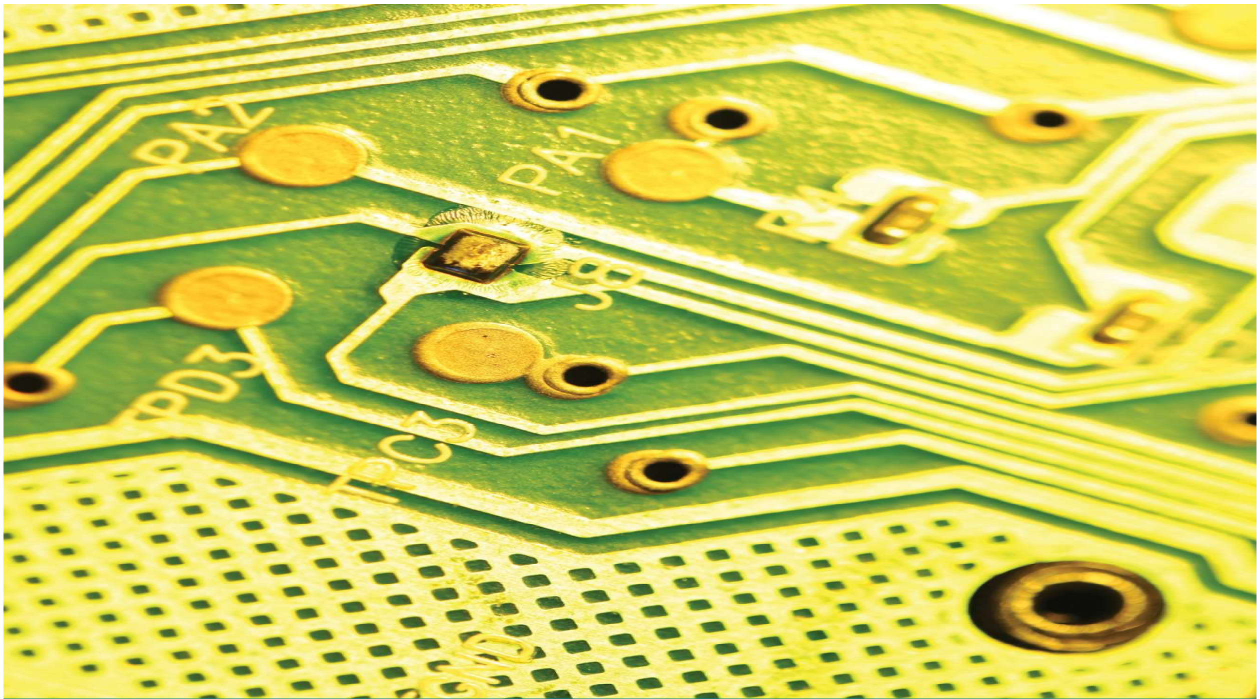


Chapter 9

Kirchhoff's laws

LEARNING INTENTIONS

In this chapter you will learn how to:

- recall and apply Kirchhoff's laws
- use Kirchhoff's laws to derive the formulae for the combined resistance of two or more resistors in series and in parallel
- recognise that ammeters are connected in series within a circuit and therefore should have low resistance
- recognise that voltmeters are connected in parallel across a component, or components, and therefore should have high resistance.

BEFORE YOU START

- Write down the name(s) of the meters you use to measure current in a component and potential difference across it.
- Draw a circuit diagram showing a circuit in which a battery is used to drive a current through a variable resistor in series with a lamp. Show on your circuit how you would connect the meters named in your list.
- Try to draw a circuit diagram to measure the potential difference of a component and the current in it. Swap with a classmate to check.

CIRCUIT DESIGN

Over the years, electrical circuits have become increasingly complex, with more and more components combining to achieve very precise results (Figure 9.1). Such circuits typically include power supplies, sensing devices, potential dividers and output devices. At one time, circuit designers would start with a simple circuit and gradually modify it until the desired result was achieved. This is impossible today when circuits include many hundreds or thousands of components.

Instead, electronics engineers (Figure 9.2) rely on computer-based design software that can work out the effect of any combination of components. This is only possible because computers can be programmed with the equations that describe how current and voltage behave in a circuit. These equations, which include Ohm's law and Kirchhoff's two laws, were established in the 18th century, but they have come into their own in the 21st century through their use in computer-aided design (CAD) systems.

Figure 9.1: A complex electronic circuit – this is the circuit board that controls a computer's hard drive.

Think about other areas of industry. How have computers changed those industrial practices in the last 30 years?

Figure 9.2: A computer engineer uses a computer-aided design (CAD) software tool to design a circuit that will form part of a microprocessor, the device at the heart of every computer.

9.1 Kirchhoff's first law

You will have learnt that current may divide up where a circuit splits into two separate branches. For example, a current of 5.0 A may split at a junction or a point in a circuit into two separate currents of 2.0 A and 3.0 A. The total amount of current remains the same after it splits. We would not expect some of the current to disappear, or extra current to appear from nowhere. This is the basis of **Kirchhoff's first law**, which states that the sum of the currents entering any point in a circuit is equal to the sum of the currents leaving that same point.

This is illustrated in Figure 9.3. In the first part, the current into point P must equal the current out, so:

$$I_1 = I_2$$

In the second part of the figure, we have one current coming into point Q, and two currents leaving. The current divides at Q. Kirchhoff's first law gives:

$$I_1 = I_2 + I_3$$

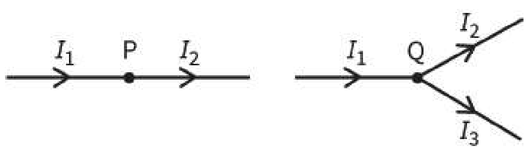


Figure 9.3: Kirchhoff's first law: current is conserved because charge is conserved.

Kirchhoff's first law is an expression of the **conservation of charge**. The idea is that the total amount of charge entering a point must exit the point. To put it another way, if a billion electrons enter a point in a circuit in a time interval of 1.0 s, then one billion electrons must exit this point in 1.0 s. The law can be tested by connecting ammeters at different points in a circuit where the current divides. You should recall that an ammeter must be connected in series so the current to be measured passes through it.

