Physics Units 1 & 2

Chapter 6 — Using electricity safely

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Contents

Theory

A cell or battery transfers energy *to* the charges that pass through it. Each component in the circuit — a lamp, a resistor, a heater — transfers energy *from* those charges to its surroundings, usually as light, thermal energy, or both. The rate at which a component transfers this energy is its **power**, and from 5A:

$$P = V\,I$$

where P is the power in watts (W), V is the potential difference across the component in volts, and I is the current through it in amperes. This subtopic compares how that power is shared out when components are connected in series and in parallel, and then applies the comparison to a question with a real answer: why the circuits in homes are wired in parallel. These are the study design's own two requirements for this subtopic: *"compare power transfers in series and parallel circuits"* and *"explain why the circuits in homes are mostly parallel circuits"* (VCE Physics Study Design, Unit 1, Area of Study 3).

What you already know. From Chapter 5:

- In a **series** circuit the components share a single path. The current has the same value through every component, and the supply's potential difference is shared between them ($V_{\text{supply}} = V_1 + V_2 + \ldots$). Resistances in series add: $R_{\text{eq}} = R_1 + R_2 + \ldots$, where R_{eq} is the **equivalent resistance** — the single resistance that could replace the whole combination with the same current (5D, 5E).
- In a **parallel** circuit the components are connected across the same two points, giving the charge separate paths called **branches**. The potential difference is the same across every branch, and the supply current is shared between the branches ($I_{\text{supply}} = I_1 + I_2 + \ldots$). For resistances in parallel, $\frac{1}{R_{\text{eq}}} = \frac{1}{R_1} + \frac{1}{R_2} + \ldots$ (5D, 5E).
- For an **ohmic** component — one whose resistance is constant, such as a resistor — the potential difference, current and resistance are related by $V = I\,R$ (5D).

Two useful forms of the power equation. For an ohmic component, $V = I\,R$ can be substituted into $P = V\,I$ in two ways:

- substituting $V = I\,R$ gives
$$P = I^2 R\,;$$
- substituting $I = \frac{V}{R}$ gives
$$P = \frac{V^2}{R}.$$

These are not new relationships: each is $P = V\,I$ with $V = I\,R$ rearranged and substituted. The formula sheet lists $P = V\,I$ and $I = V\,/\,R$; the two forms above follow from them, and you should be ready to show that step. Each form has one arrangement where it is the natural choice, because each arrangement keeps one quantity the same for every component:

Arrangement	Quantity the same for every component	Quantity shared between components	Convenient power form
Series	current I	potential difference	$P = I^2 R$
Parallel	potential difference V	current	$P = \frac{V^2}{R}$

Power in a series circuit. Since the current is the same through every component, $P = I^2 R$ shows that the power transferred to each component is proportional to its resistance:

$$\frac{P_1}{P_2}=\frac{R_1}{R_2}(\text{series}).$$

The larger resistance transfers more power. This makes sense in terms of energy per coulomb: the supply's potential difference is shared between the components in proportion to their resistances (5D, 5F), so the larger resistance takes the larger share of the voltage, and each coulomb gives up more of its energy there. The individual powers add up to the power delivered by the supply ($P_{\text{total}}=V_{\text{supply}}I$), because the energy given to each coulomb by the supply is handed over, component by component, around the loop.

Power in a parallel circuit. Since the potential difference is the same across every branch, $P=\frac{V^2}{R}$ shows that the power transferred to each branch is *inversely* proportional to its resistance:

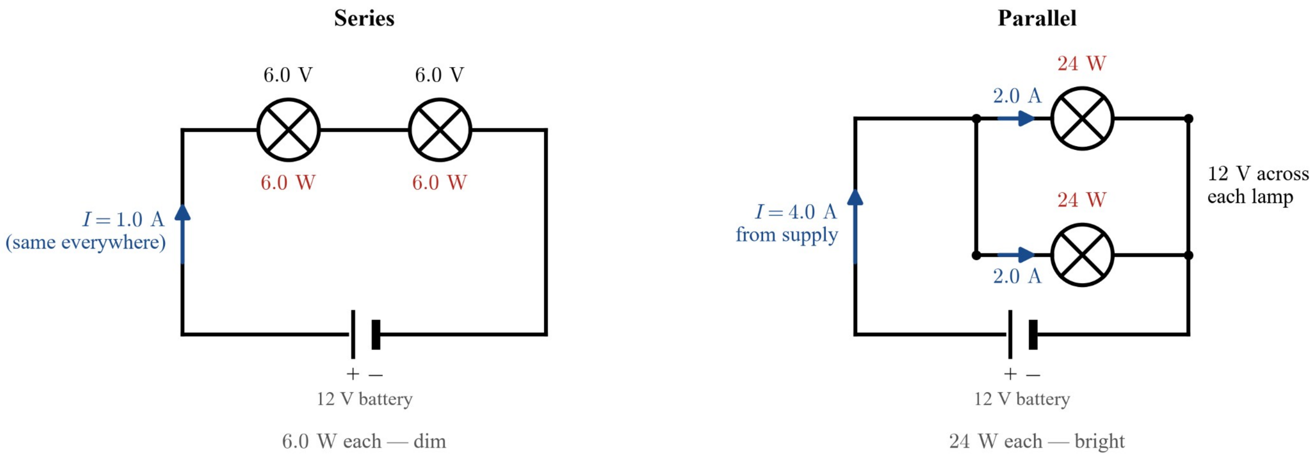
$$\frac{P_1}{P_2}=\frac{R_2}{R_1}(\text{parallel}).$$

The smaller resistance transfers more power, because the same voltage drives a larger current through it ($I=V/R$), and $P=VI$. Each branch takes its power independently of the others: switching one branch on or off does not change the potential difference across the rest. The branch powers add up to the power delivered by the supply ($P_{\text{total}}=V_{\text{supply}}I_{\text{supply}}$).

The same two components, two ways. Put the two arrangements side by side for two identical lamps, each of resistance R, connected to a supply of potential difference V:

- **In series**, the equivalent resistance is $2R$, so the current is $I=\frac{V}{2R}$. The power transferred to each lamp is $P=I^2R=\frac{V^2}{4R}$ — only one quarter of the power a single lamp would take from the same supply. Each lamp glows dimly.
- **In parallel**, each lamp has the full supply potential difference V across it, so each transfers $P=\frac{V^2}{R}$ — its full power, at normal brightness. The supply current is twice the current for a single lamp, and the total power transferred by the supply is four times the series total.

The same conclusion holds for any two components, not just identical ones: a parallel combination has a lower equivalent resistance than any one of its branches (5D), so it draws a larger current from the same supply, and transfers more total power, than the same components connected in series. The figure below shows both arrangements for two identical lamps, with the currents, voltages and powers computed.



Brightness is the observable check on all of this: the brightness of a lamp corresponds to the electrical power it transfers (to light and to thermal energy). More power means a brighter lamp.

Why homes are mostly parallel. The electricity supply to Australian homes is 230 V AC at 50 Hz; in this course household circuits are modelled with the same DC circuit ideas used above, and 6B develops that household model in full. Appliances are designed to operate at their **rated power** — the power they transfer when working normally — at the supply voltage of 230 V, and each appliance carries a label stating that power. The 230 V supply and the parallel arrangement together make this possible, for three reasons:

1. **Every appliance receives the full supply voltage.** In a parallel circuit every branch has the same potential difference as the supply, so every appliance has 230 V across it and can operate at its rated power. If the appliances were in series, the supply voltage would be shared between them; none would receive 230 V, and none would operate as designed.
2. **Each appliance can be switched independently.** Each branch has its own switch, so one appliance can be turned on or off without affecting any other. In a series circuit a single switch would control every appliance at once — and if one appliance failed so that its circuit broke, everything on that circuit would stop.
3. **Appliances can be added as needed.** Connecting another appliance simply adds another branch. Each branch draws its own current at 230 V, independent of the others.

The word *mostly* matters: a switch is connected in series with the appliance it controls, but the appliances themselves are connected in parallel across the supply. Worked Example 3 puts numbers on reason 1, by comparing a heater and a lamp in parallel with the same two appliances in series.

One consequence of parallel wiring is worth stating now. Each added branch lowers the equivalent resistance of the circuit, so the supply current grows as more appliances run at once. The wiring and the protective devices in a home's switchboard — fuses and circuit breakers — limit the current each circuit can safely carry; these devices are covered in 6E.

Practical note. In class, all circuit work is done with low-voltage DC supplies — batteries or a school laboratory power pack. The comparisons above can be checked directly with identical low-voltage lamps: two lamps in series glow dimly, and the same two lamps in parallel glow at normal brightness. The 230 V household supply is dangerous and is never used in student practicals: this matches the study design's rule that students are not permitted to carry out electrical work on equipment operating above 50 V AC or 120 V ripple-free DC. Household circuits are discussed and calculated here, but never built or opened.

Units 3 & 4 preview. The power relationships of this subtopic return in Units 3 & 4, where the same $P = VI$ and $P = I^2 R$ reasoning is applied to the energy lost in long electricity transmission lines. The comparison skill built here — choosing the power form that matches the quantity a circuit keeps the same — is assumed at that point. This preview is not assessed in Units 1 & 2.

Worked examples

Example 1 — scaffolded

In a school laboratory, a student connects a 4.0 Ω resistor and an 8.0 Ω resistor in series with a 12 V battery. (a) Calculate the equivalent resistance and the current in the circuit. (b) Calculate the potential difference across each resistor. (c) Calculate the power transferred to each resistor and the total power delivered by the battery. Which resistor transfers more power, and why?

Working	Comment
(a) $R_{eq} = R_1 + R_2 = 4.0 + 8.0 = 12\,\Omega$.	Resistances in series add.
$I = \frac{V}{R_{eq}} = \frac{12}{12} = 1.0\text{ A}$.	The same current flows through both resistors.
(b) $V_1 = I R_1 = 1.0 \times 4.0 = 4.0\text{ V}$; $V_2 = I R_2 = 1.0 \times 8.0 = 8.0\text{ V}$.	The supply voltage is shared between the resistors; check: $4.0 + 8.0 = 12\text{ V}$. ✓
(c) $P_1 = V_1 I = 4.0 \times 1.0 = 4.0\text{ W}$; $P_2 = V_2 I = 8.0 \times 1.0 = 8.0\text{ W}$.	Power to each resistor from $P = VI$.

Working	Comment
$P_{total} = 4.0 + 8.0 = 12\ \text{W}$; check: $P = V\,I = 12 \times 1.0 = 12\ \text{W}$. ✓	The individual powers add to the supply power.
The $8.0\ \Omega$ resistor transfers more power.	In series the current is the same through each resistor, so $P = I^2 R$: the larger resistance takes the larger share of the voltage and transfers more power.

Example 2 — scaffolded

The student now connects the same $4.0\ \Omega$ and $8.0\ \Omega$ resistors in parallel across the same $12\ \text{V}$ battery. (a) State the potential difference across each resistor. (b) Calculate the current in each branch and the current delivered by the battery. (c) Calculate the power transferred to each resistor and the total power, and compare the result with Example 1.

Working	Comment
(a) $V = 12\ \text{V}$ across each resistor.	In parallel, every branch has the full supply potential difference.
(b) $I_1 = \frac{V}{R_1} = \frac{12}{4.0} = 3.0\ \text{A}$; $I_2 = \frac{V}{R_2} = \frac{12}{8.0} = 1.5\ \text{A}$.	The same voltage drives a larger current through the smaller resistance.
$I_{supply} = 3.0 + 1.5 = 4.5\ \text{A}$.	The supply current is the sum of the branch currents.
(c) $P_1 = V\,I_1 = 12 \times 3.0 = 36\ \text{W}$; $P_2 = V\,I_2 = 12 \times 1.5 = 18\ \text{W}$.	Power to each branch from $P = V\,I$.
$P_{total} = 36 + 18 = 54\ \text{W}$; check: $P = V\,I = 12 \times 4.5 = 54\ \text{W}$. ✓	The branch powers add to the supply power.
In parallel the $4.0\ \Omega$ resistor transfers more power, and the total power ($54\ \text{W}$) is much larger than in series ($12\ \text{W}$).	In parallel the voltage is the same across each resistor, so $P = \frac{V^2}{R}$: the smaller resistance transfers more power. The parallel combination has a lower equivalent resistance, so it draws more current and more total power from the same supply.

Example 3 — unscaffolded

An Australian home is supplied at $230\ \text{V}$. A $2.0\ \text{kW}$ heater and a $100\ \text{W}$ lamp, both designed to operate at $230\ \text{V}$, are running in parallel in one room. (a) Calculate the current in the heater and in the lamp, and the total current drawn from the supply. (b) Treat each appliance as having a constant resistance at its operating temperature, and calculate the current and the power of each appliance if the same two appliances were instead connected in series across the $230\ \text{V}$ supply. (c) Use your answers to explain why the appliances in homes are connected in parallel rather than in series.

(a) From $P = V\,I$ rearranged to $I = \frac{P}{V}$:

$$I_{heater} = \frac{2000}{230} = 8.7\ \text{A}, I_{lamp} = \frac{100}{230} = 0.43\ \text{A}.$$

The appliances are in parallel, so the supply current is the sum of the branch currents:

$$I_{supply} = 8.7 + 0.43 = 9.1\ \text{A}.$$

(b) First find each resistance from its rating. Since each appliance operates at its rated power at $230\ \text{V}$, $P = \frac{V^2}{R}$ rearranged to $R = \frac{V^2}{P}$ gives

$$R_{\text{heater}} = \frac{230^2}{2000} = 26.45\,\Omega\,, R_{\text{lamp}} = \frac{230^2}{100} = 529\,\Omega\,.$$

In series the equivalent resistance is

$$R_{\text{eq}} = 26.45 + 529 = 555.45\,\Omega\,,$$

so the current is

$$I = \frac{230}{555.45} = 0.4141\text{ A}\,.$$

The power of each appliance follows from $P = I^2 R$:

$$P_{\text{heater}} = 0.4141^2 \times 26.45 = 4.5\text{ W}\,, P_{\text{lamp}} = 0.4141^2 \times 529 = 91\text{ W}\,.$$

(Check: the total is $4.5 + 91 = 95\text{ W}$, and $V\,I = 230 \times 0.4141 = 95\text{ W}$. ✓)

(c) In parallel, each appliance has the full 230 V across it and operates at its rated power — the heater at 2.0 kW and the lamp at 100 W. In series the supply voltage is shared between the appliances in proportion to their resistances: the high-resistance lamp takes most of it (about 219 V), leaving only about 11 V across the heater. The heater then transfers only 4.5 W — less than a quarter of one percent of its rated power — so it cannot heat the room at all, and even the lamp is below its rating. In addition, a series arrangement would give every appliance one shared switch, and a failure that broke the circuit in any one appliance would stop them all. Parallel wiring avoids every one of these problems: full voltage to each appliance, independent switching, and one appliance failing does not affect the others.

∴ in parallel: $I_{\text{heater}} = 8.7\text{ A}$, $I_{\text{lamp}} = 0.43\text{ A}$, $I_{\text{supply}} = 9.1\text{ A}$; in series: $I = 0.41\text{ A}$, $P_{\text{heater}} = 4.5\text{ W}$, $P_{\text{lamp}} = 91\text{ W}$; parallel wiring is required for appliances to operate at their rated power, independently of one another.

Example 4 — unscaffolded

A student connects two identical lamps, each with a filament resistance of $6.0\,\Omega$ when lit, to a 12 V battery — first in series, then in parallel. (a) Calculate the power transferred to each lamp in the series arrangement. (b) Calculate the power transferred to each lamp, and the current drawn from the battery, in the parallel arrangement. (c) Compare the brightness of the lamps in the two arrangements, and with a single lamp connected alone across the battery. Explain the comparison in terms of power.

(a) In series, the equivalent resistance is

$$R_{\text{eq}} = 6.0 + 6.0 = 12\,\Omega\,,$$

so the current is

$$I = \frac{12}{12} = 1.0\text{ A}\,.$$

The current is the same through both lamps, so $P = I^2 R$ gives the power of each:

$$P = 1.0^2 \times 6.0 = 6.0\text{ W}\,.$$

(b) In parallel, each lamp has the full 12 V across it, so $P = \frac{V^2}{R}$ gives

$$P = \frac{12^2}{6.0} = 24\text{ W per lamp}\,.$$

The current in each branch is $I = \frac{V}{R} = \frac{12}{6.0} = 2.0\text{ A}$, so the battery supplies $2.0 + 2.0 = 4.0\text{ A}$ in total.

(c) The brightness of a lamp corresponds to the power it transfers to light and thermal energy. In series each lamp transfers $6.0\,\mathrm{W}$; in parallel each transfers $24\,\mathrm{W}$ — four times as much. A single lamp connected alone across the $12\,\mathrm{V}$ battery also has $12\,\mathrm{V}$ across it and transfers $24\,\mathrm{W}$, which is its normal brightness. So the two lamps in parallel each glow at normal brightness, exactly as a single lamp does, while the two lamps in series each glow dimly, at one quarter of the normal power. The series pair takes only $12\,\mathrm{W}$ from the battery in total, compared with $48\,\mathrm{W}$ for the parallel pair: sharing the supply voltage between the lamps in series reduces the power — and therefore the brightness — of each one.

∴ series: $6.0\,\mathrm{W}$ each (dim); parallel: $24\,\mathrm{W}$ each with $4.0\,\mathrm{A}$ from the battery (normal brightness, as for a single lamp).

Practice questions

Question 1 Copy and complete each statement. (a) In a series circuit, the … is the same through every component, while the supply … is shared between the components. (b) In a parallel circuit, the … is the same across every branch, while the supply … is shared between the branches. (c) For an ohmic component, $P = V\,I$. Substituting $V = I\,R$ into $P = V\,I$ gives $P = \ldots$; substituting $I = \dfrac{V}{R}$ gives $P = \ldots$

Question 2 A student connects a $6.0\,\Omega$ resistor and an $18\,\Omega$ resistor in series with a $12\,\mathrm{V}$ battery. (a) Calculate the equivalent resistance of the circuit and the current in it. (b) Calculate the potential difference across each resistor. (c) Calculate the power transferred to each resistor and the total power delivered by the battery. State which resistor transfers more power, and explain why.

