 A, the number density of electrons is $3.2 \times 10^{28}\,\mathrm{m^{-3}}$, the cross-sectional area of the wire is $4.2 \times 10^{-6}\,\mathrm{m^2}$ and the magnetic field is 0.20 T. Calculate the Hall voltage in this conductor. **[3]**

e Outline how the existence of the Hall voltage can be used to verify that the charge carriers in the conductor are negatively charged. **[2]**

A proton of mass m and electric charge q enters a region of magnetic field at point X and exits at point Y. The speed of the proton at X is v. The path followed by the proton is a quarter of a circle.



a State and explain whether the speed of the proton at Y is the same as the speed at X. [2]

b Suggest why the path of the proton is circular. [2]

c **i** Show that the radius of the circular path is given by $R = \frac{mv}{qB}$, where B is the magnetic flux density. [2]

ii The speed of the proton is $3.6 \times 10^{6}\,\mathrm{m\,s^{-1}}$ at X and the magnetic flux density is 0.25 T. Show that the radius of the path is 15 cm. [2]

iii Calculate the time the proton is in the region of the magnetic field. [2]

d **i** The proton is replaced by a beam of singly ionised atoms of neon. The ions have the same speed when they enter at X. The beam splits into two beams: B_1 of radius 38.0 cm and B_2 of radius 41.8 cm. The ions in beam B_1 have mass 3.32×10^{-26} kg. Predict the mass of the ions in beam B_2. [2]

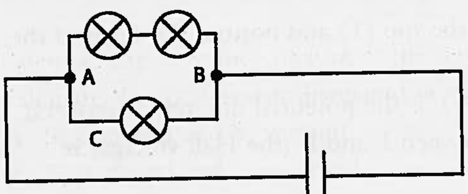
ii Suggest the implication of **d i** for nuclear structure. [2]

16 In the circuit shown A, B and C are three identical light bulbs of constant resistance. The battery has negligible internal resistance.

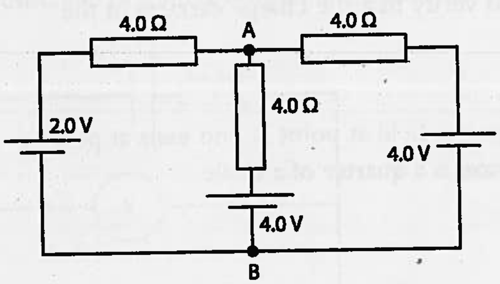
a Determine the order of brightness of the light bulbs. [2]

b Bulb C burns out. Predict how the brightness of A will change. [2]

c Bulb C operates normally, but now bulb B burns out. Compare the brightness of A and of C now to the brightness they had before B burnt out. [2]



17 Consider the circuit shown in which the batteries are assumed to have negligible internal resistance.



a Calculate the current, magnitude and direction, in each battery. [4]

b Determine the potential difference between points A and B. [2]

c Determine the total power in each battery, commenting on your answer. [3]