Questions

1 Use Kirchhoff's first law to deduce the value of the current I in Figure 9.4.

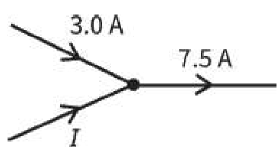


Figure 9.4: For Question 1.

2 In Figure 9.5, calculate the current in the wire X. State the direction of this current (towards P or away from P).

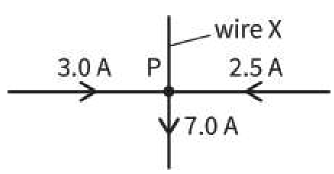


Figure 9.5: For Question 2.

Formal statement of Kirchhoff's first law

We can write Kirchhoff's first law as an equation:

$$\Sigma I_{\text{in}} = \Sigma I_{\text{out}}$$

Here, the symbol Σ (Greek letter sigma) means 'the sum of all', so ΣI_{in} means 'the sum of all currents entering into a point' and ΣI_{out} means 'the sum of all currents leaving that point'. This is the sort of equation that a computer program can use to predict the behaviour of a complex circuit.

KEY EQUATIONS

Kirchhoff's first law:

$$\Sigma I_{\text{in}} = \Sigma I_{\text{out}}$$

Questions

3 Calculate ΣI_{in} and ΣI_{out} in Figure 9.6. Is Kirchhoff's first law satisfied?

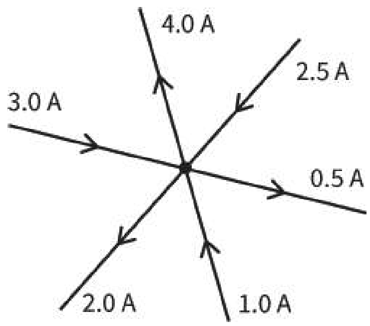


Figure 9.6: For Question 3.

4 Use Kirchhoff's first law to deduce the value and direction of the current I in Figure 9.7.

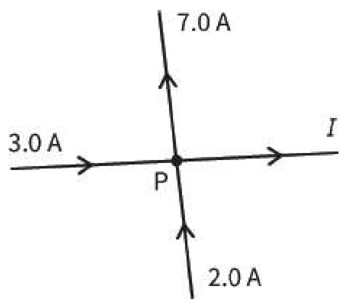


Figure 9.7: For Question 4.

9.2 Kirchhoff's second law

This law deals with e.m.f.s and voltages in a circuit. We will start by considering a simple circuit that contains a cell and two resistors of resistances R_1 and R_2 (Figure 9.8). Since this is a simple series circuit, the current I must be the same all the way around, and we need not concern ourselves further with Kirchhoff's first law. For this circuit, we can write the following equation:

$$E = IR_1 + IR_2$$

e.m.f. of battery = sum of p.d.s across the resistors

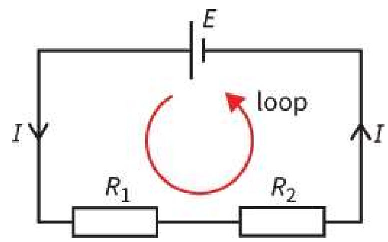


Figure 9.8: A simple series circuit.

You should not find these equations surprising. However, you may not realise that they are a consequence of applying **Kirchhoff's second law** to the circuit. This law states that the sum of the e.m.f.s around any loop in a circuit is equal to the sum of the p.d.s around the loop.

WORKED EXAMPLE

1 Use Kirchhoff's laws to find the current in the circuit in Figure 9.9.

This is a series circuit so the current is the same all the way round the circuit.

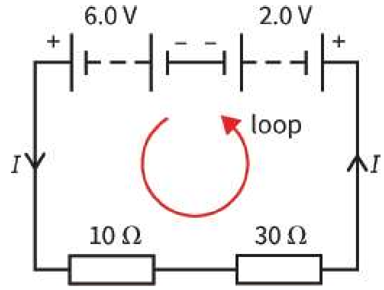


Figure 9.9: A circuit with two opposing batteries.

Step 1 We calculate the sum of the e.m.f.s:

sum of e.m.f.s = 6.0 V − 2.0 V = 4.0 V

The batteries are connected in opposite directions so we must consider one of the e.m.f.s as negative.

Step 2 We calculate the sum of the p.d.s.

sum of p.d.s = $(I \times 10) + (I \times 30) = 40\,I$

Step 3 We equate these:

$4.0 = 40\,I$

and so $I = 0.1$ A

No doubt, you could have solved this problem without formally applying Kirchhoff's second law, but you will find that in more complex problems the use of these laws will help you to avoid errors.

You will see later that Kirchhoff's second law is an expression of the conservation of energy. We shall look at another example of how this law can be applied, and then look at how it can be applied in general.

Question

5 Use Kirchhoff's second law to deduce the p.d. across the resistor of resistance *R* in the circuit shown in Figure 9.10, and hence find the value of *R*. (Assume the battery of e.m.f. 10 V has negligible internal resistance.)

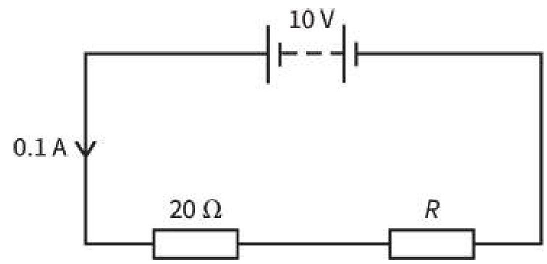


Figure 9.10: Circuit for Question 5.

An equation for Kirchhoff's second law

In a similar manner to the formal statement of the first law, the second law can be written as an equation:

$$\Sigma E = \Sigma V$$

where ΣE is the sum of the e.m.f.s and ΣV is the sum of the potential differences.

KEY EQUATION

Kirchhoff's second law:

$$\Sigma E = \Sigma V$$

9.3 Applying Kirchhoff's laws

Figure 9.11 shows a more complex circuit, with more than one 'loop'. Again, there are two batteries and two resistors. The problem is to find the current in each resistor. There are several steps in this; Worked example 2 shows how such a problem is solved.