Question 3 The student now connects the same $6.0\,\Omega$ and $18\,\Omega$ resistors in parallel across the same $12\,\mathrm{V}$ battery. (a) State the potential difference across each resistor. (b) Calculate the current in each branch and the current delivered by the battery. (c) Calculate the power transferred to each resistor and the total power. State which resistor transfers more power, and explain why.

Question 4 Two identical $8.0\,\Omega$ resistors are connected to a $16\,\mathrm{V}$ battery in three arrangements: a single resistor alone; the two in series; the two in parallel. Copy and complete the table.

Arrangement	Current from the battery	Potential difference across each resistor	Power of each resistor	Total power
One resistor alone		$16\,\mathrm{V}$		$32\,\mathrm{W}$
Two in series	$1.0\,\mathrm{A}$			
Two in parallel			$32\,\mathrm{W}$	

Question 5 In an Australian home, a $1.5\,\mathrm{kW}$ toaster and a $10\,\mathrm{W}$ LED lamp run in parallel on the $230\,\mathrm{V}$ supply. (a) Calculate the current in the toaster and in the lamp. (b) Calculate the total current drawn from the supply when both are running. (c) Copy and complete: "The toaster and the lamp are connected in parallel so that each one has the full … of the supply across it, and each can be switched on and off … of the other."

Question 6 Two identical lamps are connected in series with a $6.0\,\mathrm{V}$ battery and glow dimly. (a) State the quantity that determines how brightly a lamp glows. (b) A third identical lamp is added to the circuit in series. State what happens to the total resistance of the circuit and to the current in it. (c) Hence state and explain what happens to the brightness of the original two lamps.

Question 7 A laboratory circuit contains a $3.0\,\Omega$, a $5.0\,\Omega$ and a $4.0\,\Omega$ resistor connected in series with a $24\,\mathrm{V}$ power pack. Calculate the power transferred to each resistor, and the total power delivered by the power pack.

Question 8 A caravan's $12\,\mathrm{V}$ battery powers two lamps labelled $12\,\mathrm{V}$, $24\,\mathrm{W}$, connected in parallel. (a) Calculate the current in each lamp and the current delivered by the battery. (b) Calculate the total power transferred by the two lamps. (c) Both lamps run for $5.0\,\mathrm{h}$. Calculate the energy they use, in kW h and in joules.

Question 9 In a Victorian home, a $2.4\,\text{kW}$ heater runs for $2.5\,\text{h}$ and a $40\,\text{W}$ fan runs for $6.0\,\text{h}$, both in parallel on the $230\,\text{V}$ supply. The electricity price is $30\,\text{c}$ per kW h. (a) Calculate the energy used by each appliance, in kW h. (b) Calculate the total cost of running both appliances for these times. (c) Calculate the total current drawn from the supply while both appliances are running.

Question 10 Explain why the circuits in homes are mostly parallel circuits. Your answer should refer to the potential difference across each appliance, the rated power of the appliances, and the independent operation of appliances.

Question 11 Two identical lamps are connected to a battery. (a) The lamps are in series. The filament of one lamp breaks, opening the circuit. State and explain what happens to the other lamp. (b) The lamps are in parallel. The filament of one lamp breaks. State and explain what happens to the brightness of the other lamp. (c) State which of the two arrangements matches the wiring of lamps in homes, and give one reason why this arrangement is used there.

Question 12 The two headlights of a car are connected in parallel to the car's $12\,\text{V}$ battery. Each headlight has a resistance of $3.0\,\Omega$ when lit. (a) Calculate the current in each headlight and the current delivered by the battery. (b) Calculate the power transferred to each headlight and the total power. (c) Explain why car headlights are connected in parallel rather than in series.

Question 13 In a living room, a television and a lamp run in parallel on the $230\,\text{V}$ supply. The television is switched off while the lamp stays on. Explain what happens to the lamp, to the total current drawn from the supply, and to the total power transferred, and state what would be different if the television and the lamp were connected in series instead.

Question 14 Two identical $10\,\Omega$ resistors are connected to a $5.0\,\text{V}$ battery, first in series and then in parallel. (a) Calculate the total power transferred in the series arrangement. (b) Calculate the total power transferred in the parallel arrangement. (c) State the ratio of the parallel power to the series power, and explain the difference in terms of the equivalent resistance of each arrangement.

Question 15 A student writes: *"In a parallel circuit, the larger resistor transfers more power, because a larger resistance is a bigger obstacle to the current."* Identify the error in this statement and give the correct comparison, using the quantity that a parallel circuit keeps the same across every branch.

Question 16 A $12\,\Omega$ resistor and a $4.0\,\Omega$ resistor are connected in series with an $8.0\,\text{V}$ battery. (a) Calculate the current in the circuit and the potential difference across each resistor. (b) Calculate the power transferred to each resistor using $P = V\,I$, and check each result using $P = I^2\,R$. (c) Show that the sum of the two powers equals the power delivered by the battery.

Question 17 More appliances are switched on in a home, each one adding a parallel branch to the circuit. Explain what happens to the equivalent resistance of the circuit, to the current drawn from the supply, and to the total power transferred. State what limits the number of appliances that can safely run at once on one circuit.

Question 18 A string of 20 identical miniature lamps is wired in series and labelled $230\,\text{V}$, $24\,\text{W}$. (Strings like this are factory-sealed; in school, only low-voltage versions are ever used.) (a) Calculate the potential difference across each lamp when the string is running at its rated power, and the current in the string. (b) Calculate the power and the resistance of each lamp. (c) One lamp's filament breaks, opening the circuit. State and explain what happens to the other lamps in the string. (d) Use your answer to (c) to state one reason why the lighting circuits in homes are wired in parallel instead.

Answers

Question 1 (a) current; potential difference; (b) potential difference; current; (c) $I^2 R$; $\frac{V^2}{R}$. **Question 2** (a) $24\,\Omega$, 0.50 A; (b) 3.0 V across the $6.0\,\Omega$, 9.0 V across the $18\,\Omega$; (c) 1.5 W and 4.5 W; total 6.0 W; the $18\,\Omega$ resistor. **Question 3** (a) 12 V across each; (b) 2.0 A and 0.67 A; supply 2.7 A; (c) 24 W and 8.0 W; total 32 W; the $6.0\,\Omega$ resistor. **Question 4** One alone: 2.0 A, 32 W. Series: 8.0 V each, 8.0 W each, 16 W. Parallel: 4.0 A, 16 V each, 64 W. **Question 5** (a) toaster 6.5 A, lamp 0.043 A; (b) 6.6 A; (c) 230 V; independently. **Question 6** (a) the power it transfers; (b) resistance increases, current decreases; (c) they become dimmer — see solution. **Question 7** 12 W, 20 W, 16 W; total 48 W. **Question 8** (a) 2.0 A each; 4.0 A; (b) 48 W; (c) 0.24 kW h, $8.6\times10^5\text{ J}$. **Question 9** (a) heater 6.0 kW h, fan 0.24 kW h; (b) 187 c ($\$1.87$); (c) 11 A. **Question 10** See solution. **Question 11** (a) it goes out; (b) unchanged brightness; (c) parallel — see solution. **Question 12** (a) 4.0 A each; 8.0 A; (b) 48 W each; 96 W; (c) see solution. **Question 13** See solution. **Question 14** (a) 1.3 W; (b) 5.0 W; (c) 4.0 — see solution for the explanation. **Question 15** See solution. **Question 16** (a) 0.50 A; 6.0 V and 2.0 V; (b) 3.0 W and 1.0 W; (c) 4.0 W. **Question 17** See solution. **Question 18** (a) 11.5 V; 0.10 A; (b) 1.2 W, $110\,\Omega$; (c) all go out; (d) see solution.

Fully-worked solutions

Question 1 (a) In a series circuit, the **current** is the same through every component, while the supply **potential difference** is shared between the components. (b) In a parallel circuit, the **potential difference** is the same across every branch, while the supply **current** is shared between the branches. (c) Substituting $V = I\,R$ into $P = V\,I$ gives $P = I\times I\,R = I^2 R$; substituting $I = \frac{V}{R}$ gives $P = V\times\frac{V}{R} = \frac{V^2}{R}$.

Question 2 $V = 12\text{ V}$; $R_1 = 6.0\,\Omega$, $R_2 = 18\,\Omega$, in series. (a) $R_{eq} = R_1 + R_2 = 6.0 + 18 = 24\,\Omega$. $I = \frac{V}{R_{eq}} = \frac{12}{24} = 0.50\text{ A}$. (b) $V_1 = I\,R_1 = 0.50\times6.0 = 3.0\text{ V}$; $V_2 = I\,R_2 = 0.50\times18 = 9.0\text{ V}$. (Check: $3.0 + 9.0 = 12\text{ V}$. ✓) (c) $P_1 = V_1 I = 3.0\times0.50 = 1.5\text{ W}$; $P_2 = V_2 I = 9.0\times0.50 = 4.5\text{ W}$. $P_{total} = 1.5 + 4.5 = 6.0\text{ W}$ (check: $V\,I = 12\times0.50 = 6.0\text{ W}$ ✓). The $18\,\Omega$ resistor transfers more power. In series the current is the same through each resistor, so $P = I^2 R$: the power is proportional to the resistance, and the larger resistance takes the larger share of the supply voltage.

Question 3 The same resistors, $6.0\,\Omega$ and $18\,\Omega$, now in parallel across 12 V. (a) Each resistor has the full supply potential difference, 12 V, across it. (b) $I_1 = \frac{V}{R_1} = \frac{12}{6.0} = 2.0\text{ A}$; $I_2 = \frac{V}{R_2} = \frac{12}{18} = 0.67\text{ A}$. $I_{supply} = 2.0 + 0.67 = 2.7\text{ A}$. (c) $P_1 = V\,I_1 = 12\times2.0 = 24\text{ W}$; $P_2 = V\,I_2 = 12\times0.67 = 8.0\text{ W}$. $P_{total} = 24 + 8.0 = 32\text{ W}$ (check: $V\,I = 12\times2.67 = 32\text{ W}$ ✓). The $6.0\,\Omega$ resistor transfers more power. In parallel the potential difference is the same across each resistor, so $P = \frac{V^2}{R}$: the power is inversely proportional to the resistance, because the same voltage drives a larger current through the smaller resistance.

Question 4 $V = 16\text{ V}$; each resistor $R = 8.0\,\Omega$. One resistor alone: $I = \frac{V}{R} = \frac{16}{8.0} = 2.0\text{ A}$; the power of the resistor is the total power, 32 W (check: $V\,I = 16\times2.0 = 32\text{ W}$ ✓). Two in series: the current is given as 1.0 A (check: $R_{eq} = 16\,\Omega$, so $I = \frac{16}{16} = 1.0\text{ A}$ ✓). Each resistor has $V = I\,R = 1.0\times8.0 = 8.0\text{ V}$ across it, so each transfers $P = V\,I = 8.0\times1.0 = 8.0\text{ W}$, and the total power is $8.0 + 8.0 = 16\text{ W}$. Two in parallel: each has 16 V across it, so the current in each branch is 2.0 A and the supply current is $2.0 + 2.0 = 4.0\text{ A}$. Each transfers 32 W (given), so the total power is $32 + 32 = 64\text{ W}$. The completed table:

Arrangement	Current from the battery	Potential difference across each resistor	Power of each resistor	Total power
One resistor alone	2.0 A	16 V	32 W	32 W
Two in series	1.0 A	8.0 V	8.0 W	16 W
Two in parallel	4.0 A	16 V	32 W	64 W

Question 5 $V = 230\ \text{V}$; $P_{\text{toaster}} = 1.5\ \text{kW} = 1500\ \text{W}$; $P_{\text{lamp}} = 10\ \text{W}$. (a) $I = \frac{P}{V}$: toaster $I = \frac{1500}{230} = 6.5\ \text{A}$; lamp $I = \frac{10}{230} = 0.043\ \text{A}$. (b) The appliances are in parallel, so the supply current is the sum of the branch currents: $I = 6.5 + 0.043 = 6.6\ \text{A}$. (c) The toaster and the lamp are connected in parallel so that each one has the full $230\ \text{V}$ of the supply across it, and each can be switched on and off **independently** of the other.

Question 6 Model answer. (a) The brightness of a lamp is determined by the power it transfers — the rate at which electrical energy is transferred to light and thermal energy. (b) Adding a third identical lamp in series increases the total resistance of the circuit (resistances in series add), so the current in the circuit decreases. (c) The original two lamps become dimmer. The current through them is now smaller, and since $P = I^2 R$ for each lamp (with its resistance unchanged), each transfers less power and glows less brightly.

Question 7 $V = 24\ \text{V}$; $R_1 = 3.0\ \Omega$, $R_2 = 5.0\ \Omega$, $R_3 = 4.0\ \Omega$ in series. $R_{\text{eq}} = 3.0 + 5.0 + 4.0 = 12\ \Omega$, so $I = \frac{24}{12} = 2.0\ \text{A}$, the same through every resistor. Using $P = I^2 R$: $P_1 = 2.0^2 \times 3.0 = 12\ \text{W}$; $P_2 = 2.0^2 \times 5.0 = 20\ \text{W}$; $P_3 = 2.0^2 \times 4.0 = 16\ \text{W}$. Total power: $12 + 20 + 16 = 48\ \text{W}$. Check: $P = V I = 24 \times 2.0 = 48\ \text{W}$. ✓

Question 8 $V = 12\ \text{V}$; each lamp rated $24\ \text{W}$ at $12\ \text{V}$, in parallel. (a) Each lamp has $12\ \text{V}$ across it and operates at its rated power, so $I = \frac{P}{V} = \frac{24}{12} = 2.0\ \text{A}$ in each lamp. The battery supplies $2.0 + 2.0 = 4.0\ \text{A}$. (b) $P_{\text{total}} = 24 + 24 = 48\ \text{W}$ (check: $V I = 12 \times 4.0 = 48\ \text{W}$ ✓). (c) $P = 48\ \text{W} = 0.048\ \text{kW}$; $t = 5.0\ \text{h}$. From $E = P t$ (5C): $E = 0.048 \times 5.0 = 0.24\ \text{kW h}$, and $E = 0.24 \times 3.6 \times 10^6 = 8.6 \times 10^5\ \text{J}$ (to two significant figures).

Question 9 $V = 230\ \text{V}$; heater $2.4\ \text{kW}$ for $2.5\ \text{h}$; fan $40\ \text{W} = 0.040\ \text{kW}$ for $6.0\ \text{h}$; price $30\ \text{c}$ per kW h. (a) From $E = P t$ (5C): heater $E = 2.4 \times 2.5 = 6.0\ \text{kW h}$; fan $E = 0.040 \times 6.0 = 0.24\ \text{kW h}$. (b) Total energy $= 6.0 + 0.24 = 6.24\ \text{kW h}$. cost $= 6.24 \times 30 = 187\ \text{c}$, that is, \$1.87. (c) $I = \frac{P}{V}$ for each appliance: heater $I = \frac{2400}{230} = 10.4\ \text{A}$; fan $I = \frac{40}{230} = 0.17\ \text{A}$. The appliances are in parallel, so the total current is $10.4 + 0.17 = 10.6\ \text{A} = 11\ \text{A}$ (to two significant figures).

Question 10 Model answer. A full-mark answer would include:

- the supply to Australian homes is $230\ \text{V}$, and every appliance is designed to operate at its rated power at this voltage;
- in a parallel circuit, every branch has the full supply potential difference across it, so each appliance has $230\ \text{V}$ across it and operates at its rated power; in series, the supply voltage would be shared between the appliances, so none would receive $230\ \text{V}$ and none would operate as designed;
- in parallel, each appliance is on its own branch with its own switch, so appliances can be switched on and off independently of one another;
- if one appliance fails so that its circuit breaks, only its own branch stops; the other branches keep working. In a series circuit, one break would stop every appliance on the circuit;
- (for example) a heater and a lamp in parallel both run at their rated powers; the same two in series would share $230\ \text{V}$, and the heater would transfer only a tiny fraction of its rated power.

Question 11 Model answer. (a) When one lamp's filament breaks, the circuit becomes open: there is no longer a complete path for the charge, so the current falls to zero everywhere in the series loop. The other lamp transfers no power ($P = I^2 R$ with $I = 0$), so it goes out. (b) In parallel, each lamp is on its own branch across the battery. The potential difference across the other lamp is unchanged — still equal to the battery voltage — so its current and its power ($P = \frac{V^2}{R}$) are unchanged, and its brightness stays the same. Only the current in the broken branch falls to zero. (c) The parallel arrangement matches the wiring of lamps in homes. Reason (any one): each lamp receives the full supply voltage and operates as designed; each lamp can be switched independently; one lamp failing (or being removed) does not affect the others.

Question 12 $V = 12\,\text{V}$; each headlight $R = 3.0\,\Omega$, in parallel. (a) Each headlight has $12\,\text{V}$ across it, so $I = \frac{V}{R} = \frac{12}{3.0} = 4.0\,\text{A}$ in each. The battery supplies $4.0 + 4.0 = 8.0\,\text{A}$. (b) $P = V\,I = 12 \times 4.0 = 48\,\text{W}$ for each headlight; total power $48 + 48 = 96\,\text{W}$ (check: $V\,I = 12 \times 8.0 = 96\,\text{W}$ ✓). (c) Model answer. In parallel, each headlight has the full $12\,\text{V}$ across it, so each operates at its designed power and brightness. If the headlights were in series, they would share the $12\,\text{V}$ ($6.0\,\text{V}$ each, being identical), so each would transfer only a quarter of its designed power and both would be dim. Worse, if one headlight failed and its circuit broke, the current would fall to zero and both would go out at once — a parallel arrangement means one headlight failing leaves the other still lit, which matters for safety.

Question 13 Model answer. The television and the lamp are on separate parallel branches, so switching the television off opens only its branch. The lamp still has the full $230\,\text{V}$ across it, so its current, its power and its brightness are all unchanged. The total current drawn from the supply decreases, because the supply current is the sum of the branch currents and the television's branch no longer draws its share. The total power transferred decreases for the same reason: the supply now transfers power only to the lamp. If the two were in series, switching the television off would break the only path around the circuit, the current would fall to zero, and the lamp would go out as well.