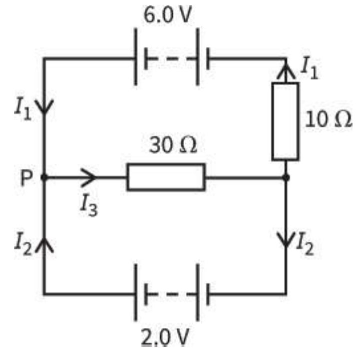


Figure 9.11: Kirchhoff's laws are needed to determine the currents in this circuit.

Signs and directions

Caution is necessary when applying Kirchhoff's second law. You need to take account of the ways in which the sources of e.m.f. are connected and the directions of the currents. Figure 9.12 shows one loop from a larger complicated circuit to illustrate this point. Only the components and currents in this particular loop are shown.

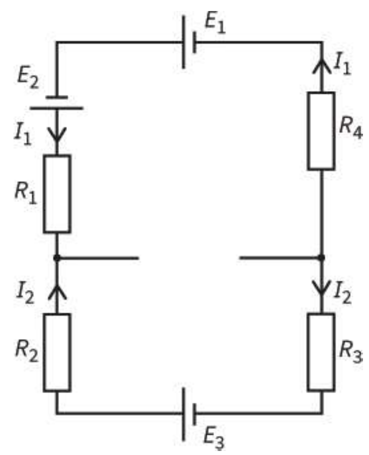


Figure 9.12: A loop extracted from a complicated circuit.

e.m.f.s

Starting with the cell of e.m.f. E_1 and working **anticlockwise** around the loop (because E_1 is 'pushing current' anticlockwise):

$$\text{sum of e.m.f.s} = E_1 + E_2 - E_3$$

Note that E_3 is opposing the other two e.m.f.s.

p.d.s

Starting from the same point, and working **anticlockwise** again:

$$\text{sum of p.d.s} = I_1R_1 - I_2R_2 - I_2R_3 + I_1R_4$$

Note that the direction of current I_2 is clockwise, so the p.d.s that involve I_2 are negative.

WORKED EXAMPLE

2 Calculate the current in each of the resistors in the circuit shown in Figure 9.11.

Step 1 Mark the currents. The diagram shows I_1, I_2 and I_3.

Hint: *It does not matter if we mark these in the wrong directions, as they will simply appear as negative quantities in the solutions.*

Step 2 Apply Kirchhoff's first law. At point P, this gives:

$$I_1 + I_2 = I_3 \quad (1)$$

Step 3 Choose a loop and apply Kirchhoff's second law. Around the upper loop, this gives:

$$6.0 = (I_3 \times 30) + (I_1 \times 10) \quad (2)$$

Step 4 Repeat step 3 around other loops until there are the same number of equations as unknown currents. Around the lower loop, this gives:

$$2.0 = I_3 \times 30 \quad (3)$$

We now have three equations with three unknowns (the three currents).

Step 5 Solve these equations as simultaneous equations. In this case, the situation has been chosen to give simple solutions. Equation 3 gives I_3 = 0.067 A, and substituting this value in Equation 2 gives I_1 = 0.400 A. We can now find I_2 by substituting in equation 1:

$$I_2 = I_3 - I_1 = 0.067 - 0.400 = -0.333 \text{ A} \approx -0.33 \text{ A}$$

Thus I_2 is negative–it is in the opposite direction to the arrow shown in Figure 9.11.

Note that there is a third 'loop' in this circuit; we could have applied Kirchhoff's second law to the outermost loop of the circuit. This would give a fourth equation:

$$6 - 2 = I_1 \times 10$$

However, this is not an independent equation; we could have arrived at it by subtracting equation 3 from equation 2.

Questions

6 You can use Kirchhoff's second law to find the current I in the circuit shown in Figure 9.13. Choosing the best loop can simplify the problem.

a Which loop in the circuit should you choose?

b Calculate the current I.

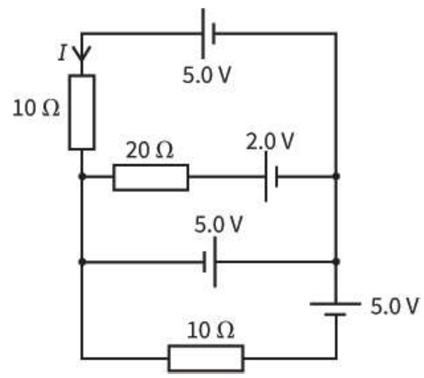


Figure 9.13: Careful choice of a suitable loop can make it easier to solve problems like this. For Question 6.

7 Use Kirchhoff's second law to deduce the resistance R of the resistor shown in the circuit loop of Figure 9.14.

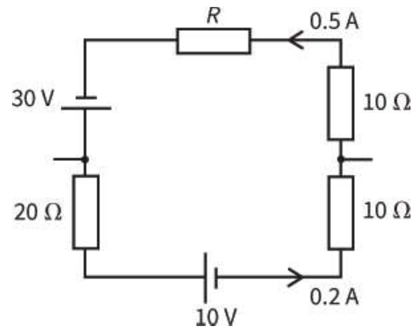


Figure 9.14: For Question 7.

Conservation of energy

Kirchhoff's second law is a consequence of the principle of conservation of energy. If a charge, say 1 C, moves around the circuit, it **gains** energy as it moves through each source of e.m.f. and loses energy as it passes through each p.d. If the charge moves all the way round the circuit so that it ends up where it started, it must have the same energy at the end as at the beginning. (Otherwise we would be able to create energy from nothing simply by moving charges around circuits.)

So:

energy gained passing through sources of e.m.f. = energy lost passing through components with p.d.s

You should recall that an e.m.f. in volts is simply the energy gained per 1 C of charge as it passes through a source. Similarly, a p.d. is the energy lost per 1 C as it passes through a component.