Question 14 $V = 5.0\,\text{V}$; $R = 10\,\Omega$ each. (a) Series: $R_{\text{eq}} = 10 + 10 = 20\,\Omega$. $P = \frac{V^2}{R_{\text{eq}}} = \frac{5.0^2}{20} = 1.25 = 1.3\,\text{W}$ (to two significant figures). (b) Parallel: $\frac{1}{R_{\text{eq}}} = \frac{1}{10} + \frac{1}{10} = \frac{2}{10}$, so $R_{\text{eq}} = 5.0\,\Omega$. $P = \frac{V^2}{R_{\text{eq}}} = \frac{5.0^2}{5.0} = 5.0\,\text{W}$. (c) $\frac{P_{\text{parallel}}}{P_{\text{series}}} = \frac{5.0}{1.25} = 4.0$. Model explanation: the parallel combination has a lower equivalent resistance than the series combination ($5.0\,\Omega$ compared with $20\,\Omega$), so it draws a larger current from the same supply. The power delivered by the supply is $P = V\,I$ with V fixed, so the larger current means the larger power — here, four times as large.

Question 15 Model answer. The error is applying series reasoning to a parallel circuit. In a parallel circuit the potential difference is the same across every branch, so the correct comparison comes from $P = \frac{V^2}{R}$: the power transferred to a branch is *inversely* proportional to its resistance, and the larger resistor transfers *less* power, not more. Equivalently, from $P = V\,I$: the same voltage drives a smaller current through the larger resistance ($I = \frac{V}{R}$), and a smaller current at the same voltage means less power. The "bigger obstacle" idea does describe what happens in *series*, where the same current passes through every component and $P = I^2 R$ makes the larger resistance transfer more power.

Question 16 $V = 8.0\,\text{V}$; $R_1 = 12\,\Omega$, $R_2 = 4.0\,\Omega$ in series. (a) $R_{\text{eq}} = 12 + 4.0 = 16\,\Omega$; $I = \frac{8.0}{16} = 0.50\,\text{A}$. $V_1 = I\,R_1 = 0.50 \times 12 = 6.0\,\text{V}$; $V_2 = I\,R_2 = 0.50 \times 4.0 = 2.0\,\text{V}$. (Check: $6.0 + 2.0 = 8.0\,\text{V}$ ✓.) (b) Using $P = V\,I$: $P_1 = 6.0 \times 0.50 = 3.0\,\text{W}$; $P_2 = 2.0 \times 0.50 = 1.0\,\text{W}$. Check using $P = I^2 R$: $P_1 = 0.50^2 \times 12 = 3.0\,\text{W}$ ✓; $P_2 = 0.50^2 \times 4.0 = 1.0\,\text{W}$ ✓. (c) The sum of the two powers is $3.0 + 1.0 = 4.0\,\text{W}$. The power delivered by the battery is $P = V\,I = 8.0 \times 0.50 = 4.0\,\text{W}$, which is the same. The energy given to the charge by the battery is transferred, all of it, to the two resistors.

Question 17 Model answer. Each appliance added to a home circuit is another branch in parallel. Adding a branch adds another term to $\frac{1}{R_{\text{eq}}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots$, so the equivalent resistance of the circuit decreases. The supply potential difference stays at $230\,\mathrm{V}$, so from $I=\frac{V}{R_{\mathrm{eq}}}$ the current drawn from the supply increases — equivalently, the supply current is the sum of the branch currents, and there is now one more branch drawing its own current. The total power transferred, $P=V\,I$, increases for the same reason. The number of appliances that can safely run at once is limited by the circuit's protective devices — the fuse or circuit breaker in the switchboard, which open the circuit if the current exceeds the safe rating of the wiring; these devices are covered in 6E.

Question 18 20 identical lamps in series; supply $230\,\mathrm{V}$; string rating $24\,\mathrm{W}$. (a) In series the supply potential difference is shared equally between identical lamps, so each lamp has $\frac{230}{20}=11.5\,\mathrm{V}$ across it. The current in the (series) string is the same everywhere; from $P=V\,I$, $I=\frac{P}{V}=\frac{24}{230}=0.10\,\mathrm{A}$. (b) The power of each lamp is one twentieth of the total: $P=\frac{24}{20}=1.2\,\mathrm{W}$. The resistance of each lamp is $R=\frac{V}{I}=\frac{11.5}{0.1043}=110\,\Omega$ (to two significant figures), where $0.1043\,\mathrm{A}$ is the unrounded current. (Check: $P=I^2R=0.1043^2\times 110=1.2\,\mathrm{W}$ ✓.) (c) When one lamp's filament breaks, the circuit becomes open. Because the lamps are in series, there is then no complete path anywhere in the string: the current falls to zero in every lamp, and all of the other lamps go out. (d) Model answer. In a home's parallel lighting circuits, each lamp is on its own branch, so one lamp failing (or being removed) leaves the others lit — the opposite of the series string, where one failure puts every lamp out. (Parallel wiring also gives every lamp the full supply voltage, so each operates at its rated power.)

Chapter 6 Using electricity safely — 6B Household electrical systems as DC circuit models

Theory

In Chapter 5 you built the toolkit for analysing DC circuits: charge, current, potential difference, energy and power (5A), the behaviour of meters (5C), and resistance in series and parallel circuits (5D–5F). In 6A you compared power transfers in series and parallel circuits and saw why the circuits in homes are mostly parallel circuits. This subtopic puts those ideas to work on the largest circuit you use every day: the electrical system of a home. The wiring inside the walls cannot be seen, so a model is the tool that lets you analyse it. By the end you will be able to represent a household electrical system as a simple DC circuit containing fuses, switches, circuit breakers, loads and earth, and to calculate the currents that flow in it.

The supply is AC — the model is DC. The electricity delivered to Australian homes is an **alternating current** (AC) supply: the charges in the wires do not drift steadily one way, but oscillate back and forth 50 times each second. The **frequency** of the supply is therefore $50\,\text{Hz}$. The quoted potential difference of the supply is $230\,\text{V}$. A **direct current** (DC) supply, such as a battery, pushes charge steadily in one direction at a constant potential difference.

Every relationship you have used so far — $I = Q / t$, $V = E / Q$, $P = E / t = V\,I$ and $I = V / R$ — was built for DC circuits. To use them on a household system, the AC supply is replaced in the model by a $230\,\text{V}$ DC supply, and the whole system is drawn and analysed as an ordinary DC circuit. Modelling a complicated real system with a simpler one you can calculate with is a standard move in physics: the model keeps the features that matter for the question (the supply voltage, the connections, and the loads) and sets aside the features that do not (the back-and-forth motion of the charge).

The model has limits, and you should be able to state them. In the real supply the potential difference and the current are continually changing in size and direction, while the model uses a fixed $230\,\text{V}$ and a steady one-way current. Any conclusion that depends on the direction of the current, or on the voltage changing with time, is outside what this model can tell you. For calculating the current drawn by an appliance, the power it transfers and the energy it uses, the DC model is accurate and is the one used in this course.

From the street to the power point. Electrical energy reaches a home through cables from the electricity network and enters the **switchboard** (the panel, sometimes called the fuse box, where the home's circuits begin). From the switchboard, separate **circuits** run to different parts of the home — for example, one circuit for the lights, one for the power points in the living areas, and one for the kitchen. Every circuit is connected across the same supply, and within each circuit the appliances are connected in parallel, as 6A described.

Each circuit passes through protective devices in the switchboard. Older homes use **fuses**; most modern switchboards use **circuit breakers**, and switchboards also contain a **main switch** that can disconnect the whole home at once. The switchboard of a real home also contains **residual current devices** (RCDs, often called safety switches); the way these devices operate and compare with each other is treated in full in 6E.

The three wires: active, neutral and earth. Three conductors run from the switchboard to each appliance.

- The **active** wire is the wire that carries charge from the supply to the appliance. In the DC model it is the wire leaving the positive terminal of the supply.
- The **neutral** wire is the return wire, carrying charge from the appliance back to the supply. In the DC model it is the wire returning to the negative terminal.
- The **earth** wire is a safety conductor. It does not carry charge during normal operation: in a correctly working circuit the current in the earth wire is zero. One end of the earth wire is connected to the ground at the switchboard, and the other end is connected to any exposed metal parts of an appliance, such as the metal case of a washing machine or the body of a toaster.

The DC model of a household circuit. A single household circuit, modelled as a DC circuit, contains the following elements.

Household item	In the DC model	Role
Electricity supply (230 V AC, 50 Hz)	a 230 V DC supply	transfers energy to the charge
Active and neutral wires	connecting wires (outward and return paths)	carry charge to and from the loads
Main switch	a switch in series in the active wire	connects or disconnects the whole circuit
Fuse or circuit breaker	an automatic switch in series in the active wire	opens the circuit when the current becomes too large
Wall or appliance switch	a switch in series with one load	connects or disconnects that appliance
Appliances (the **loads**)	resistances in parallel	transfer energy from the charge to the surroundings
Earth wire	a conductor from metal cases to ground, outside the working circuit	safety path for a fault current; normally carries no current

A **load** is any part of a circuit that transfers energy from the charge to the surroundings — in a home, the appliances. Every load is connected in parallel across the supply, so every appliance receives the full 230 V and can be switched on and off independently (the full discussion of why homes are wired this way is in 6A).

Notice the pattern in the table: every control and protective device — the main switch, the fuse or circuit breaker, and each appliance switch — sits **in series in the active wire**, while all the loads sit **in parallel** across the supply. This placement is deliberate. A device in series carries the full current of the circuit, so a fuse or circuit breaker in the active wire senses the whole current and can open the whole circuit. Opening the active wire also disconnects the appliances from the supply side of the circuit; a switch placed in the neutral wire instead would stop an appliance working but would leave it connected to the supply.

Currents in a household circuit. An appliance's label states its power rating, as 5C described. Since every appliance receives 230 V, the current it draws follows from $P = V I$ rearranged as

$$I = \frac{P}{V}.$$

A 2300 W heater, for example, draws $I = 2300 / 230 = 10$ A. Because the loads are in parallel, the current from the supply is the sum of the currents in the individual appliances: adding appliances adds currents.

Each circuit's fuse or circuit breaker has a **rated current**: the current above which it opens the circuit. A fuse is a short piece of thin wire that melts when the current exceeds its rating; a circuit breaker is a switch that opens automatically when the current exceeds its rating. (The detailed comparison of these devices, and of RCDs, is in 6E.) If the total current drawn by the appliances on one circuit exceeds the rating, the fuse melts or the breaker opens and the circuit is disconnected. This is called an **overload**. For example, a 2300 W heater (10 A) and a 1150 W jug (5.0 A) on the same 10 A circuit draw 15 A in total, so the protective device opens the circuit. The remedy is to move one of the appliances to a different circuit.

Faults: short circuits and earth faults. A **short circuit** occurs when the active wire comes into contact with the neutral wire through a path of almost zero resistance — for example, when a damaged cord lets the two wires touch inside a plug. With almost no resistance in the loop, $I = V / R$ gives a very large current, which heats the wires and can start a fire. The fuse or circuit breaker responds by opening the circuit almost immediately, which is exactly the job it is there to do.

An **earth fault** occurs when the active wire comes loose inside an appliance and touches its metal case. Because the case is connected to the earth wire, the fault provides a low-resistance path from the active wire to ground: a large current flows through the earth wire, the fuse melts or the breaker opens, and the appliance is disconnected from the supply. All of this happens before anyone touches the case, so the earth wire has done its job. Without an earth connection, the case would remain **live** — connected to the supply — and the first person to touch it could provide the path for the current to ground, receiving an electric shock (the effects of current on the body are treated in 6E). This is why appliances with metal cases have an earth connection, and why an earth wire, even though it normally carries no current, is a required part of the model.

Practical note. The household supply is dangerous, and the modelling in this subtopic is done on paper and with low-voltage DC circuits in class — batteries or a lab power pack. A class circuit with a $6.0\ \text{V}$ battery and lamps standing in for the appliances behaves as the model predicts, without any of the danger. This matches the study design's rule that students are not permitted to carry out electrical work on the internal components of electrical products or equipment that operates above $50\ \text{V}$ AC or $120\ \text{V}$ ripple-free DC. In Victoria, under the *Electricity Safety Act 1998* (Vic.), only a person who holds an appropriate current electrical licence may carry out electrical work above these voltages. Household wiring is installed according to the Wiring Rules, AS/NZS 3000, and appliances must meet the requirements of AS/NZS 3100. In practice this means: never open a switchboard or a meter box, never open an appliance, and never use an appliance with a damaged cord — report it instead.

Units 3 & 4 preview. The household model built here reappears in Units 3 & 4, where the generation, transmission and household consumption of electricity are analysed quantitatively and the supply is treated as the AC system it really is. Fluency with $I = P / V$, with parallel currents adding, and with the roles of the active, neutral and earth wires, built here, is assumed at that point. This preview is not assessed in Units 1 & 2.

Worked examples

Example 1 — scaffolded

A kitchen circuit is modelled as a $230\ \text{V}$ DC supply with a circuit breaker and a switch in series in the active wire, and two loads in parallel: a $1150\ \text{W}$ jug and a $230\ \text{W}$ blender. (a) Calculate the current in each appliance. (b) Calculate the total current drawn from the supply when both appliances are on. (c) State the potential difference across each appliance.

Working	Comment
Use $I = P / V$ with $V = 230\ \text{V}$ for each load.	The loads are in parallel, so each receives the full supply voltage.
(a) Jug: $I = 1150 / 230 = 5.0\ \text{A}$.	Power rating divided by supply voltage.
Blender: $I = 230 / 230 = 1.0\ \text{A}$.	Same relationship, smaller power, smaller current.
(b) $I_{\text{total}} = 5.0 + 1.0 = 6.0\ \text{A}$.	In a parallel circuit the supply current is the sum of the currents in the branches.
(c) Each appliance has $230\ \text{V}$ across it.	Parallel loads are connected directly across the supply.

The circuit breaker must be rated above $6.0\ \text{A}$ for both appliances to run together.

Example 2 — scaffolded

A living-room circuit is protected by a $10\ \text{A}$ fuse. A student plugs in a $2300\ \text{W}$ heater and a $230\ \text{W}$ television, both modelled as loads in parallel across the $230\ \text{V}$ supply. (a) Calculate the current drawn by each appliance. (b) Calculate the total current. (c) State what happens, and justify your answer.

Working	Comment
(a) Heater: $I = 2300 / 230 = 10\ \text{A}$.	$I = P / V$ for each parallel load.
Television: $I = 230 / 230 = 1.0\ \text{A}$.	Same relationship.
(b) $I_{\text{total}} = 10 + 1.0 = 11\ \text{A}$.	Parallel currents add.
(c) $11\ \text{A} > 10\ \text{A}$, so the fuse melts and the circuit is disconnected.	The fuse opens the circuit when the current exceeds its rated current. This is an overload.

The heater alone already uses the fuse's full rating, so nothing else can run on that circuit at the same time.

Example 3 — unscaffolded

An electric heater connected to a $230\,\text{V}$ supply draws a current of $8.0\,\text{A}$. (a) Calculate the power of the heater. (b) Calculate the resistance of the heater. (c) Calculate the energy the heater transfers in $2.0\,\text{h}$, in kW h and in joules.

The power follows from $P = V\,I$:

$$P = 230 \times 8.0 = 1840\,\text{W} = 1.84\,\text{kW}.$$

The resistance follows from $I = V\,/\,R$ rearranged as $R = V\,/\,I$:

$$R = \frac{230}{8.0} = 29\,\Omega\,(\text{to two significant figures}).$$

For the energy, use $E = P\,t$ with the power in kW and the time in h (5C):

$$E = 1.84 \times 2.0 = 3.7\,\text{kW h}.$$

Converting to joules using $1\,\text{kW h} = 3.6 \times 10^6\,\text{J}$:

$$E = 3.68 \times 3.6 \times 10^6 = 1.3 \times 10^7\,\text{J}.$$

∴ the heater is rated at $1.8\,\text{kW}$ (to two significant figures), has a resistance of $29\,\Omega$, and transfers $3.7\,\text{kW h}$ ($1.3 \times 10^7\,\text{J}$) in $2.0\,\text{h}$.

Example 4 — unscaffolded

Inside a metal-cased toaster, the active wire comes loose and touches the case. The case is connected to the earth wire, and the circuit is protected by a fuse. Using the DC circuit model, explain what happens when the wire touches the case, and why a person who then touches the case is protected. State what would be different if the case had no earth connection.

When the active wire touches the case, the supply is connected to the case, and the earth wire provides a low-resistance path from the case to ground. In the model this is a loop containing the supply and almost no resistance, so by $I = V\,/\,R$ the current becomes very large — a short circuit through the earth wire. The large current exceeds the fuse's rated current, the fuse melts, and the circuit is opened, disconnecting the toaster from the supply.

A person who touches the case after this is protected because the fuse has already opened the circuit: the case is no longer connected to the supply, so there is no potential difference between the case and the ground to drive a current through the person. Even in the brief moment before the fuse melts, most of the fault current takes the earth wire, because its resistance is far lower than the resistance of a person.

If the case had no earth connection, the loose wire would make the case live but no large fault current would flow, so the fuse would not melt. The case would remain connected to the supply, and the first person to touch it could provide the path to ground, receiving an electric shock (the effects of current on the body, and the current levels at which it becomes dangerous, are treated in 6E).

Practice questions

Question 1 The electricity supply to Australian homes is an AC supply. (a) State what AC and DC stand for. (b) State one difference between the charge flow in an AC supply and in a DC supply. (c) State the quoted potential difference and the frequency of the Australian household supply. (d) Explain why household systems are still modelled as DC circuits in this course.

Question 2 Copy and complete the table below, giving the DC circuit model element that represents each part of a household circuit.