1 volt = 1 joule per coulomb

Hence, we can think of Kirchhoff's second law as:

energy gained per coulomb around loop = energy lost per coulomb around loop

Here is another way to think of the meaning of e.m.f. A 1.5 V cell gives 1.5 J of energy to each coulomb of charge that passes through it. The charge then moves round the circuit, transferring the energy to components in the circuit. The consequence is that, by driving 1 C of charge around the circuit, the cell transfers 1.5 J of energy. Hence, the e.m.f. of a source simply tells us the amount of energy (in joules) transferred by the source in driving unit charge (1 C) around a circuit.

Questions

8 Use the idea of the energy gained and lost by a 1 C charge to explain why two 6 V batteries connected together in series can give an e.m.f. of 12 V or 0 V, but connected in parallel they give an e.m.f. of 6 V.

9 Apply Kirchhoff's laws to the circuit shown in Figure 9.15 to determine the current that will be shown by the ammeters A_1, A_2 and A_3.

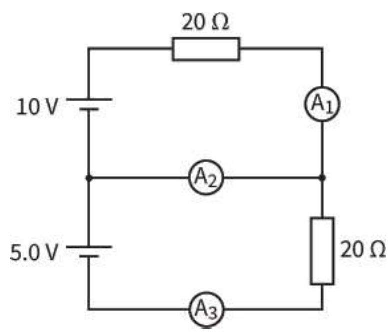


Figure 9.15: Kirchhoff's laws make it possible to deduce the ammeter readings.

9.4 Resistor combinations

You are already familiar with the formulae used to calculate the combined resistance R of two or more resistors connected in series or in parallel. To derive these formulae we have to use Kirchhoff's laws.

Resistors in series

Take two resistors of resistances R_1 and R_2 connected in series (Figure 9.16). According to Kirchhoff's first law, the current in each resistor is the same. The p.d. V across the combination is equal to the sum of the p.d.s across the two resistors:

$$V = V_1 + V_2$$

Since $V = IR$, $V_1 = IR_1$ and $V_2 = IR_2$, we can write:

$$IR = IR_1 + IR_2$$

Cancelling the common factor of current I gives:

$$R = R_1 + R_2$$

KEY EQUATION

Total resistance R of three or more resistors in series = $R_1 + R_2 + R_3 + \ldots$

For three or more resistors, the equation for total resistance R becomes:

$$R = R_1 + R_2 + R_3 + \ldots$$

You must learn how to derive this equation using Kirchhoff's laws.

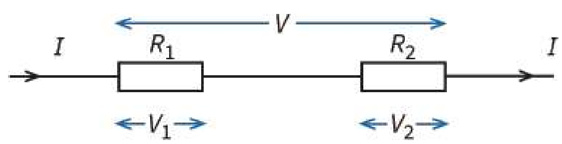


Figure 9.16: Resistors in series.

Questions

10 Calculate the combined resistance of two 5 Ω resistors and a 10 Ω resistor connected in series.

11 The cell shown in Figure 9.17 provides an e.m.f. of 2.0 V. The p.d. across one lamp is 1.2 V. Determine the p.d. across the other lamp.

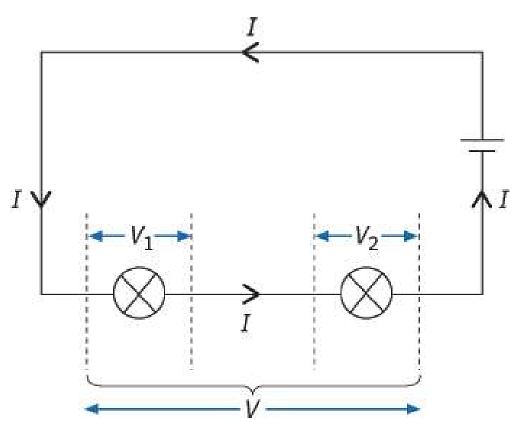


Figure 9.17: A series circuit for Question 11.

12 You have five 1.5 V cells. How would you connect all five of them to give an e.m.f. of:

a 7.5 V
b 1.5 V
c 4.5 V?

Resistors in parallel

For two resistors of resistances R_1 and R_2 connected in parallel (Figure 9.18), we have a situation where the current divides between them. Hence, using Kirchhoff's first law, we can write:

$$I = I_1 + I_2$$

If we apply Kirchhoff's second law to the loop that contains the two resistors, we have:

$$I_1R_1 - I_2R_2 = 0\ \text{V}$$

(because there is no source of e.m.f. in the loop).

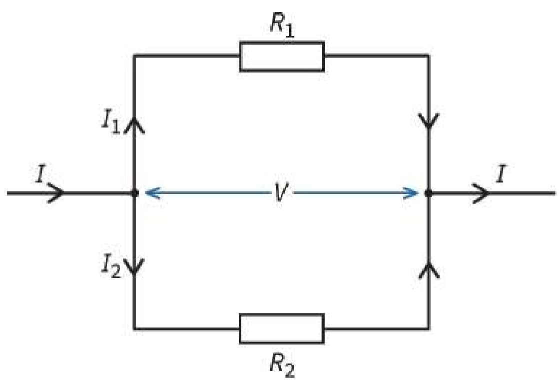


Figure 9.18: Resistors connected in parallel.

This equation states that the two resistors have the same p.d. V across them. Hence we can write:

$$I = \frac{V}{R}$$
$$I_1 = \frac{V}{R_1}$$
$$I_2 = \frac{V}{R_2}$$

Substituting in $I = I_1 + I_2$ and cancelling the common factor V gives:

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

For three or more resistors, the equation for total resistance R becomes:

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$$

KEY EQUATION

Total resistance R of three or more resistors in parallel is given by the equation $\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$

You must learn how to derive this equation using Kirchhoff's laws.

To summarise, when components are connected in parallel:

- all have the same p.d. across their ends
- the current is shared between them
- we use the reciprocal formula to calculate their combined resistance.