Household item	Element in the DC model
(a) electricity supply	…

Household item	Element in the DC model
(b) fuse or circuit breaker	…
(c) wall switch for a light	…
(d) the appliances	…
(e) earth wire	…

Question 3 A television is labelled $460\,\mathrm{W}$ and is connected to the $230\,\mathrm{V}$ household supply. (a) Write the relationship between power, potential difference and current. (b) Calculate the current drawn by the television. (c) Calculate the resistance of the television. (d) Calculate the energy the television uses in $5.0\,\mathrm{h}$, in kW h.

Question 4 A $2300\,\mathrm{W}$ heater and a $115\,\mathrm{W}$ fan are both connected to one $230\,\mathrm{V}$ household circuit, in parallel. (a) Calculate the current drawn by each appliance. (b) Calculate the total current drawn from the supply. (c) State the potential difference across each appliance. (d) State what happens to the other appliance when one of them is switched off, and explain why.

Question 5 A circuit is protected by an $8.0\,\mathrm{A}$ fuse. The appliances running on the circuit draw a combined power of $1610\,\mathrm{W}$ from the $230\,\mathrm{V}$ supply. (a) Calculate the total current in the circuit. (b) State whether the fuse melts, and justify your answer. (c) Describe what a fuse does when the current exceeds its rated current.

Question 6 The earth wire is one of the three conductors that run to a household appliance. (a) State the part of an appliance that the earth wire is connected to. (b) State the current in the earth wire when the appliance is working correctly. (c) Describe what the earth wire does if the active wire comes loose and touches the case.

Question 7 A kettle is labelled $2000\,\mathrm{W}$ and is connected to the $230\,\mathrm{V}$ supply. Calculate (a) the current drawn by the kettle and (b) the resistance of the kettle.

Question 8 A power-point circuit is protected by a $16\,\mathrm{A}$ circuit breaker. A $1500\,\mathrm{W}$ frypan, a $2000\,\mathrm{W}$ kettle and an $800\,\mathrm{W}$ rice cooker are all running at once on this circuit, in parallel across the $230\,\mathrm{V}$ supply. Calculate the total current and state what happens, justifying your answer.

Question 9 A lighting circuit contains eight $10\,\mathrm{W}$ LED lamps in parallel, connected to the $230\,\mathrm{V}$ supply. (a) Calculate the total power drawn by the lamps. (b) Calculate the total current drawn from the supply. (c) Calculate the energy used by the lamps in $4.0\,\mathrm{h}$, in kW h. (d) Calculate the cost of this energy at $30\,\mathrm{c}$ per kW h.

Question 10 An appliance draws a current of $3.0\,\mathrm{A}$ from the $230\,\mathrm{V}$ supply. (a) Calculate the power of the appliance. (b) Calculate the energy the appliance uses in $4.0\,\mathrm{h}$, in kW h. (c) Convert this energy to joules.

Question 11 A $2300\,\mathrm{W}$ heater is running on a circuit protected by a $10\,\mathrm{A}$ fuse. A student wants to plug a $230\,\mathrm{W}$ television into the same circuit. Calculate the total current that would flow if both appliances run together, and state whether the circuit can run both, justifying your answer.

Question 12 In the household DC model, the fuse or circuit breaker is placed in series in the active wire, not in parallel with the loads. Explain why the series connection is necessary for the device to do its job.

Question 13 In the household DC model, every appliance is connected in parallel across the supply. State two features of this arrangement and explain how each one follows from the parallel connection. (The full argument for why homes are wired in parallel is in 6A.)

Question 14 The insulation of a cord is damaged and the active wire touches the neutral wire inside a plug. Using the DC circuit model, explain why the current becomes very large, and state what happens next.

Question 15 The earth wire carries no current when an appliance is working correctly. Explain why it is nevertheless a required part of a household circuit, making reference to a fault in which the active wire touches a metal case.

Question 16 The DC model of a household circuit keeps the supply voltage, the connections and the loads, and sets aside everything about the supply being AC. State two features of the real $230\,\mathrm{V}$, $50\,\mathrm{Hz}$ AC supply that the DC model does not represent.

Question 17 A student suggests testing the household DC model by wiring a real lamp into a real power point in the classroom. Explain why this is not permitted, making reference to the study design's rule for student electrical work and to who is legally allowed to carry out electrical work in Victoria.

Question 18 A fuse in a household circuit keeps melting, and a resident suggests replacing it with a fuse of much higher rated current so that it stops melting. Explain, using the model of the circuit, why this would be dangerous.

Answers

Question 1 (a) alternating current; direct current; (b) in AC the charge oscillates back and forth, in DC it flows steadily one way; (c) 230 V, 50 Hz; (d) the DC relationships apply directly, and the supply voltage, connections and loads are what matter for current, power and energy calculations. **Question 2** (a) a 230 V DC supply; (b) an automatic switch in series in the active wire; (c) a switch in series with the load; (d) resistances (loads) in parallel; (e) a conductor from metal cases to ground, outside the working circuit. **Question 3** (a) $P = V\,I$; (b) 2.0 A; (c) 115 Ω; (d) 2.3 kW h. **Question 4** (a) heater 10 A, fan 0.50 A; (b) 10.5 A; (c) 230 V across each; (d) the other appliance keeps working — parallel branches are independent. **Question 5** (a) 7.0 A; (b) no — 7.0 A is below the 8.0 A rating; (c) it melts and opens the circuit. **Question 6** (a) the exposed metal parts (the case); (b) zero; (c) it provides a low-resistance path to ground, so a large fault current flows and the fuse melts or the breaker opens. **Question 7** (a) 8.7 A; (b) 26 Ω. **Question 8** 19 A; this exceeds the 16 A rating, so the circuit breaker opens the circuit. **Question 9** (a) 80 W; (b) 0.35 A; (c) 0.32 kW h; (d) 9.6 c. **Question 10** (a) 690 W; (b) 2.8 kW h; (c) 9.9×10^6 J. **Question 11** 11 A; no — 11 A exceeds the 10 A fuse rating, so the fuse would melt. **Question 12** In series it carries the full circuit current and can open the whole circuit; in parallel it would not carry the loads' current. **Question 13** Every appliance receives the full 230 V, and each appliance can be switched independently of the others — both follow from each load being connected directly across the supply. **Question 14** The loop has almost zero resistance, so $I = V / R$ gives a very large current; the fuse melts or the breaker opens the circuit. **Question 15** On a fault it provides a low-resistance path so a large current flows and the protective device opens the circuit before anyone touches the live case. **Question 16** Any two of: the charge oscillates rather than flowing one way; the supply frequency is 50 Hz, meaning the charge oscillates back and forth 50 times each second; the real voltage changes with time rather than staying fixed. **Question 17** The supply is 230 V AC, above the study design's 50 V AC limit for student electrical work; only a licensed electrician may carry out electrical work in Victoria. **Question 18** The fuse protects the wiring; a larger fuse would allow currents large enough to overheat the wires without melting, creating a fire risk.

Fully-worked solutions

Question 1 (a) AC stands for alternating current and DC stands for direct current. (b) In an AC supply the charges oscillate back and forth, reversing direction repeatedly; in a DC supply the charges flow steadily in one direction. (c) The Australian household supply has a quoted potential difference of 230 V and a frequency of 50 Hz. (d) The circuit relationships used in this course ($I = Q / t$, $V = E / Q$, $P = V\,I$, $I = V / R$) are DC relationships. Modelling the household supply as a 230 V DC supply keeps the features that matter for calculating currents, powers and energies — the supply voltage, the connections and the loads — and sets aside the back-and-forth motion of the charge, which does not affect those calculations.

Question 2 (a) The electricity supply is modelled as a 230 V DC supply. (b) A fuse or circuit breaker is modelled as an automatic switch in series in the active wire: it opens the circuit when the current exceeds its rated current. (c) A wall switch is modelled as a switch in series with the load it controls. (d) The appliances are modelled as resistances (the loads) connected in parallel across the supply. (e) The earth wire is modelled as a conductor connecting metal cases to ground, outside the working circuit: it carries no current in normal operation.

Question 3 (a) $P = V\,I$. (b) $I = P / V = 460 / 230 = 2.0\text{ A}$. (c) $R = V / I = 230 / 2.0 = 115\ \Omega$. (d) $P = 460\text{ W} = 0.46\text{ kW}$, so $E = P\,t = 0.46 \times 5.0 = 2.3\text{ kW h}$.

Question 4 (a) Heater: $I = 2300 / 230 = 10\text{ A}$. Fan: $I = 115 / 230 = 0.50\text{ A}$. (b) The loads are in parallel, so the supply current is the sum of the branch currents: $I_{\text{total}} = 10 + 0.50 = 10.5\text{ A}$. (c) Each appliance is connected directly across the supply, so each has 230 V across it. (d) When one appliance is switched off, the other keeps working as before. Parallel branches are independent: switching one branch off does not change the potential difference across the other, so its current is unchanged.

Question 5 (a) $I = P / V = 1610 / 230 = 7.0\text{ A}$. (b) The fuse does not melt: 7.0 A is below its 8.0 A rated current, so the circuit stays connected. (c) When the current exceeds its rated current, the thin wire inside the fuse heats until it melts, breaking the circuit and disconnecting the supply from the loads.

Question 6 (a) The earth wire is connected to the exposed metal parts of the appliance, such as a metal case. (b) When the appliance is working correctly the current in the earth wire is zero. (c) If the active wire touches the case, the earth wire provides a low-resistance path from the case to ground. A large fault current flows, the fuse melts or the circuit breaker opens, and the appliance is disconnected from the supply before anyone touching the case can be harmed.

Question 7 (a) $I = P / V = 2000 / 230 = 8.7\ \text{A}$. (b) $R = V / I = 230 / 8.696 = 26\ \Omega$ (to two significant figures). Equivalently, $R = V^2 / P = 230^2 / 2000 = 26\ \Omega$.

Question 8 Total power: $P = 1500 + 2000 + 800 = 4300\ \text{W}$. The total current is

$$I = \frac{P}{V} = \frac{4300}{230} = 19\ \text{A}\left(\text{to two significant figures}\right).$$

This is an overload: $19\ \text{A}$ exceeds the circuit breaker's $16\ \text{A}$ rated current, so the breaker opens the circuit. The three appliances cannot all run on this circuit at once; one of them must be moved to a different circuit.

Question 9 (a) $P = 8 \times 10 = 80\ \text{W}$. (b) $I = P / V = 80 / 230 = 0.35\ \text{A}$. (c) $P = 0.080\ \text{kW}$, so $E = P\,t = 0.080 \times 4.0 = 0.32\ \text{kW h}$. (d) $\text{cost} = 0.32 \times 30 = 9.6\ \text{c}$.

Question 10 (a) $P = V\,I = 230 \times 3.0 = 690\ \text{W}$. (b) $P = 0.69\ \text{kW}$, so $E = P\,t = 0.69 \times 4.0 = 2.76\ \text{kW h} = 2.8\ \text{kW h}$ (to two significant figures). (c) $E = 2.76 \times 3.6 \times 10^6 = 9.9 \times 10^6\ \text{J}$ (to two significant figures).

Question 11 Heater: $I = 2300 / 230 = 10\ \text{A}$. Television: $I = 230 / 230 = 1.0\ \text{A}$. Together the appliances would draw $10 + 1.0 = 11\ \text{A}$. The circuit cannot run both: $11\ \text{A}$ exceeds the fuse's $10\ \text{A}$ rated current, so the fuse would melt and disconnect the circuit. The heater alone already uses the fuse's full rating.

Question 12 Model answer. The fuse or circuit breaker must be in series in the active wire because a series element carries the full current of the circuit: every coulomb that flows to the loads passes through it, so it senses the total current and opens the whole circuit when that current becomes too large. Placed in parallel with the loads, the device would carry only its own branch current, not the loads' current, and opening it would not disconnect the loads from the supply. The active wire is chosen rather than the neutral because opening the active disconnects the appliances from the supply side of the circuit.

Question 13 Model answer. Two features (others are possible): (1) Every appliance receives the full $230\ \text{V}$. This follows from the parallel connection because each load is connected directly across the two supply wires, so each appliance operates at its rated power. (2) Each appliance can be switched on and off independently. This follows from the parallel connection because each appliance is in its own branch: switching one branch off does not break the path to any other, so the currents in the remaining branches are unchanged. (The full comparison of power transfers in series and parallel, and the complete argument for why homes are wired in parallel, is in 6A.)

Question 14 Model answer. When the active wire touches the neutral wire, the loop from the supply contains almost no resistance — only the resistance of the wires themselves. By $I = V / R$, with $V = 230\ \text{V}$ and R almost zero, the current becomes very large. This is a short circuit. The large current heats the wires, and the fuse melts or the circuit breaker opens the circuit almost immediately, disconnecting the supply before the wiring overheats.

Question 15 Model answer. The earth wire is required because it is the safety path for a fault current. If the active wire comes loose inside an appliance and touches its metal case, the case becomes live. Because the case is connected to the earth wire, which is connected to ground, the fault provides a low-resistance path: a large current flows from the active wire through the case and the earth wire to ground. This large current exceeds the rated current of the fuse or circuit breaker, which opens the circuit and disconnects the appliance. Without the earth wire, no large fault current would flow, the protective device would not open, and the case would stay live until a person touched it and provided the path to ground themselves, receiving an electric shock.

Question 16 Model answer. Any two of: (1) In the real supply the charges oscillate back and forth 50 times each second, while in the model the current flows steadily in one direction. (2) The real potential difference is continually changing with time, while the model uses a fixed $230\ \text{V}$. (3) Conclusions that depend on the direction of the current cannot be drawn from the model, because the model's current has a fixed direction that the real current does not have.

Question 17 Model answer. The household supply is $230\ \text{V}$ AC, which is far above the study design's limit for student electrical work: students are not permitted to carry out electrical work on the internal components of electrical products or equipment that operates above $50\ \text{V}$ AC or $120\ \text{V}$ ripple-free DC. In Victoria, under the *Electricity Safety Act 1998* (Vic.), only a person who holds an appropriate current electrical licence may carry out electrical work at these voltages. The model is therefore tested in class with low-voltage DC circuits — batteries or a lab power pack — never with the household supply.

Question 18 Model answer. The fuse is matched to the circuit it protects: its rated current is chosen so that it melts before the current becomes large enough to overheat the circuit's wiring. If a fuse keeps melting, the circuit is drawing more current than it was designed for — the model shows the total current is the sum of the parallel loads' currents, and that sum is too large for the circuit. Replacing the fuse with one of much higher rated current removes the protection: currents large enough to overheat the wires, melt their insulation and start a fire could now flow without the fuse melting. The correct response to a fuse that keeps melting is to move appliances to other circuits, or to have the circuit assessed by a licensed electrician.

Theory

In 5D you modelled resistance and met **ohmic** devices: components whose resistance stays constant, so that the current through them is proportional to the potential difference across them and their current–potential difference (I–V) graph is a straight line through the origin. Electronic circuits are built from components that do *not* behave like that — components whose resistance changes with temperature, with light, with the direction of connection, or with the setting of a control. This subtopic introduces those components — the filament lamp, the diode, the light-emitting diode (LED), the thermistor, the light-dependent resistor (LDR) and the potentiometer — and the idea that links many of them: the **transducer**, a device that converts one form of energy into another. Consistent with the study design, quantitative analysis here is restricted to the two relationships $I = V / R$ and $P = V I$.

Ohmic and non-ohmic — recap. A component is **non-ohmic** when its resistance is not constant. Its I–V graph is not a straight line through the origin: it may curve, or it may carry current in one direction only. A non-ohmic component still has a resistance at any one operating point — that is, at any one pair of potential difference and current values — and that resistance is still the ratio

$$R = \frac{V}{I}.$$

The difference from an ohmic device is that the ratio gives a *different* value at different points on the graph. When you are asked for the resistance of a non-ohmic component, always state the potential difference and current at which that resistance applies.

The filament lamp. A filament lamp — the traditional wire-filament light bulb — contains a thin coil of wire, the **filament**, which glows white-hot when a current passes through it. The lamp is non-ohmic. As the current increases, the filament gets hotter, and the resistance of a metal wire increases as its temperature increases: the heating makes the atoms of the metal vibrate more, so the moving electrons collide with them more often and the current is opposed more strongly. On an I–V graph, the lamp's curve bends away from the current axis as the potential difference rises: the current still increases, but less than in proportion, because the resistance is increasing at the same time.

One everyday consequence follows from this. When a lamp is first switched on, the filament is cold and its resistance is at its lowest, so the first surge of current is larger than the steady current once the filament is hot. Filament lamps tend to fail at the moment of switching on, when this surge is greatest.

The diode. A **diode** is a component that allows current in one direction only. It is made from a **semiconductor** — a material, usually silicon, whose electrical properties are between those of a conductor and an insulator. The two ways of connecting a diode have names. When it is connected so that current can pass, it is **forward-biased**; when it is connected the other way round, so that current cannot pass, it is **reverse-biased**.

A forward-biased silicon diode does not conduct immediately. It needs a minimum potential difference across it, called the **threshold voltage**, which is about $0.6\ \text{V}$ for a silicon diode. Above the threshold the current increases steeply and the diode's resistance becomes small, so while it is conducting, the voltage drop across a silicon diode stays close to $0.6\ \text{V}$ over a wide range of currents. A reverse-biased diode carries no current — in this course the reverse current is taken to be zero — so it behaves like an open switch.

In circuit diagrams a diode is drawn as a triangle pointing at a bar; the triangle shows the one direction in which (conventional) current can pass. The diode is strongly non-ohmic: its resistance depends on the direction of connection and on the potential difference across it, and its I–V graph runs along zero current until the threshold voltage is reached, then rises steeply. Diodes are used to protect circuits against reversed connections and to change alternating current into direct current; the second use is developed in 12E (Option 2.12).

The light-emitting diode (LED). An **LED** is a diode that emits light when it is forward-biased and conducting. Like any diode, it conducts in one direction only and has a threshold voltage; for the red LEDs commonly used in school laboratories this is about $2.0\ \text{V}$, and LEDs of other colours have different thresholds. Once conducting, an LED keeps roughly its threshold voltage across it while the current is set by the rest of the circuit. LEDs are designed to operate at small currents, typically $10-20\,\mathrm{mA}$ ($1\,\mathrm{mA}=10^{-3}\,\mathrm{A}$); at larger currents they overheat and are destroyed, so an LED circuit always includes a resistor in series with the LED to limit the current. The method for choosing that resistor is shown in the worked examples below.

Like a diode, an LED must be connected the right way round: the longer lead connects toward the positive side of the supply. An LED converts electrical energy into light, with some thermal energy as well; energy transfers and transformations in common devices are treated in 6D. In circuit diagrams an LED is drawn as a diode symbol with two small arrows pointing away from it, representing the emitted light.

The thermistor. A **thermistor** is a resistor whose resistance depends on temperature. The thermistors used in this course have a **negative temperature coefficient (NTC)**: their resistance decreases as their temperature increases. (PTC thermistors, whose resistance increases with temperature, also exist but are not used here.) The change is large: a common NTC thermistor has a resistance of the order of $10\,\mathrm{k}\,\Omega$ at room temperature ($25\,°\mathrm{C}$), falling to a few hundred ohms at the temperature of boiling water. That makes the thermistor useful as a temperature sensor, for example in a car's outside-temperature display or in a thermostat. In circuit diagrams a thermistor is drawn as a resistor with a small t marking to show that temperature affects it.

The light-dependent resistor (LDR). An **LDR** is a resistor whose resistance depends on the intensity of the light falling on it. Its resistance decreases as the light intensity increases: a typical school-laboratory LDR has a resistance of the order of $1\,\mathrm{M}\,\Omega$ in darkness, falling to a few hundred ohms in bright light. LDRs are used as light sensors, for example in circuits that switch outdoor lighting on at dusk. In circuit diagrams an LDR is drawn as a resistor inside a circle, with two arrows pointing in to represent the incoming light.

The potentiometer. A **potentiometer** is a resistor whose value can be adjusted by turning a spindle or sliding a control. It has three terminals: the two ends of a resistive track, and a third connection to a moving contact called the **wiper**. Turning the spindle moves the wiper along the track. Between the wiper and one end of the track, the resistance rises smoothly from zero to the full value of the track as the spindle is turned one way, and falls again as it is turned back.

Two uses follow. Connected with two terminals — the wiper and one end — the potentiometer is a **variable resistor**, used to adjust the current in a circuit. Connected with all three terminals, it is an adjustable **voltage divider**; the analysis of voltage dividers is treated in 5F. Everyday examples include the volume control of an audio system and the dimming control of an instrument panel. At any fixed wiper position, the track between two fixed points is ohmic: its resistance is constant. In circuit diagrams a potentiometer is drawn as a resistor with a third lead, ending in an arrow, touching the track.

The components are summarised below.

Component	What it does	Resistance behaviour	Ohmic?
Fixed resistor	limits the current; provides a voltage drop	constant	yes
Filament lamp	glows when its filament is hot	increases as the current heats the filament	no
Diode	passes current in one direction only	very high when reverse-biased; small when forward-biased above about $0.6\,\mathrm{V}$	no
LED	emits light when conducting	as for a diode; conducts above its threshold voltage	no
Thermistor (NTC)	senses temperature	decreases as temperature increases	no
LDR	senses light intensity	decreases as light intensity increases	no
Potentiometer	adjustable resistor or adjustable voltage divider	set by the wiper position; constant at a fixed setting	ohmic at a fixed setting

Transducers. A **transducer** is a device that converts one form of energy into another. Some of the components above are transducers, and they come in two kinds. An **input transducer** (or sensor) converts a non-electrical quantity into an electrical signal; an **output transducer** converts electrical energy into another form.

Transducer	Conversion	Kind
Thermistor	temperature into a change of resistance	input (sensor)
LDR	light intensity into a change of resistance	input (sensor)
Potentiometer	position into a change of resistance	input (control)
LED	electrical energy into light	output

A diode on its own is not treated as a transducer: its role is to control the direction of the current, not to convert energy from one form into another. Every component transforms some energy when a current passes through it — that is the subject of 6D — but the word *transducer* is reserved for components whose purpose is that conversion.

Working quantitatively with these components. Two ideas are used throughout. First, in a series circuit the potential differences (voltage drops) across the components add to the supply potential difference, as in 5A and 5D. Second, for a non-ohmic component the resistance is found at the operating point: take the potential difference and current at that point and use $R = V / I$. The only relationships needed are $I = V / R$ and $P = V I$.

The most common design task is choosing the series resistor for an LED. Given the supply potential difference V_{s}, the voltage drop V_{LED} across the conducting LED (about its threshold voltage) and the desired current I:

1. The resistor must drop what is left: $V_{\mathrm{R}} = V_{\mathrm{s}} - V_{\mathrm{LED}}$.
2. The resistor sets the current, since the same current passes through both components in series: $R = V_{\mathrm{R}} / I$.
3. Check the power transferred by the resistor, $P = V_{\mathrm{R}} I$. A typical small resistor is rated at about $0.25\ \mathrm{W}$, so the calculated power must be below this.

Practical investigation — I–V graphs for non-ohmic devices. The operation of simple circuits containing resistors, variable resistors, diodes and other non-ohmic devices is investigated by measuring I–V graphs. A suitable framework:

- **Aim.** Obtain and compare the I–V graphs of a fixed resistor, a filament lamp and a silicon diode.
- **Circuit.** A low-voltage DC supply (a battery pack or a school power pack at a few volts), the component under test, an ammeter in series with it (5C), a voltmeter across it (5C), and a potentiometer or variable resistor to vary the potential difference across the component.
- **Method.** Starting from zero, take paired readings of the potential difference and the current. For the diode, also reverse its connections and repeat, to show the reverse-biased behaviour.
- **Expected results.** Fixed resistor: a straight line through the origin (ohmic). Filament lamp: a curve bending away from the current axis as the filament heats. Diode: zero current until about $0.6\ \mathrm{V}$ in forward bias, then a steep rise; approximately zero current in reverse bias.
- **Safety and practice.** Use low-voltage DC only: the study design does not permit students to carry out electrical work on equipment operating above $50\ \mathrm{V}$ AC or $120\ \mathrm{V}$ ripple-free DC, and household mains ($230\ \mathrm{V}$ AC) is never used in class circuits. A filament lamp becomes hot — allow it to cool before handling it. Always include a series resistor when testing a diode or an LED so that the current stays small, and check the polarity — which way round each component is connected, with the correct lead toward the positive side — of every diode and LED before closing the switch. Have the teacher check an unfamiliar circuit before the switch is closed, and record every reading, with its unit and the meter setting used, in your logbook: the logbook is submitted as a requirement for satisfactory completion of the unit.

Worked examples

Example 1 — scaffolded

A student measures the current through a filament lamp at two different potential differences: $0.40\ \mathrm{A}$ at $2.0\ \mathrm{V}$, and $0.60\ \mathrm{A}$ at $6.0\ \mathrm{V}$. (a) Calculate the resistance of the lamp at each operating point. (b) Account for the difference. (c) Calculate the power transferred by the lamp at $6.0\ \mathrm{V}$.

Working	Comment
(a) At $2.0\ \mathrm{V}$: $R = V / I = 2.0 / 0.40 = 5.0\ \Omega$.	Resistance at an operating point is the ratio V / I.
At $6.0\ \mathrm{V}$: $R = V / I = 6.0 / 0.60 = 10\ \Omega$.	The same ratio, evaluated at the second point.
(b) The larger current heats the filament to a higher temperature, and the resistance of the metal increases with temperature.	The lamp is non-ohmic: its resistance depends on the operating point.
(c) $P = V\,I = 6.0 \times 0.60 = 3.6\ \mathrm{W}$.	Power is the potential difference times the current.

Example 2 — scaffolded

A red LED is to run at a current of $20\ \mathrm{mA}$ from a $6.0\ \mathrm{V}$ battery. The voltage drop across the conducting LED is $2.0\ \mathrm{V}$. (a) Calculate the potential difference the series resistor must drop. (b) Calculate the resistance needed. (c) Calculate the power transferred by the resistor and by the LED.

Working	Comment
(a) $V_{\mathrm{R}} = 6.0 - 2.0 = 4.0\ \mathrm{V}$.	In series, the voltage drops add to the supply potential difference.
(b) $I = 20\ \mathrm{mA} = 0.020\ \mathrm{A}$. $R = V / I = 4.0 / 0.020 = 200\ \Omega$.	The same current passes through the resistor and the LED.
(c) Resistor: $P = V\,I = 4.0 \times 0.020 = 0.080\ \mathrm{W}$.	Below the $0.25\ \mathrm{W}$ rating of a typical small resistor.
LED: $P = V\,I = 2.0 \times 0.020 = 0.040\ \mathrm{W}$.	Use the LED's own voltage drop, $2.0\ \mathrm{V}$.

Check: the supply transfers $P = V\,I = 6.0 \times 0.020 = 0.12\ \mathrm{W}$, which equals $0.080\ \mathrm{W} + 0.040\ \mathrm{W}$. ✓

Example 3 — unscaffolded

An NTC thermistor and a fixed $2.0\ \mathrm{k}\,\Omega$ resistor are connected in series across a $12\ \mathrm{V}$ supply. At $20\ \mathrm{°C}$ the thermistor's resistance is $10\ \mathrm{k}\,\Omega$; at $80\ \mathrm{°C}$ it is $2.0\ \mathrm{k}\,\Omega$. (a) Calculate the current in the circuit at $20\ \mathrm{°C}$. (b) Calculate the potential difference across the thermistor at $20\ \mathrm{°C}$. (c) Calculate the current at $80\ \mathrm{°C}$ and explain the change.

The total resistance in series is the sum of the two resistances (5D). At $20\ \mathrm{°C}$:

$$R_{\text{total}} = 10\,000 + 2000 = 12\,000\ \Omega\,,\ I = \frac{V}{R} = \frac{12}{12\,000} = 0.0010\ \mathrm{A} = 1.0\ \mathrm{mA}\,.$$

The potential difference across the thermistor follows from $V = I\,R$:

$$V = 0.0010 \times 10\,000 = 10\ \mathrm{V}\,.$$

(The fixed resistor drops $0.0010 \times 2000 = 2.0\ \mathrm{V}$, and $10\ \mathrm{V} + 2.0\ \mathrm{V} = 12\ \mathrm{V}$, the supply. ✓)

At $80\ \mathrm{°C}$ the thermistor's resistance has fallen to $2.0\ \mathrm{k}\,\Omega$, so

$$R_{\text{total}} = 2000 + 2000 = 4000\ \Omega\,,\ I = \frac{12}{4000} = 0.0030\ \mathrm{A} = 3.0\ \mathrm{mA}\,.$$

∴ the current is $1.0\ \mathrm{mA}$ at $20\ \mathrm{°C}$, rising to $3.0\ \mathrm{mA}$ at $80\ \mathrm{°C}$. Heating an NTC thermistor lowers its resistance, so the total resistance of the circuit falls and the current increases. This is the behaviour on which thermistor temperature sensors rely.

Example 4 — unscaffolded

A student connects an LED directly across a $6.0\,\text{V}$ battery, with no series resistor. The LED glows very brightly for an instant and is then permanently damaged. Explain why the LED was damaged, referring to its threshold voltage and resistance once conducting, and state how the circuit should have been designed.

An LED is a diode with a threshold voltage of roughly $2.0\,\text{V}$ (for a red LED). Connected directly across $6.0\,\text{V}$, it is forward-biased well above its threshold, where its resistance is very small. With no resistor in the circuit there is almost nothing to limit the current, so the current becomes very large. The power transferred by the LED, $P = V\,I$, becomes far larger than the LED is designed to handle, the LED overheats, and it is destroyed.

The correct design places a resistor in series with the LED. The resistor drops the potential difference left over after the LED's own drop — here $6.0\,\text{V} - 2.0\,\text{V} = 4.0\,\text{V}$ — and its resistance sets the current through the circuit, $I = V / R$. Choosing the resistor so the current is about $10 - 20\,\text{mA}$ keeps the LED within its normal operating range.

Practice questions

Question 1 Copy and complete the table below.

Component	Its resistance depends on …	One use
Thermistor (NTC)		
LDR		
Diode		
LED		
Potentiometer		

Question 2 A student measures the current through a filament lamp at several potential differences, with the results below.

V (V)	1.0	4.0	6.0	8.0
I (A)	0.25	0.63	0.75	0.80

(a) Calculate the resistance of the lamp at each potential difference.
(b) State whether the lamp is ohmic, and justify your answer using your calculated values.
(c) Explain the behaviour of the resistance as the current increases.

Question 3 (a) Name the bias condition of a diode when it is connected so that current can pass, and the condition when it is connected so that current cannot pass. (b) State the approximate potential difference across a forward-biased silicon diode at which it begins to conduct. (c) State the current in a reverse-biased diode, as modelled in this course. (d) State whether a diode is ohmic, and justify your answer.

Question 4 An LED with a voltage drop of $2.0\,\text{V}$ when conducting is to run at a current of $15\,\text{mA}$ from a $5.0\,\text{V}$ supply, with a resistor in series. (a) Calculate the potential difference the resistor must drop. (b) Convert the current to amperes, and calculate the resistance needed. (c) Calculate the power transferred by the resistor. (d) Calculate the power transferred by the LED.

Question 5 An NTC thermistor with a resistance of $5.0\,\text{k}\,\Omega$ at a low temperature is connected in series with a fixed $1.0\,\text{k}\,\Omega$ resistor across a $6.0\,\text{V}$ supply. (a) State how the resistance of the thermistor changes as its temperature increases. (b) State what the label *negative temperature coefficient* means. (c) Calculate the current in the circuit at the low temperature. (d) State and explain what happens to the current as the thermistor warms.

Question 6 A potentiometer is marked $10\,\text{k}\,\Omega$. (a) State the number of terminals it has, and the name of the moving contact. (b) State what happens to the resistance between the wiper and one end of the track as the spindle is turned. (c) State the arrangement the potentiometer forms when all three terminals are connected into a circuit, and name the subtopic where that arrangement is analysed. (d) Give one everyday example of a potentiometer in use.

Question 7 A $12\,\mathrm{V}$ car dashboard bulb draws a current of $0.50\,\mathrm{A}$ when lit at its normal brightness. (a) Calculate the resistance of the bulb at this operating point. (b) Calculate the power transferred by the bulb. (c) Calculate the energy the bulb transfers when it runs for $2.0\,\mathrm{min}$.

Question 8 An LDR of resistance $200\,\Omega$ in bright light is connected in series with a fixed $800\,\Omega$ resistor across a $6.0\,\mathrm{V}$ supply. (a) Calculate the current in the circuit. (b) Calculate the potential difference across the LDR. (c) Calculate the potential difference across the fixed resistor, and check that the two voltage drops add to the supply potential difference.

Question 9 A white LED has a voltage drop of $3.0\,\mathrm{V}$ when conducting. It is to run at $25\,\mathrm{mA}$ from a $9.0\,\mathrm{V}$ supply, with a resistor in series. Calculate the resistance needed and the power transferred by the resistor.

Question 10 A silicon diode, forward-biased, is connected in series with a $120\,\Omega$ resistor across a $3.0\,\mathrm{V}$ supply. The voltage drop across the conducting diode is $0.6\,\mathrm{V}$. (a) Calculate the potential difference across the resistor. (b) Calculate the current in the circuit. (c) Calculate the power transferred by the resistor.

Question 11 A $10\,\mathrm{k}\,\Omega$ potentiometer is connected as a variable resistor, using the wiper and one end of the track, across a $6.0\,\mathrm{V}$ battery. (a) With the potentiometer set to $4.0\,\mathrm{k}\,\Omega$, calculate the current. (b) With the potentiometer set to its maximum value, calculate the current. (c) State how the current changes as the resistance setting increases, and explain why.

Question 12 An NTC thermistor has a resistance of $3.0\,\mathrm{k}\,\Omega$ at $25\,°\mathrm{C}$ and $500\,\Omega$ at $100\,°\mathrm{C}$. It is connected in series with a fixed $1.0\,\mathrm{k}\,\Omega$ resistor across a $12\,\mathrm{V}$ supply. (a) Calculate the current in the circuit at $25\,°\mathrm{C}$. (b) Calculate the current in the circuit at $100\,°\mathrm{C}$. (c) Account for the difference between the two currents.

Question 13 Explain why an LED must always be connected in series with a resistor. Your answer should refer to the LED's threshold voltage, its resistance once conducting, and the role of the resistor in setting the current.

Question 14 A device can be protected against a battery being inserted the wrong way round by connecting a diode in series with it. Explain how this protection works, describing the diode's behaviour for both orientations of the battery.

Question 15 For each of the thermistor, the LDR and the LED, state whether it is an input transducer or an output transducer, and describe the energy conversion it performs.

Question 16 A student writes: "A thermistor and an LDR are both resistors whose resistance changes, so an LDR can replace a thermistor in a temperature-sensing circuit." Identify the error in this reasoning and explain why the substitution would not work reliably.

Question 17 A student connects an LED into a working circuit, but it does not glow. Another student says the LED must be broken. Evaluate this claim, referring to the behaviour of a diode, and state what should be checked first.

Question 18 Describe how you would obtain the I–V graph of a silicon diode in the laboratory. Include the circuit components and their connections, the measurements you would take, the result you would expect in forward bias and in reverse bias, and two safety or good-practice points relevant to the investigation.