WORKED EXAMPLE

3 Two 10 Ω resistors are connected in parallel. Calculate the total resistance.

Step 1 We have $R_1 = R_2 = 10\ \Omega$, so:

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$\frac{1}{R} = \frac{1}{10} + \frac{1}{10} = \frac{2}{10} = \frac{1}{5}$$

Step 2 Inverting both sides of the equation gives:

$R = 5\ \Omega$

Hint: *Take care not to forget this step! Nor should you write* $\frac{1}{R} = \frac{1}{5} = 5\ \Omega$, *as then you are saying* $\frac{1}{5} = 5$).

You can also determine the resistance as follows:

$$\begin{aligned} R &= \left(R_1{}^{-1} + R_2{}^{-1}\right)^{-1} \\ &= \left(10^{-1} + 10^{-1}\right)^{-1} = 5\Omega \end{aligned}$$

Questions

13 Calculate the total resistance of four 10 Ω resistors connected in parallel.

14 Calculate the resistances of the following combinations:

- **a** 100 Ω and 200 Ω in series
- **b** 100 Ω and 200 Ω in parallel
- **c** 100 Ω and 200 Ω in series and this in parallel with 200 Ω.

15 Calculate the current drawn from a 12 V battery of negligible internal resistance connected to the ends of the following:

- **a** 500 Ω resistor
- **b** 500 Ω and 1000 Ω resistors in series
- **c** 500 Ω and 1000 Ω resistors in parallel.

16 You are given one 200 Ω resistor and two 100 Ω resistors. What total resistances can you obtain by connecting some, none, or all of these resistors in various combinations?

Solving problems with parallel circuits

Here are some useful ideas that may help when you are solving problems with parallel circuits (or checking your answers to see whether they seem reasonable).

- When two or more resistors are connected in parallel, their combined resistance is smaller than any of their individual resistances. For example, three resistors of 2 Ω, 3 Ω and 6 Ω connected together in parallel have a combined resistance of 1 Ω. This is less than the smallest of the individual resistances. This comes about because, by connecting the resistors in parallel, you are providing extra pathways for the current. Since the combined resistance is lower than the individual resistances, it follows that connecting two or more resistors in parallel will increase the current drawn from a supply. Figure 9.19 shows a hazard that can arise when electrical appliances are connected in parallel.
- When components are connected in parallel, they all have the same p.d. across them. This means that you can often ignore parts of the circuit that are not relevant to your calculation.
- Similarly, for resistors in parallel, you may be able to calculate the current in each one individually, then add them up to find the total current. This may be easier than working out their combined resistance using the reciprocal formula. (This is illustrated in Question 19.)

Figure 9.19: a Correct use of an electrical socket. **b** Here, too many appliances (resistances) are connected in parallel. This reduces the total resistance and increases the current drawn, to the point where it becomes dangerous.

Questions

17 Three resistors of resistances 20 Ω, 30 Ω and 60 Ω are connected together in parallel. Select which of the following gives their combined resistance:

110 Ω,   50 Ω,   20 Ω,   10 Ω

(No need to do the calculation!)

18 In the circuit in Figure 9.20 the battery of e.m.f. 10 V has negligible internal resistance. Calculate the current in the 20 Ω resistor shown in the circuit.

19 Determine the current drawn from the battery in Figure 9.20.

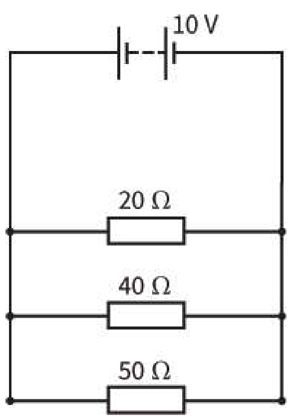


Figure 9.20: Circuit diagram for Questions 18 and 19.

20 What value of resistor must be connected in parallel with a 20 Ω resistor so that their combined resistance is 10 Ω?

21 You are supplied with a number of 100 Ω resistors. Describe how you could combine the minimum number of these to make a 250 Ω resistor.

22 Calculate the current at each point (A–E) in the circuit shown in Figure 9.21.

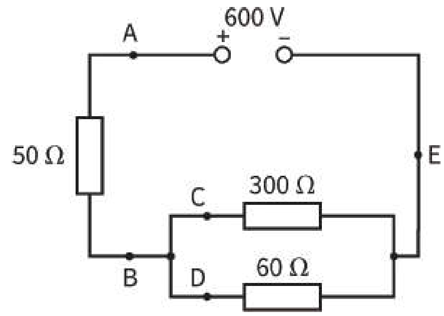


Figure 9.21: For Question 22.

PRACTICAL ACTIVITY 10.1

Ammeters and voltmeters

Ammeters and voltmeters are connected differently in circuits (Figure 9.22). Ammeters are always connected in series, since they measure the current in a circuit. For this reason, an ammeter should have as low a resistance as possible so that as little energy as possible is dissipated in the ammeter itself. Inserting an ammeter with a higher resistance could significantly reduce the current flowing in the circuit. The ideal resistance of an ammeter is zero. Digital ammeters have very low resistances.

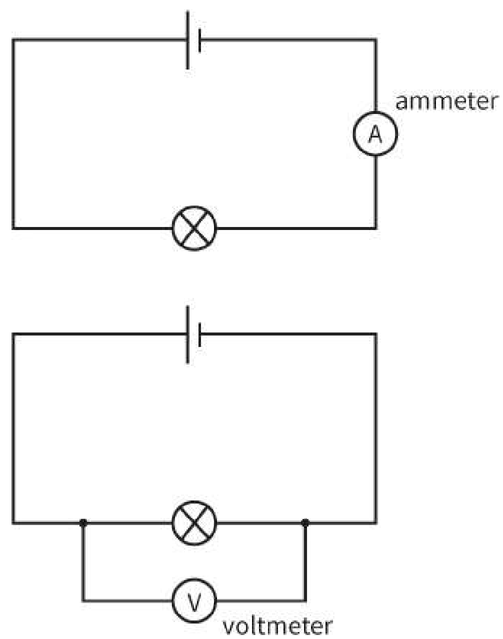


Figure 9.22: How to connect up an ammeter and a voltmeter.