Answers

Question 1 Thermistor: temperature; temperature sensor. LDR: light intensity; light sensor. Diode: the direction of connection (and the potential difference across it); protection against reversed connections. LED: the direction of connection (and the potential difference across it); indicator light. Potentiometer: the position of the wiper (set by the user); volume control. **Question 2** (a) $4.0\,\Omega$, $6.3\,\Omega$, $8.0\,\Omega$, $10\,\Omega$; (b) no — the resistance is not constant; (c) the filament heats up, and the resistance of the metal increases with temperature. **Question 3** (a) forward-biased; reverse-biased; (b) about $0.6\,\text{V}$; (c) zero; (d) no — its resistance is not constant and it conducts in one direction only. **Question 4** (a) $3.0\,\text{V}$; (b) $0.015\,\text{A}$, $200\,\Omega$; (c) $0.045\,\text{W}$; (d) $0.030\,\text{W}$. **Question 5** (a) it decreases; (b) the resistance decreases as the temperature increases; (c) $1.0\,\text{mA}$; (d) the current increases, because the thermistor's resistance falls and so the total resistance falls. **Question 6** (a) three terminals; the wiper; (b) it rises from zero to $10\,\text{k}\,\Omega$ (one way) and falls again (the other way); (c) an adjustable voltage divider; 5F; (d) any one, for example a volume control. **Question 7** (a) $24\,\Omega$; (b) $6.0\,\text{W}$; (c) $720\,\text{J}$. **Question 8** (a) $6.0\,\text{mA}$; (b) $1.2\,\text{V}$; (c) $4.8\,\text{V}$; $1.2\,\text{V} + 4.8\,\text{V} = 6.0\,\text{V}$. ✓ **Question 9** $240\,\Omega$; $0.15\,\text{W}$. **Question 10** (a) $2.4\,\text{V}$; (b) $0.020\,\text{A}$ $(20\,\text{mA})$; (c) $0.048\,\text{W}$. **Question 11** (a) $1.5\,\text{mA}$; (b) $0.60\,\text{mA}$; (c) the current decreases, because $I = V / R$ and the potential difference is constant. **Question 12** (a) $3.0\,\text{mA}$; (b) $8.0\,\text{mA}$; (c) heating the NTC thermistor lowers its resistance, so the total resistance falls and the current rises. **Question 13** See solutions. **Question 14** See solutions. **Question 15** See solutions. **Question 16** See solutions. **Question 17** See solutions. **Question 18** See solutions.

Fully-worked solutions

Question 1 A thermistor's resistance depends on temperature; it is used as a temperature sensor. An LDR's resistance depends on the light intensity falling on it; it is used as a light sensor. A diode's resistance depends on the direction of connection (and on the potential difference across it): very high when reverse-biased, small when forward-biased above about $0.6\,\text{V}$; it is used to protect circuits against reversed connections. An LED has the same directional behaviour and emits light when conducting; it is used as an indicator light. A potentiometer's resistance between the wiper and one end is set by the wiper position; it is used as a volume control, a dimming control, or any adjustable resistor or voltage divider.

Question 2 (a) Using $R = V / I$ at each operating point: $R = 1.0 / 0.25 = 4.0\,\Omega$; $R = 4.0 / 0.63 = 6.3\,\Omega$; $R = 6.0 / 0.75 = 8.0\,\Omega$; $R = 8.0 / 0.80 = 10\,\Omega$. (b) The lamp is not ohmic: for an ohmic device the resistance is constant and the I–V graph is a straight line through the origin, but here the resistance increases from $4.0\,\Omega$ to $10\,\Omega$ as the potential difference increases. (c) As the current increases, the filament gets hotter. The resistance of a metal increases with temperature, because the atoms of the metal vibrate more and oppose the moving electrons more strongly, so the resistance of the lamp increases.

Question 3 (a) A diode that is connected so current can pass is forward-biased; connected so current cannot pass, it is reverse-biased. (b) A forward-biased silicon diode begins to conduct at about $0.6\,\text{V}$, its threshold voltage. (c) The current in a reverse-biased diode is taken to be zero in this course. (d) A diode is not ohmic: its resistance is not constant — it is very high when reverse-biased and small when forward-biased above the threshold — and it conducts in one direction only, which an ohmic device never does.

Question 4 (a) The voltage drops in series add to the supply potential difference, so the resistor must drop $V_{\text{R}} = 5.0 - 2.0 = 3.0\,\text{V}$. (b) $I = 15\,\text{mA} = 0.015\,\text{A}$. The same current passes through the resistor, so $R = V / I = 3.0 / 0.015 = 200\,\Omega$. (c) $P = V\,I = 3.0 \times 0.015 = 0.045\,\text{W}$. (d) $P = V\,I = 2.0 \times 0.015 = 0.030\,\text{W}$, using the LED's own voltage drop.

Question 5 (a) The resistance of the thermistor decreases as its temperature increases. (b) *Negative temperature coefficient* means the resistance decreases as the temperature increases. (c) $R_{\text{total}} = 5000 + 1000 = 6000\,\Omega$, so $I = V / R = 6.0 / 6000 = 0.0010\,\text{A} = 1.0\,\text{mA}$. (d) As the thermistor warms, its resistance falls, so the total resistance of the circuit falls and, with the supply potential difference unchanged, the current $I = V / R$ increases.

Question 6 (a) A potentiometer has three terminals: the two ends of the resistive track and the moving contact, called the wiper. (b) The resistance between the wiper and one end of the track rises smoothly from zero to the full $10\,\text{k}\,\Omega$ as the spindle is turned one way, and falls back as it is turned the other way. (c) With all three terminals connected, the potentiometer is an adjustable voltage divider; voltage dividers are analysed in 5F. (d) One everyday example is the volume control of an audio system (or the dimming control of an instrument panel).

Question 7 (a) $R = V / I = 12 / 0.50 = 24\,\Omega$. (b) $P = V\,I = 12 \times 0.50 = 6.0\,\text{W}$. (c) $t = 2.0\,\text{min} = 120\,\text{s}$, so $E = P\,t = 6.0 \times 120 = 720\,\text{J}$.

Question 8 (a) $R_{\text{total}} = 200 + 800 = 1000\,\Omega$, so $I = V / R = 6.0 / 1000 = 0.0060\,\text{A} = 6.0\,\text{mA}$. (b) $V = I\,R = 0.0060 \times 200 = 1.2\,\text{V}$ across the LDR. (c) $V = I\,R = 0.0060 \times 800 = 4.8\,\text{V}$ across the fixed resistor. Check: $1.2\,\text{V} + 4.8\,\text{V} = 6.0\,\text{V}$, the supply potential difference. ✓

Question 9 The resistor must drop $V_{\text{R}} = 9.0 - 3.0 = 6.0\,\text{V}$. The current is $I = 25\,\text{mA} = 0.025\,\text{A}$, the same through both components, so $R = V / I = 6.0 / 0.025 = 240\,\Omega$. The power transferred by the resistor is $P = V\,I = 6.0 \times 0.025 = 0.15\,\text{W}$.

Question 10 (a) The resistor drops what the diode does not: $V_{\text{R}} = 3.0 - 0.6 = 2.4\,\text{V}$. (b) $I = V / R = 2.4 / 120 = 0.020\,\text{A} = 20\,\text{mA}$, the same current through the diode. (c) $P = V\,I = 2.4 \times 0.020 = 0.048\,\text{W}$.

Question 11 (a) $I = V / R = 6.0 / 4000 = 0.0015\,\text{A} = 1.5\,\text{mA}$. (b) $I = V / R = 6.0 / 10\,000 = 0.00060\,\text{A} = 0.60\,\text{mA}$. (c) The current decreases as the resistance setting increases: from $I = V / R$, with the supply potential difference constant, a larger resistance gives a smaller current.

Question 12 (a) At $25\,°\text{C}$: $R_{\text{total}} = 3000 + 1000 = 4000\,\Omega$, so $I = 12 / 4000 = 0.0030\,\text{A} = 3.0\,\text{mA}$. (b) At $100\,°\text{C}$: $R_{\text{total}} = 500 + 1000 = 1500\,\Omega$, so $I = 12 / 1500 = 0.0080\,\text{A} = 8.0\,\text{mA}$. (c) The current is larger at $100\,°\text{C}$ because the NTC thermistor's resistance is lower at the higher temperature, so the total resistance of the circuit is lower and the current $I = V / R$ is larger.

Question 13 Model answer. An LED is a diode, so it has a threshold voltage (about $2.0\,\text{V}$ for a red LED) above which it conducts. Above the threshold its resistance is very small, so if it were connected directly across a supply of potential difference greater than the threshold, almost nothing would limit the current and the current would become very large. The power transferred by the LED, $P = V\,I$, would then exceed what the LED can withstand, and it would overheat and be destroyed. The series resistor drops the potential difference left over after the LED's own drop and, through $I = V / R$, sets the current through the circuit to a safe value, typically $10 - 20\,\text{mA}$.

Question 14 Model answer. With the battery connected the correct way round, the diode is forward-biased, so once its threshold voltage is exceeded it conducts and the device operates normally. If the battery is reversed, the diode becomes reverse-biased; in this course the reverse current is taken to be zero, so the diode behaves like an open switch and no current flows anywhere in the circuit. The device is therefore protected, because the reversed battery simply cannot drive a current through it. (The diode must itself be rated for the supply's potential difference, so that it is not damaged while blocking.)

Question 15 Model answer. A thermistor is an input transducer (a sensor): it converts a temperature into a change of resistance, producing an electrical signal that varies with temperature. An LDR is also an input transducer: it converts the light intensity falling on it into a change of resistance. An LED is an output transducer: it converts electrical energy into light.

Question 16 Model answer. The error is assuming that because two components are resistors whose resistance changes, they respond to the same quantity. A thermistor's resistance depends on temperature; an LDR's resistance depends on light intensity. In a temperature-sensing circuit an LDR would respond to changes in the light falling on it — for example, room lighting being turned on or daylight changing — rather than to the temperature, so its readings would not track the temperature reliably. The substitution fails because the two transducers convert different physical quantities.

Question 17 Model answer. The claim is not justified. An LED is a diode, so it conducts in one direction only: if it is connected the wrong way round it is reverse-biased, the current is zero, and it does not glow — without being broken. Before concluding that the LED is faulty, the student should check its orientation (the longer lead connects toward the positive side of the supply) and try it the other way round, and also check that the circuit is delivering a current and that the supply potential difference exceeds the LED's threshold voltage.

Question 18 Model answer. Build a low-voltage DC circuit: a battery pack or school power pack at a few volts, the silicon diode, a resistor in series to limit the current, an ammeter in series with the diode (5C), a voltmeter connected in parallel across the diode (5C), and a potentiometer or variable resistor to vary the potential difference across the diode. Starting from zero, increase the potential difference step by step and record paired readings of the potential difference across the diode and the current through it; then reverse the diode's connections and repeat to measure the reverse-biased behaviour. Expected result: in forward bias, the current is approximately zero until the potential difference reaches about $0.6\ \mathrm{V}$, then increases steeply; in reverse bias, the current remains approximately zero at every setting. Safety and good practice (any two): use low-voltage DC only, since the study design does not permit student electrical work above $50\ \mathrm{V}$ AC or $120\ \mathrm{V}$ ripple-free DC; keep the series resistor in the circuit at all times so the current stays small; check the diode's orientation before closing the switch; have the teacher check the circuit before first use; and record every reading, with its unit and meter setting, in the logbook.

Theory

Every electrical device in a home takes energy from a supply — a battery or the household mains — and puts it to work: heating water, producing light, charging a battery, making sound. The physics of these devices comes down to two questions: where does the energy go, and what does it become? This section follows energy through seven components — resistors, light bulbs, diodes, thermistors, light dependent resistors (LDRs), light-emitting diodes (LEDs) and potentiometers — and into the common devices built from them. The electrical quantities used here — charge, current, potential difference, energy and power — were introduced in Section 5A.

Transfers and transformations. An **energy transfer** is the movement of energy from one object or place to another: energy transfers from a battery to a bulb along the wires of a torch, and from a hot filament to the surrounding air. An **energy transformation** is a change in the form of energy: chemical energy becomes electrical energy in a battery, and electrical energy becomes thermal energy and light in a bulb. Real devices do both: the supply transforms stored energy into electrical energy and transfers it around the circuit, and the components transform it into the forms the device is meant to produce — along with forms it is not. In every case the total energy is conserved: energy is never created or destroyed, so a device cannot deliver more energy than it receives.

How energy moves around a circuit. From Section 5A: a power supply transfers energy to the charges in a circuit. The potential difference V across a component is the energy E transferred per unit charge Q as the charges pass through the component:

$$V=\frac{E}{Q}.$$

When a current I flows through a component across which the potential difference is V, electrical energy is transformed at a rate (power)

$$P=V\,I,$$

and the energy transformed in a time t is

$$E=P\,t=V\,I\,t.$$

These relationships are enough for every calculation in this section. Energy is measured in joules (J), power in watts (W), and household-scale energies are often given in kilowatt-hours using the conversion from Section 5C: $1\,\text{kW h}=3.6\times10^{6}\,\text{J}$.

Resistors — electrical energy to thermal energy. When a current flows through a resistor, the moving charges interact with the material of the resistor and transfer energy to it. The resistor warms up: electrical energy is transformed into thermal energy. This is often called the **heating effect** of a current. The energy transformed in a time t is $E=P\,t$, so a larger current, a larger potential difference, or a longer operating time each increase the thermal energy produced.

In many devices this thermal energy is exactly the point. The **heating element** of a kettle, a toaster, an electric heater or an electric blanket is a resistor built to become hot and transfer thermal energy where it is wanted — to the water, the bread, the room or the bed. In most other devices the warming of resistors and connecting wires is unwanted: it is energy that never reaches the intended output, and it ends up transferred to the surroundings as thermal energy.

Light bulbs — electrical to thermal, then light. A traditional **light bulb** — an **incandescent** lamp, meaning one that glows because it is hot — passes a current through a thin tungsten wire called the **filament**. The filament is a resistor; the current heats it until it is white-hot, and Section 2C showed that hot objects emit electromagnetic radiation. The chain of transformations is therefore

$$\text{electrical}\rightarrow\text{thermal}\rightarrow\text{light}.$$

Only a small fraction of the electrical energy becomes visible light. Most of it becomes thermal energy — transferred to the glass of the bulb, to the air around it, and radiated as infrared. In energy terms a filament bulb is a poor converter of electrical energy into light: it behaves more like a heater that happens to glow.

Diodes — one-way components. A **diode** is a component that allows current in one direction only. In the conducting direction it has a low resistance; in the reverse direction its resistance is very high and almost no current flows. While a diode conducts, there is a small potential difference across it, so a small amount of electrical energy is transformed into thermal energy in the diode itself.

The one-way property is what makes diodes useful. The household supply is alternating current (AC), in which the current reverses direction repeatedly (Section 6B), but batteries, phone chargers and most electronic devices need direct current (DC), flowing one way. Because a diode allows current in only one direction, diodes are the components used in power supplies and chargers to convert AC into DC; Section 12E shows how this is done in a charging circuit.

Light-emitting diodes — electrical to light, directly. A **light-emitting diode (LED)** is a diode that transforms electrical energy directly into light, without first being heated white-hot. Because it skips the hot-filament step, an LED transforms a much larger fraction of its electrical energy into light and far less into thermal energy. An LED lamp giving the same light output as a filament bulb therefore needs far less input power, stays almost cool to the touch, and lasts far longer. This is why LEDs have replaced filament bulbs in torches, indicator lights, traffic lights, household lamps and displays. The comparison is quantified in Worked Example 3 and Question 17.

Thermistors and LDRs — components that sense. Some components are built not to transform large amounts of energy but to respond to their surroundings. A **thermistor** is a resistor whose resistance depends on temperature; the type used in school circuits has a resistance that **decreases** as the temperature increases. A **light dependent resistor (LDR)** is a resistor whose resistance depends on the light intensity falling on it: its resistance **decreases** as the light intensity increases.

Neither component is a source of energy. When a current flows through a thermistor or an LDR, electrical energy is transformed into thermal energy, just as in any resistor. Their usefulness lies in the resistance change: connected into a circuit, a change of temperature or light intensity changes the resistance, which changes the current and the potential differences in the circuit. The circuit can then use that change — to update the display of an oven thermometer, to switch a heater on or off (a thermostat), to trigger a fire alarm (thermistor), or to switch an outdoor lamp on at dusk (LDR). Section 12E builds trigger circuits of this kind. A fixed resistor cannot do any of this, because its resistance does not respond to its surroundings.

Potentiometers — components that adjust. A **potentiometer** is a resistor with three connections: one at each end of a resistive track, and a third on a moving contact that slides along the track. As the contact moves, it picks up a chosen fraction of the potential difference along the track, so a potentiometer works as an adjustable voltage divider (Section 5F). It is the component behind user controls: the volume control of a radio, the dimmer of a lamp, the tuning control of an instrument. When a current flows in the track, electrical energy is transformed into thermal energy as in any resistor. The amounts are usually small, but a volume control or dimmer in use can feel slightly warm for exactly this reason.

The seven components are summarised below.

Component	What it does	Main energy transformation	Found in
Resistor	opposes the current by a fixed amount	electrical → thermal	kettles, toasters, heaters, electric blankets (as the heating element)
Light bulb	filament glows because it is white-hot	electrical → thermal → light (mostly thermal)	older lamps, vehicle lights
Diode	allows current in one direction only	electrical → thermal (small) while conducting	chargers, power supplies
LED	emits light when conducting	electrical → light, with some thermal	indicator lights, torches, traffic lights, lamps
Thermistor	resistance decreases as	electrical → thermal; the	oven thermometers,

Component	What it does	Main energy transformation	Found in
	temperature increases	resistance varies with temperature	thermostats, fire alarms
LDR	resistance decreases as light intensity increases	electrical → thermal; the resistance varies with light intensity	automatic outdoor lights
Potentiometer	adjustable voltage divider	electrical → thermal	volume controls, lamp dimmers

Accounting for the energy in a device. When describing a device, account for all of the energy. The energy taken from the supply equals the sum of the energies transformed in every component; nothing disappears. The **useful** output is what the device is for: light from a lamp, thermal energy in a kettle's water, chemical energy stored in a charging battery. Everything else is **wasted** — most often transformed into thermal energy that warms the device and its surroundings. A filament bulb is the clearest example: its thermal output is large but useless for lighting. The fraction of the input energy that becomes useful output is the **efficiency** of the device; Section 9D makes this idea quantitative. For now the important point is comparative: for the same useful output, a device that wastes less energy needs less input power.

Units 3 & 4 preview. The energy accounting built here continues in Units 3 & 4, where generation, transmission and household consumption are analysed — including the thermal energy transformed in transmission lines as current flows through their resistance. This preview is not assessed in Units 1 & 2.