Voltmeters measure the potential difference between two points in the circuit. For this reason, they are connected in parallel (i.e., between the two points), and they should have a very high resistance to take as little current as possible. The ideal resistance of a voltmeter would be infinite. In practice, voltmeters have typical resistance of about 1 MΩ. A voltmeter with a resistance of 10 MΩ measuring a p.d. of 2.5 V will take a current of 2.5×10^{-7} A and dissipate just 0.625 μJ of heat energy from the circuit every second.

Figure 9.23 shows some measuring instruments.

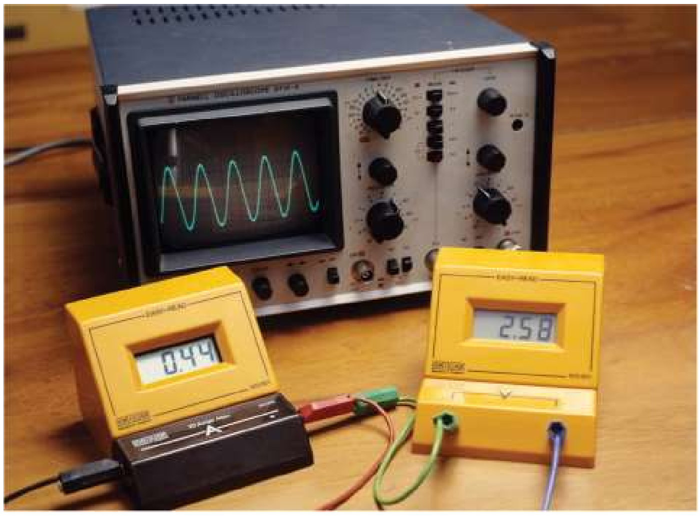


Figure 9.23: Electrical measuring instruments: an ammeter, a voltmeter and an oscilloscope. The oscilloscope can display rapidly changing voltages.

Question

23 a A 10 V power supply of negligible internal resistance is connected to a 100 Ω resistor. Calculate the current in the resistor.

b An ammeter is now connected in the circuit, to measure the current. The resistance of the ammeter is 5.0 Ω. Calculate the ammeter reading.

REFLECTION

Kirchhoff's Laws formalise facts that you might already have been familiar with.

Make a list of the main points that these laws have helped clarify in your mind.

Compare your list with two or three other people's lists.

Are they identical?

Thinking back on this chapter, what things might you want more help with?

SUMMARY

Kirchhoff's first law states that the sum of the current currents entering any point in a circuit is equal to the sum of the currents leaving that point.
Kirchhoff's second law states that the sum of the e.m.f.s around any loop in a circuit is equal to the sum of the p.d.s around the loop.
The combined resistance of resistors in series is given by the formula: $$R = R_1 + R_2 + ...$$
The combined resistance of resistors in parallel is given by the formula: $$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots.$$
Ammeters have a low resistance and are connected in series in a circuit.
Voltmeters have a high resistance and are connected in parallel in a circuit.

EXAM-STYLE QUESTIONS

1 Which row in this table is correct? **[1]**

A	Kirchhoff's first law is an expression of the conservation of charge.	Kirchhoff's second law is an expression of the conservation of charge.
B	Kirchhoff's first law is an expression of the conservation of charge.	Kirchhoff's second law is an expression of the conservation of energy.
C	Kirchhoff's first law is an expression of the conservation of energy.	Kirchhoff's second law is an expression of the conservation of charge.
D	Kirchhoff's first law is an expression of the conservation of energy.	Kirchhoff's second law is an expression of the conservation of energy.

Table 9.1

2 What is the current I_1 in this circuit diagram? **[1]**

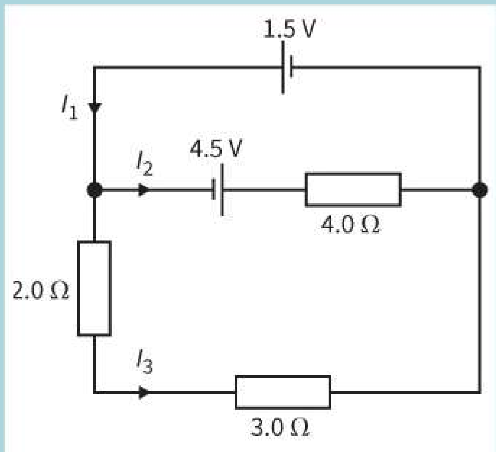


Figure 9.24

A −0.45 A

B +0.45 A

C +1.2 A

D +1.8 A

3 Use Kirchhoff's first law to calculate the unknown currents in these examples.

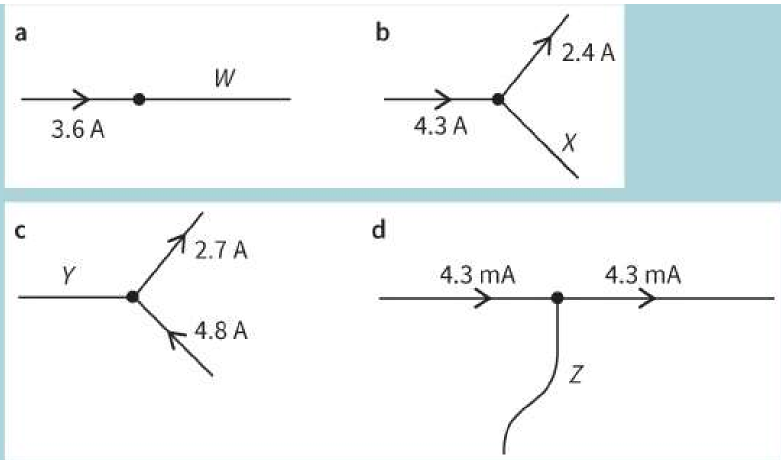


Figure 9.25

For each example, state the direction of the current. **[4]**

4 This diagram shows a part of a circuit.

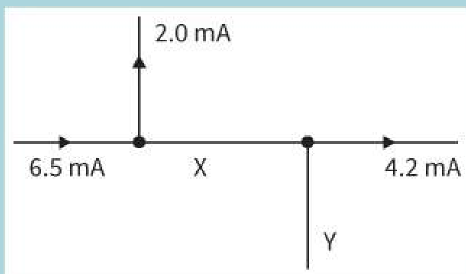


Figure 9.26

Copy the circuit and write in the currents at X and at Y, and show their directions. **[2]**