In the laboratory. The transformations of these components can be observed directly in low-voltage DC circuits: a filament bulb in a working circuit is too hot to touch after a few minutes, a resistor carrying a current is noticeably warm, and an LED stays almost cool while giving comparable light. Record the meter readings, the observed warming and your energy calculations in your logbook. As always in this course, practical work uses batteries and low-voltage power packs only; the household supply is $230\,\mathrm{V}$ AC at $50\,\mathrm{Hz}$ and is dangerous. This matches the study design's rule that students are not permitted to carry out electrical work on equipment operating above $50\,\mathrm{V}$ AC or $120\,\mathrm{V}$ ripple-free DC — appliances are studied through their labels, never by opening them.

Throughout this section, calculations use $E = P\,t = V\,I\,t$ and $P = V\,I$ (Section 5A) and $I = V\,/\,R$ (Section 5D), and energies are in joules unless stated otherwise.

Worked examples

Example 1 — scaffolded

An LED camp lantern is connected to a $12\,\mathrm{V}$ battery and draws a current of $0.40\,\mathrm{A}$. (a) Calculate the power of the lantern. (b) Calculate the energy transformed in $2.0\,\mathrm{h}$ of use, in joules. (c) State the main energy transformation in the LEDs.

Working	Comment
$V = 12\,\mathrm{V},\ I = 0.40\,\mathrm{A}$.	List the data.
(a) $P = V\,I = 12 \times 0.40 = 4.8\,\mathrm{W}$.	Power is the rate at which electrical energy is transformed.
(b) $t = 2.0 \times 3600 = 7200\,\mathrm{s}$.	Convert hours to seconds before using $E = P\,t$ with the power in watts.
$E = P\,t = 4.8 \times 7200 = 34\,560\,\mathrm{J} = 3.5 \times 10^4\,\mathrm{J}$.	Round to two significant figures, matching the data.
(c) Electrical → light, with some thermal.	An LED transforms most of its electrical energy directly into light; a small amount becomes thermal energy.

Example 2 — scaffolded

A torch contains a battery and a filament bulb. Describe the energy transfers and transformations from the stored energy in the battery to the energy reaching the surroundings.

Working	Comment
Energy is stored in the battery as chemical energy.	The battery is the power supply; its stored energy is the source for the circuit.
Chemical → electrical: the battery transfers energy to the charges in the circuit.	The potential difference across the bulb is the energy transferred per unit charge, $V = E / Q$.
The charges transfer energy to the filament as they pass through the bulb.	The rate of transfer is $P = V I$.
Electrical → thermal and light: the filament becomes white-hot and glows.	Most of the energy becomes thermal energy; a small fraction is visible light.
Light and thermal energy transfer from the filament to the surroundings; the thermal energy warms the torch body and the air.	The total energy is conserved: chemical energy in = light + thermal energy out.

Example 3 — unscaffolded

A $6.0\,\text{V}$ torch can be fitted with either a filament bulb ($6.0\,\text{V}$, $0.50\,\text{A}$) or an LED lamp ($6.0\,\text{V}$, $0.050\,\text{A}$); both give similar brightness. (a) Calculate the power of each. (b) Calculate the energy taken from the battery in $4.0\,\text{h}$ of use for each, in joules. (c) The battery stores $45\,\text{kJ}$ of energy. Calculate how long the torch runs with each lamp, and comment on the results.

The power of each lamp is $P = V I$:

$$P_{\text{filament}} = 6.0 \times 0.50 = 3.0\,\text{W}\,, P_{\text{LED}} = 6.0 \times 0.050 = 0.30\,\text{W}\,.$$

In $4.0\,\text{h} = 14\,400\,\text{s}$ the energies taken from the battery are $E = P t$:

$$E_{\text{filament}} = 3.0 \times 14\,400 = 43\,200\,\text{J} = 4.3 \times 10^4\,\text{J}\,,$$

$$E_{\text{LED}} = 0.30 \times 14\,400 = 4320\,\text{J} = 4.3 \times 10^3\,\text{J}\,.$$

With the battery storing $45\,\text{kJ} = 45\,000\,\text{J}$, the running times follow from $t = E / P$:

$$t_{\text{filament}} = \frac{45\,000}{3.0} = 15\,000\,\text{s} = 4.2\,\text{h}\,, t_{\text{LED}} = \frac{45\,000}{0.30} = 150\,000\,\text{s} \approx 42\,\text{h}\,.$$

∴ the filament bulb uses $4.3 \times 10^4\,\text{J}$ and the LED $4.3 \times 10^3\,\text{J}$ in $4.0\,\text{h}$, and the same battery runs the LED torch for about $42\,\text{h}$ — ten times longer than the filament torch. Both lamps give similar light, but the filament bulb takes ten times the input power to produce it: for every joule of useful light output, roughly nine joules are transformed into thermal energy, while the LED transforms a much larger fraction of its electrical energy directly into light. For the same useful output, the LED needs far less input power.

Example 4 — unscaffolded

A phone charger plugs into the household mains and contains diodes in its power supply and an LED indicator light. (a) State the conducting property of a diode. (b) Describe the energy transformations that occur while a phone is charging. (c) Explain why the charger feels slightly warm during use.

(a) A diode allows current in one direction only; in the reverse direction its resistance is very high and almost no current flows.

(b) Electrical energy from the mains is the input. Inside the phone battery, some of this energy is transformed into stored chemical energy. The diodes help convert the AC from the mains into the DC the battery needs by allowing current in only one direction (Section 12E shows the circuit in detail). A small amount of electrical energy is transformed into thermal energy in the conducting diodes and the other components of the charger, and the LED indicator transforms a small amount of electrical energy into light to show the charger is on.

(c) The warming is the wasted part of the energy transfer. Some of the electrical energy from the mains is transformed into thermal energy in the diodes, resistors and other components of the charger rather than into chemical energy in the battery. This thermal energy transfers to the charger's casing and then to the surrounding air, so the charger feels warm. Energy is conserved throughout: $$ = +

- .$$

Practice questions

Where needed, use $1\,\text{kW h} = 3.6 \times 10^6\,\text{J}$.

Question 1 (a) Distinguish between an energy transfer and an energy transformation, giving one example of each. (b) State the main energy transformation in each of: (i) a resistor carrying a current; (ii) an LED; (iii) a filament light bulb.

Question 2 A filament bulb used as a vehicle headlight is labelled $12\,\text{V}$, $4.0\,\text{A}$. (a) Write the relationship between power P, potential difference V and current I. (b) Calculate the power of the bulb. (c) Calculate the energy transformed in $20\,\text{min}$ of use, in joules. (d) State the main energy transformations in the bulb.

Question 3 The indicator light on the front panel of a device is an LED operating at $2.0\,\text{V}$ with a current of $0.015\,\text{A}$. (a) Calculate the power of the LED. (b) Calculate the energy the LED transforms in $24\,\text{h}$, in joules. (c) State two reasons manufacturers use LEDs rather than filament lamps for indicator lights.

Question 4 For each of the thermistor, the LDR and the potentiometer: (a) state the quantity that changes its resistance, and how the resistance changes; (b) give one common device that contains one.

Question 5 The heating element of a kettle is a resistor. The kettle is labelled $1.8\,\text{kW}$ and takes $2.5\,\text{min}$ to boil a full load of water. (a) Convert the power to watts. (b) Calculate the energy transformed by the element in this time, in joules. (c) State the energy transformation in the element, and say where most of this energy goes. (d) Explain why the element becomes hot while the current flows.

Question 6 (a) Describe the construction of a potentiometer. (b) Give two common devices that contain a potentiometer. (c) State the main energy transformation in the resistive track while a current flows. (d) A potentiometer is used as a dimmer for a lamp. State what happens to the energy transformed per second in the lamp as the lamp is dimmed.

Question 7 A $100\,\Omega$ resistor inside an audio amplifier carries a current of $0.15\,\text{A}$. (a) Calculate the potential difference across the resistor. (b) Calculate the rate at which electrical energy is transformed into thermal energy in the resistor. (c) Calculate the energy transformed in $10\,\text{min}$.

Question 8 A filament bulb is labelled $60\,\text{W}$, $230\,\text{V}$. While the bulb is lit, calculate (a) the current in the bulb and (b) its resistance. (The resistance of a filament changes with temperature; give the resistance for the bulb while it is operating.)

Question 9 An automatic garden light contains an LDR and a switching circuit, and turns itself on at dusk. Describe how the LDR is involved, and explain why the LDR itself cannot be the source of the lamp's energy.

Question 10 A student writes: "In a torch, the energy stored in the battery is used up in the bulb." Identify the error in this statement and correct it, using the idea of conservation of energy.

Question 11 A thermistor is connected directly across a $6.0\,\text{V}$ supply. At $20\,°\text{C}$ its resistance is $300\,\Omega$. (a) Calculate the current in the thermistor. (b) Calculate the power of the thermistor. (c) The temperature of the thermistor increases. State what happens to its resistance, to the current, and to the rate at which electrical energy is transformed in it.

Question 12 An oven thermometer uses a thermistor rather than a fixed resistor in its sensing circuit. Justify this choice, referring to how the thermometer works.

Question 13 A diode in the power supply of a device has a potential difference of $0.70\ \mathrm{V}$ across it while conducting a current of $0.20\ \mathrm{A}$. (a) Calculate the power transformed in the diode. (b) Calculate the energy transformed in the diode in $1.0\ \mathrm{h}$ of operation, in joules. (c) State the main form into which this energy is transformed.

Question 14 A household replaces its filament bulbs with LED lamps of the same light output. With reference to the energy transformations in each type of lamp, justify the replacement.

Question 15 An electric blanket contains resistive wire and is labelled $80\ \mathrm{W}$. (a) Calculate the energy transformed when it runs for $30\ \mathrm{min}$, in joules. (b) On its low setting the blanket's power is $30\ \mathrm{W}$. Calculate the energy it transforms in $8.0\ \mathrm{h}$ overnight, in kW h.

Question 16 A lamp dimmer built around a potentiometer can feel slightly warm while the lamp is in use. Explain the warming, and state what happens to the energy transformed per second in the lamp as the lamp is dimmed.

Question 17 An older traffic light uses a $100\ \mathrm{W}$ filament bulb for its red signal; a modern unit uses an LED array rated at $10\ \mathrm{W}$ for the same purpose. Each signal is on for $24\ \mathrm{h}$. (a) Calculate the energy used by each, in kW h. (b) Convert each energy to joules. (c) Compare the two, and state what the difference says about the energy transformations in the two signals.

Question 18 A television set contains diodes in its power supply, LEDs for the display and the standby indicator, resistors throughout its circuits, and a potentiometer in its volume control. Describe the energy transfers and transformations in the television while it is on, identifying the useful outputs and the wasted energy.

Answers

Question 1 (a) a transfer moves energy from one object or place to another; a transformation changes its form; (b)(i) electrical → thermal; (ii) electrical → light (and some thermal); (iii) electrical → thermal and light (mostly thermal). **Question 2** (a) $P = V\,I$; (b) $48\,\text{W}$; (c) $5.8 \times 10^4\,\text{J}$; (d) electrical → thermal and light. **Question 3** (a) $0.030\,\text{W}$; (b) $2.6 \times 10^3\,\text{J}$; (c) see solutions. **Question 4** Thermistor: temperature increases ⇒ resistance decreases, e.g. an oven thermometer. LDR: light intensity increases ⇒ resistance decreases, e.g. an automatic outdoor light. Potentiometer: adjusted by the user, e.g. a volume control. **Question 5** (a) $1800\,\text{W}$; (b) $2.7 \times 10^5\,\text{J}$; (c) electrical → thermal; mostly to the water; (d) see solutions. **Question 6** (a) a resistive track with three connections and a moving contact; (b) e.g. a radio volume control, a lamp dimmer; (c) electrical → thermal; (d) the energy transformed per second in the lamp decreases. **Question 7** (a) $15\,\text{V}$; (b) $2.3\,\text{W}$; (c) $1.4 \times 10^3\,\text{J}$. **Question 8** (a) $0.26\,\text{A}$; (b) $880\,\Omega$. **Question 9** As the light intensity falls, the LDR's resistance rises and the switching circuit turns the lamp on; the LDR only senses — the lamp's energy comes from the supply. **Question 10** Energy is conserved; it is transformed into thermal energy and light in the bulb, not destroyed. **Question 11** (a) $0.020\,\text{A}$; (b) $0.12\,\text{W}$; (c) resistance decreases, current increases, power increases. **Question 12** The thermistor's resistance changes with temperature, so the circuit's reading changes with temperature; a fixed resistor's does not. **Question 13** (a) $0.14\,\text{W}$; (b) $5.0 \times 10^2\,\text{J}$; (c) thermal. **Question 14** An LED transforms electrical energy directly into light with far less thermal energy wasted, so it needs less input power for the same light output. **Question 15** (a) $1.4 \times 10^5\,\text{J}$; (b) $0.24\,\text{kW h}$. **Question 16** The current in the resistive track transforms electrical energy into thermal energy; the energy transformed per second in the lamp decreases as it is dimmed. **Question 17** (a) $2.4\,\text{kW h}$ (filament), $0.24\,\text{kW h}$ (LED); (b) $8.6 \times 10^6\,\text{J}$, $8.6 \times 10^5\,\text{J}$; (c) the filament signal uses ten times the energy for the same light output. **Question 18** Useful: light from the display; wasted: thermal energy in the resistors, diodes, potentiometer and display, plus a little light from the standby LED; the total is conserved.

Fully-worked solutions

Question 1 (a) An energy **transfer** is the movement of energy from one object or place to another, for example energy transferring from a battery to a bulb along the wires of a torch, or thermal energy transferring from a hot kettle to the surrounding air. An energy **transformation** is a change in the form of energy, for example chemical energy becoming electrical energy in a battery, or electrical energy becoming light in an LED. (b)(i) A resistor carrying a current: electrical → thermal. (ii) An LED: electrical → light (with some thermal). (iii) A filament bulb: electrical → thermal and light, with most of the energy becoming thermal energy.

Question 2 $V = 12\,\text{V}$, $I = 4.0\,\text{A}$, $t = 20\,\text{min} = 1200\,\text{s}$. (a) The relationship is $P = V\,I$. (b) $P = V\,I = 12 \times 4.0 = 48\,\text{W}$. (c) $E = P\,t = 48 \times 1200 = 57\,600\,\text{J} = 5.8 \times 10^4\,\text{J}$ (to two significant figures). (d) The current heats the filament until it is white-hot: electrical → thermal and light, with most of the energy becoming thermal energy.

Question 3 $V = 2.0\,\text{V}$, $I = 0.015\,\text{A}$. (a) $P = V\,I = 2.0 \times 0.015 = 0.030\,\text{W}$. (b) $t = 24 \times 3600 = 86\,400\,\text{s}$, so $E = P\,t = 0.030 \times 86\,400 = 2592\,\text{J} = 2.6 \times 10^3\,\text{J}$ (to two significant figures). (c) For the same light output an LED needs far less power than a filament lamp, so it uses less energy and wastes far less as thermal energy; the LED also stays almost cool and lasts far longer, which suits a device that is left on continuously.

Question 4 Thermistor: its resistance depends on temperature; for the type used in school circuits the resistance decreases as the temperature increases; found for example in an oven thermometer, a thermostat or a fire alarm. LDR: its resistance depends on the light intensity falling on it; the resistance decreases as the light intensity increases; found for example in an automatic outdoor light. Potentiometer: its moving contact is adjusted by the user, selecting a fraction of the potential difference along its resistive track; found for example in a volume control or a lamp dimmer.

Question 5 $P = 1.8\,\text{kW}$, $t = 2.5\,\text{min} = 150\,\text{s}$. (a) $P = 1800\,\text{W}$. (b) $E = P\,t = 1800 \times 150 = 270\,000\,\text{J} = 2.7 \times 10^5\,\text{J}$ (to two significant figures). (c) The transformation is electrical → thermal; most of the energy transfers to the water, with some warming the kettle body and the surrounding air. (d) As the current flows, the moving charges interact with the material of the element and transfer energy to it — the heating effect of a current — so the element's temperature rises.

Question 6 (a) A potentiometer has a resistive track with a connection at each end and a third connection to a moving contact that slides along the track; the contact picks up a chosen fraction of the potential difference along the track, so the potentiometer works as an adjustable voltage divider. (b) For example: the volume control of a radio and the dimmer of a lamp. (c) Electrical → thermal, as in any resistor. (d) Dimming the lamp means it glows less brightly, so the energy transformed per second in the lamp — its power — decreases.

Question 7 $R=100\,\Omega$, $I=0.15\text{ A}$. (a) From $I=V/R$, $V=IR=0.15\times100=15\text{ V}$. (b) $P=VI=15\times0.15=2.25\text{ W}=2.3\text{ W}$ (to two significant figures). (c) $t=10\times60=600\text{ s}$, so $E=Pt=2.25\times600=1350\text{ J}=1.4\times10^3\text{ J}$ (to two significant figures). All of this energy is transformed into thermal energy in the resistor.

Question 8 $P=60\text{ W}$, $V=230\text{ V}$. (a) From $P=VI$, $I=\dfrac{P}{V}=\dfrac{60}{230}=0.26\text{ A}$ (to two significant figures). (b) From $I=V/R$, $R=\dfrac{V}{I}=\dfrac{230}{0.261}=880\,\Omega$ (to two significant figures). This is the operating resistance of the hot filament; when the bulb is cold the resistance is lower, because a filament is non-ohmic (Section 6C).

Question 9 Model answer. As dusk falls, the light intensity on the LDR decreases, so the LDR's resistance increases. The circuit detects this change in resistance — through the resulting change in current and potential differences — and the switching circuit turns the lamp on. In the morning the process reverses: light intensity increases, the resistance decreases, and the lamp switches off. The LDR itself is a sensing component, not a source of energy: it does not supply the lamp with energy. The lamp's energy comes from the power supply (a battery or the mains), and is transformed into light and thermal energy in the lamp.

Question 10 Model answer. The error is the idea that energy can be "used up", as if it disappeared. Energy is conserved: it cannot be created or destroyed. In the torch, the chemical energy stored in the battery is transformed into electrical energy, which the bulb transforms into thermal energy and light. That energy then transfers to the torch body and to the surroundings. The energy is no longer stored in the battery — but it has not vanished; it has changed form and moved into the surroundings.