5 Look at these four circuits.

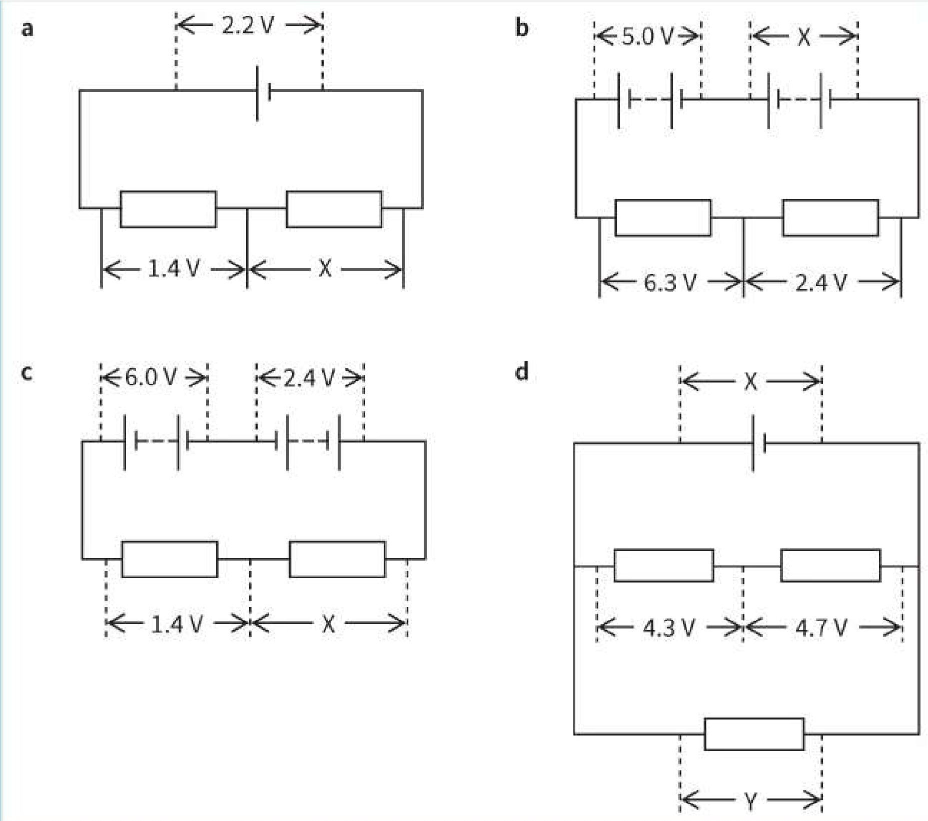


Figure 9.27

Determine the unknown potential difference (or differences) in each case. **[5]**

6 A filament lamp and a 220 Ω resistor are connected in series to a battery of e.m.f. 6.0 V. The battery has negligible internal resistance. A high-resistance voltmeter placed across the resistor measures 1.8 V.

Calculate:

a the current drawn from the battery **[1]**

b the p.d. across the lamp **[1]**

c the total resistance of the circuit **[1]**

d the number of electrons passing through the battery in a time of 1.0 minute. **[4]**

(The elementary charge is 1.6×10^{-19} C.)

[Total: 7]

7 The circuit diagram shows a 12 V power supply connected to some resistors.

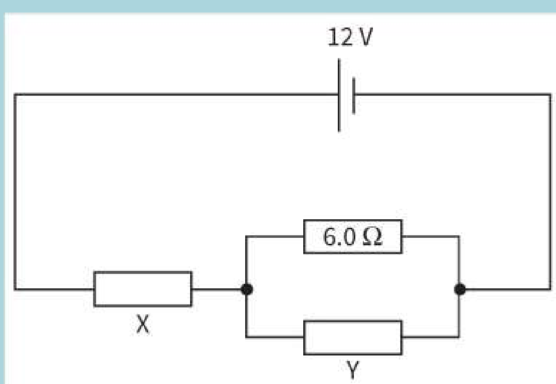


Figure 9.28

The current in the resistor X is 2.0 A and the current in the 6.0 Ω resistor is 0.5 A. Calculate:

a the current in resistor Y **[1]**

b the resistance of resistor Y **[2]**

c the resistance of resistor X. **[2]**

[Total: 5]

8 **a** Explain the difference between the terms e.m.f. and potential difference. **[2]**

b This circuit contains batteries and resistors. You may assume that the batteries have negligible internal resistance.

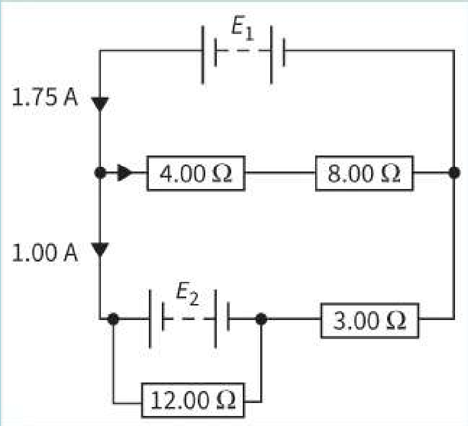


Figure 9.29

i Use Kirchhoff's first law to find the current in the 4.00 Ω and 8.00 Ω resistors. **[1]**

ii Calculate the e.m.f. of E_1. **[2]**

iii Calculate the value of E_2. **[2]**

iv Calculate the current in the 12.00 Ω resistor. **[2]**

[Total: 9]

9 **a** Explain why an ammeter is designed to have a low resistance. **[1]**

A student builds the circuit, as shown, using a battery of negligible internal resistance. The reading on the voltmeter is 9.0 V.

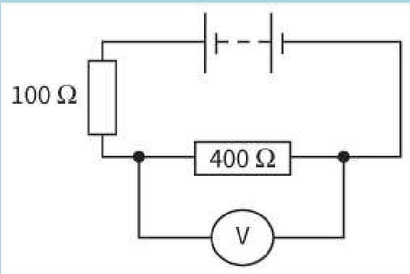


Figure 9.30

b **i** The voltmeter has a resistance of 1200 Ω. Calculate the e.m.f. of the battery. **[4]**

ii The student now repeats the experiment using a voltmeter of resistance 12 kΩ. Show that the reading on this voltmeter would be 9.5 V. **[3]**

iii Refer to your answers to **i** and **ii** and explain why a voltmeter should have as high a resistance as possible. **[2]**

[Total: 10]

10 a Explain what is meant by the resistance of a resistor. **[1]**

b This diagram shows a network of resistors connected to a cell of e.m.f. 6.0 V.

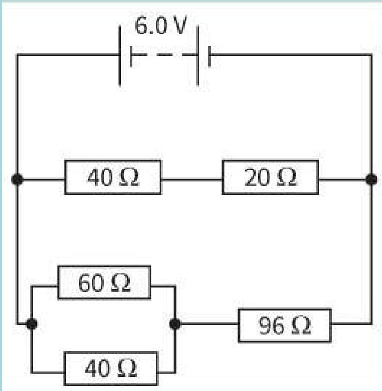


Figure 9.31

Show that the resistance of the network of resistors is 40 Ω. **[3]**

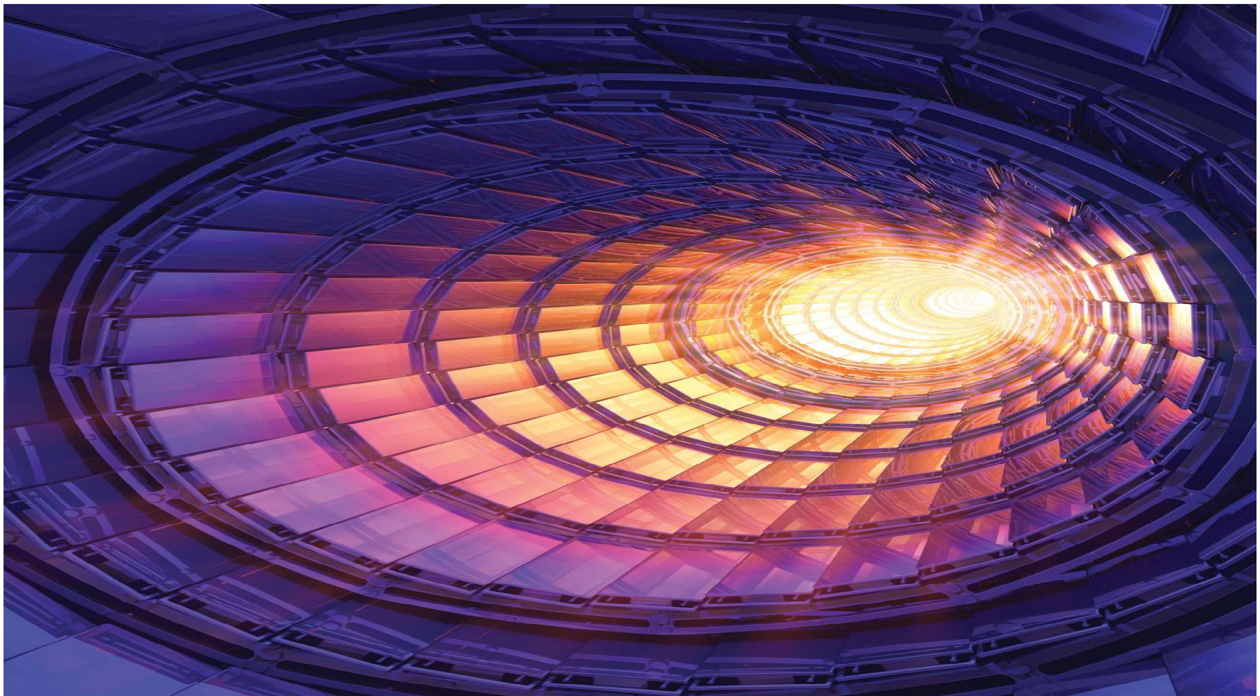
c Calculate the current in the 60 Ω resistor. **[3]**

[Total: 7]

SELF-EVALUATION CHECKLIST

After studying the chapter, complete a table like this:

I can	See topic…	Needs more work	Almost there	Ready to move on
state and use Kirchhoff's first law	9.1, 9.3			
state and use Kirchhoff's second law that states that the sum of the e.m.f.s around any loop in a circuit is equal to the sum of the p.d.s around the loop	9.2, 9.3			
calculate the total resistance of two or more resistors in series	9.4			
calculate the resistance of two or more resistors in parallel	9.4			
understand that ammeters have a low resistance and are connected in series in a circuit	9.4			
understand that voltmeters have a high resistance and are connected in parallel in a circuit.	9.4			



Chapter 10

Resistance and resistivity

LEARNING INTENTIONS

In this chapter you will learn how to:

- state Ohm's law
- sketch and explain the *I*–*V* characteristics for various components
- sketch the temperature characteristic for an NTC thermistor
- solve problems involving the resistivity of a material.

BEFORE YOU START

- Do you understand the terms introduced in Chapters 8 and 9: current, charge, potential difference, e.m.f., resistance and their relationships to one another?
- What are their units?
- Take turns in challenging a partner to define a term or to write down an equation linking different terms. Do not use the textbook or your notes to look up the terms.

SUPERCONDUCTIVITY

As metals are cooled, their resistance decreases. It was discovered as long ago as 1911 that when mercury was cooled using liquid helium to 4.1 K (4.1 degrees above absolute zero), its resistance suddenly fell to zero. This phenomenon was named **superconductivity**. Other metals, such as lead at 7.2 K, also become superconductors.

When charge flows in a superconductor, it can continue in that superconductor without the need for any potential difference and without dissipating any energy. This means that large currents can occur without the unwanted heating effect that would occur in a normal metallic or semiconducting conductor.

Initially, superconductivity was only of scientific interest and had little practical use, as the liquid