Question 11 $V=6.0\text{ V}$, $R=300\,\Omega$ at $20\,°\text{C}$. (a) $I=\dfrac{V}{R}=\dfrac{6.0}{300}=0.020\text{ A}$. (b) $P=VI=6.0\times0.020=0.12\text{ W}$. (c) As the temperature increases, the resistance of the thermistor decreases. With the potential difference fixed at 6.0 V, the current $I=V/R$ therefore increases, and the power $P=VI$ — the rate at which electrical energy is transformed into thermal energy — also increases.

Question 12 Model answer. The thermometer works by responding to temperature. A thermistor's resistance changes with temperature — it decreases as the temperature increases — so the current and potential differences in the sensing circuit change as the oven warms up, and the meter reading can be marked in degrees Celsius. A fixed resistor's resistance does not respond to temperature, so a circuit containing only a fixed resistor gives the same reading at every temperature and cannot act as a thermometer.

Question 13 $V=0.70\text{ V}$, $I=0.20\text{ A}$. (a) $P=VI=0.70\times0.20=0.14\text{ W}$. (b) $t=3600\text{ s}$, so $E=Pt=0.14\times3600=504\text{ J}=5.0\times10^2\text{ J}$ (to two significant figures). (c) The energy is transformed mainly into thermal energy in the conducting diode, which is why components in a power supply can feel slightly warm.

Question 14 Model answer. A filament bulb transforms electrical energy into thermal energy first, heating its filament white-hot, and only a small fraction of the electrical energy becomes visible light; most is wasted as thermal energy transferred to the surroundings. An LED transforms electrical energy directly into light, wasting far less as thermal energy. For the same light output, the LED therefore needs far less input power: less energy is taken from the supply, less is wasted, and the household's electricity use (and cost) falls. The LED also stays cooler and lasts longer.

Question 15 $P=80\text{ W}$. (a) $t=30\text{ min}=1800\text{ s}$, so $E=Pt=80\times1800=144\,000\text{ J}=1.4\times10^5\text{ J}$ (to two significant figures). (b) $P=30\text{ W}=0.030\text{ kW}$, $t=8.0\text{ h}$. From $E=Pt$ with the power in kW and the time in h: $E=0.030\times8.0=0.24\text{ kW h}\ (=0.24\times3.6\times10^6=8.6\times10^5\text{ J})$.

Question 16 Model answer. The warming comes from the heating effect of the current: while a current flows in the potentiometer's resistive track, electrical energy is transformed into thermal energy there, and that thermal energy transfers to the dimmer's casing and the surrounding air. As the lamp is dimmed, the energy transformed per second in the lamp decreases — that is what dimming means — while some electrical energy continues to be transformed into thermal energy in the track.

Question 17 Filament: $P = 100\ \mathrm{W} = 0.10\ \mathrm{kW}$; LED array: $P = 10\ \mathrm{W} = 0.010\ \mathrm{kW}$; $t = 24\ \mathrm{h}$. (a) From $E = P\,t$ with the power in kW and the time in h: filament: $E = 0.10 \times 24 = 2.4\ \mathrm{kW\ h}$; LED: $E = 0.010 \times 24 = 0.24\ \mathrm{kW\ h}$. (b) Filament: $E = 2.4 \times 3.6 \times 10^6 = 8\,640\,000\ \mathrm{J} = 8.6 \times 10^6\ \mathrm{J}$. LED: $E = 0.24 \times 3.6 \times 10^6 = 864\,000\ \mathrm{J} = 8.6 \times 10^5\ \mathrm{J}$ (each to two significant figures). (c) For the same light output and the same time, the filament signal uses ten times the energy of the LED signal. The filament bulb wastes most of its electrical energy as thermal energy, while the LED transforms a far larger fraction directly into light.

Question 18 Model answer. Electrical energy from the household mains is the input. Inside the set, the diodes in the power supply help convert the AC supply into DC; while conducting, they transform a small amount of electrical energy into thermal energy. The LEDs of the display transform electrical energy into light — the useful output of the television — and the circuits' resistors, and the potentiometer in the volume control, transform electrical energy into thermal energy. The standby LED transforms a small amount of electrical energy into light. The useful output is the light of the display; everything else — the thermal energy warming the set and the surrounding air, and the small standby light — is wasted energy. Throughout, energy is conserved: the energy taken from the mains equals the light output plus all of the thermal energy transferred to the surroundings.

Scope — *VCE Physics Study Design, Unit 1, Area of Study 3*: “compare the operation of safety devices including fuses, circuit breakers and residual current devices (RCDs)”; and “describe the causes, effects and first aid treatment of electric shock and identify the approximate danger thresholds for current and duration.”

Theory

In 6B you modelled a home’s electrical system as a simple DC circuit containing fuses, switches, circuit breakers, loads and the earth wire, and you saw the fuse or circuit breaker open the circuit when the current became too large. This subtopic first compares the three safety devices found in switchboards — fuses, circuit breakers and residual current devices (RCDs) — and separates the two jobs they are often confused with: protecting the wiring, and protecting people. The second half turns from circuits to people: what causes an electric shock, what the current does to the body, the approximate thresholds of current and time at which it becomes dangerous, and what to do — and what not to do — for someone who has been shocked.

Why safety devices are needed. Every wire and every appliance is designed to carry currents up to a certain value. A current transfers energy to everything it passes through, so a current larger than the design value transfers more energy each second, the wiring overheats, its insulation can melt, and a fire can start. In Victoria, fire brigades respond to more than 300 domestic electrical fires each year, and many of these fires are caused by old wiring.

Source: Energy Safe Victoria, Household wiring, retrieved 2026-08-18.

Two different hazards need protection: **too much current in the wiring** (a fire risk) and **current through a person** (an electric shock). The devices in a switchboard deal with these two hazards differently, and the most common confusion is to think that all of them protect people. They do not.

Fuses — protecting the wiring. A **fuse** is a short piece of thin wire, enclosed in a cartridge or a fuse holder, placed in series in the active wire of a circuit (6B). It has a **rated current**. While the current is below the rating, the fuse element warms only slightly and nothing happens. When the current exceeds the rating, the element heats until it melts — the fuse **blows** — and the circuit is broken. A small overload (a current a little above the rating) takes some time to melt the element; a short circuit (a very large current) melts it almost immediately.

Once a fuse has blown it must be replaced — with a fuse of the same rated current. The rating is chosen to match the wiring of the circuit, so that the fuse melts before the current becomes large enough to overheat the wires. A fuse of larger rating would let currents flow that overheat the wiring without ever melting, removing the protection. Older Australian switchboards used **rewirable fuses**, in which a length of fuse wire was wrapped into a porcelain fuse holder; most modern switchboards use circuit breakers instead. Fuses protect the wiring and the appliances; a fuse does not protect a person from electric shock, because the current that harms a person is far too small to melt it (the numbers follow below).

Circuit breakers — protecting the wiring, and resettable. A **circuit breaker** is an automatic switch in series in the active wire. Like a fuse, it has a rated current and it opens the circuit when the current exceeds that rating — but it opens rather than melts, so it can be reset after the fault is cleared. Two mechanisms inside the breaker cover the two kinds of overcurrent:

- a **thermal mechanism** for sustained overloads. The current heats a **bimetallic strip** — two bonded metals that expand by different amounts when heated, so the strip bends. When the current stays above the rating, the strip bends far enough to release the mechanism and the switch opens. The response takes a short time, which is deliberate: appliances often draw a brief surge of current when they start, and the breaker should not open every time that happens.
- a **magnetic mechanism** for very large currents. The large current of a short circuit produces a strong magnetic force in a coil inside the breaker, and the force trips the switch almost immediately.

A circuit breaker can also be operated by hand as a switch to isolate a circuit. As Energy Safe Victoria puts it: “A circuit breaker provides short-circuit and over-current protection such as when a power point is overloaded”, and

"Fuses and circuit breakers protect against short circuits and current overloads." Both devices respond to currents measured in amperes — a typical household breaker is rated at $8\,\mathrm{A}$, $10\,\mathrm{A}$, $16\,\mathrm{A}$ or $20\,\mathrm{A}$.

Source: Energy Safe Victoria, Household wiring, retrieved 2026-08-18.

Residual current devices (RCDs) — protecting people. An RCD — commonly called a **safety switch** in Australia — does what neither a fuse nor a circuit breaker can do: it responds to currents of only tens of milliamperes. It does this by sensing not the *size* of the current but its *balance*. In a correctly working circuit, the current in the active wire equals the current in the neutral wire: every coulomb that flows out to the appliances returns (6B). An RCD passes both wires through a detector and compares the two currents continuously. If some of the current leaks out of the circuit — through damaged insulation, through moisture, or through a person who is touching a live part and is also in contact with the ground — the two currents are no longer equal. The difference is called the **residual current**. When the residual current reaches the RCD's rated value — $30\,\mathrm{mA}$ for the RCDs installed for personal protection in homes — the RCD opens the circuit.

Energy Safe Victoria describes a safety switch as a device that "monitors the flow of electricity through a circuit", detects "a problem that may pose a risk to personal safety", and "turns the power off within 0.03 of a second" — about $0.03\,\mathrm{s}$, which is far shorter than a single heartbeat. A domestic RCD "always has a test button and '30ma' printed on them". In Victoria, "All switchboards must have RCDs fitted", and "RCDs protect from electrical shock by turning off a circuit when triggered by a leakage current."

Source: Energy Safe Victoria, Household wiring, retrieved 2026-08-18. Source: Energy Safe Victoria, Residential property safety checks, retrieved 2026-08-18.

An RCD is an *additional* form of protection, used together with fuses and circuit breakers, not instead of them — and it "will not prevent all electric shocks" (Energy Safe Victoria). One limitation follows directly from its operating principle: if a person touches the active and the neutral conductors at the same time, the current through the person still flows out along the active wire and back along the neutral wire, the two currents remain equal, and the RCD detects no residual current at all. It cannot tell the difference between a person and an appliance in that situation. Equally, "Surge diverters and circuit breakers do not act as safety switches for personal protection against electric shock" — a surge diverter protects appliances from a brief voltage surge, such as one caused by a lightning strike, and does nothing for a person.

Source: Energy Safe Victoria, Household wiring, retrieved 2026-08-18.

Comparing the three devices.

Device	Responds to	Protects	After it operates
Fuse	a current above its rated value	the wiring and appliances against overloads and short circuits	it must be replaced by a fuse of the same rated current
Circuit breaker	a current above its rated value	the wiring and appliances against overloads and short circuits	it can be reset once the fault is cleared
RCD (safety switch)	a residual current: an imbalance of $30\,\mathrm{mA}$ or more between the active and neutral currents	people, against electric shock	it can be reset; its test button checks that it works

The comparison that matters most is numerical. Fuses and circuit breakers respond in **amperes**; an RCD responds at $30\,\mathrm{mA}$, that is, $0.03\,\mathrm{A}$. The current that can kill a person is hundreds of times smaller than the current that blows a $10\,\mathrm{A}$ fuse or trips a $16\,\mathrm{A}$ breaker. That is why a fuse or a circuit breaker on its own cannot protect a person from electric shock — and why every switchboard must also contain RCDs.

Electric shock — causes. An **electric shock** occurs when the body becomes part of an electric circuit and current passes through it. In a home this usually means touching something **live** — connected to the active side of the $230\,\mathrm{V}$ supply (6B) — while also being in contact with the ground or with something connected to it. The common causes are:

- damaged cords, cracked plugs and exposed live parts — insulation that has worn or been pulled loose can leave the live conductor reachable;
- faulty appliances, for example an active wire that has come loose and touched a metal case with no earth connection (6B);
- water and damp. Energy Safe Victoria notes that "Electric shocks received in the vicinity of a swimming pool are more likely to be fatal than those received in other locations, as bare feet, minimum clothing and wet skin reduce your body's insulation and resistance", and that "many victims of serious and fatal electrical accidents are barefooted";
- doing electrical work without a licence. Energy Safe Victoria's rule is plain: "NEVER do your own electrical work." In Victoria, under the *Electricity Safety Act 1998* (Vic.), only a person with the appropriate current electrical licence may carry out electrical work.

Source: Energy Safe Victoria, Using electricity safely, retrieved 2026-08-27. Source: Energy Safe Victoria, Electrical emergencies, retrieved 2026-08-18.

Electric shock — what the current does. The harm in an electric shock is done by the **current** through the body, not by the voltage alone. For a given potential difference, the current is set by the body's resistance, $I = V / R$ (5A, 5D). The body's resistance is not a fixed value: dry, unbroken skin provides tens of thousands of ohms, while wet or broken skin may provide only a few thousand ohms or less. Contact with the $230\,\text{V}$ supply can therefore drive currents ranging from a few milliamperes to well over $100\,\text{mA}$, depending on the condition of the skin and on the path the current takes. The path matters: currents on a hand-to-hand or hand-to-foot path pass through the chest.

The effects described by WorkSafe Victoria include "a serious or fatal electrical shock", "internal and external burns, nerve and muscle damage, eye and lung injuries", and fire or explosion from the associated arc. A shock that is not immediately fatal can still be grave: as Energy Safe Victoria puts it, "Electricity can kill in an instant." Two effects of the $50\,\text{Hz}$ alternating current used in Australian homes are particularly important:

- the current can cause a sustained contraction of the muscles. A person gripping a live conductor may be physically unable to let go, so the shock continues;
- a current through the chest can disrupt the rhythm of the heart, causing **ventricular fibrillation** — a condition in which the heart quivers instead of pumping blood. Without treatment it is fatal.

Source: WorkSafe Victoria, Electrical safety, retrieved 2026-08-18. Source: Energy Safe Victoria, Electrical emergencies, retrieved 2026-08-18.

Danger thresholds — approximate values of current and duration. The effects of a shock depend on the size of the current, the path it takes, the condition of the skin, and the **duration** — how long it lasts. For $50\,\text{Hz}$ alternating current on a hand-to-foot path, the approximate thresholds are:

Approximate current	Effect
below about $1\,\text{mA}$	the threshold of perception — a tingling sensation, usually with no harmful effect
$1–10\,\text{mA}$	the shock is felt and may be painful; below about $10\,\text{mA}$ the person can usually let go
$10–30\,\text{mA}$	the muscles may contract; at and above about $10\,\text{mA}$ (the **let-go threshold**) a person gripping a conductor may be unable to release it; breathing may be affected
above about $30\,\text{mA}$	increasing risk of ventricular fibrillation; the risk grows as both the current and the duration grow
above about $100\,\text{mA}$	severe burns, cardiac arrest; likely to be fatal

Source: International Electrotechnical Commission, IEC 60479-1, Effects of current on human beings and livestock — Part 1: General aspects, retrieved 2026-08-18. The values are approximate, for $50\,\text{Hz}$ *AC on a hand-to-foot path.*

The study design calls these the **approximate danger thresholds** deliberately: they vary from person to person and with the conditions of contact. Notice how the $30\,\mathrm{mA}$ rating of a domestic RCD sits at the bottom of the danger range — the RCD is designed to disconnect the circuit before the current through a person can do more than startle them.

Duration matters as much as size. The same current transfers more energy the longer it flows ($E = P\,t$, from 5A), and the risk of ventricular fibrillation rises sharply once a shock lasts as long as a heartbeat (about $1\,\mathrm{s}$). This is why the RCD's speed is the point of it: at $0.03\,\mathrm{s}$, the shock is over in about one thirtieth of a heartbeat, long before the heart's rhythm is likely to be disrupted.

First aid for electric shock. If someone is receiving an electric shock, the order of actions matters, because a rescuer who acts wrongly can become a second victim.

1. **Do not put yourself in danger. Look first, don't touch.** The person may still be in contact with the electric current; if you touch them, you can receive a shock yourself.
2. **Isolate the supply before approaching** — switch off the electricity at the mains or at the power point, and unplug the cord. If the supply cannot be switched off, use a dry object that does not conduct, such as a dry wooden broom handle, to separate the person from the source.
3. **Call triple zero (000)** and ask for an ambulance. "Electricity can kill in an instant. If lives are in danger, call 000" (Energy Safe Victoria).
4. **When it is safe, check whether the person responds and is breathing.** If they are not breathing normally, start CPR.
5. **Cool any burns** under running water for at least 20 minutes.
6. **Seek medical attention even after a seemingly mild shock.** The heart should be checked, and an electric shock can cause internal damage that cannot be seen.

Source: healthdirect Australia, Electric shocks and burns, retrieved 2026-08-18. Source: Energy Safe Victoria, Electrical emergencies, retrieved 2026-08-18.

Practical note. In class, all circuit work is done with low-voltage DC supplies — batteries or a lab power pack. This matches the study design's rule that students are not permitted to carry out electrical work on the internal components of electrical products or equipment that operates above $50\,\mathrm{V}$ AC or $120\,\mathrm{V}$ ripple-free DC; in Victoria only a licensed electrician may work above these voltages (*Electricity Safety Act 1998* (Vic.)). Students may use approved appliances that plug into the $230\,\mathrm{V}$ supply, but must never open them or access their internal components. In practice: never open a switchboard or a meter box, never use an appliance with a damaged cord (report it instead), and treat every household conductor as dangerous. An RCD's test button is there so the device can be checked: pressing it should make the RCD cut the power to its circuit, proving that it works — do this in class only when your teacher directs it, and record the result in your logbook.

Units 3 & 4 preview. The generation and transmission of electricity are analysed in Units 3 & 4, where the household supply is treated as the AC system it really is. Fluency with the three safety devices — what each responds to and what each protects — and with the idea that currents of tens of milliamperes through the body are dangerous, built here, is assumed at that point. This preview is not assessed in Units 1 & 2.

Worked examples

Example 1 — scaffolded

A person with wet hands touches the metal case of a faulty appliance. The case is live at $230\,\mathrm{V}$ relative to the ground, and the person is standing barefoot on a concrete floor. The resistance of the body along the current path is about $2000\,\Omega$. (a) Calculate the current through the person. (b) Use the danger-threshold table to describe the likely effect of this current. (c) The circuit is protected by a $30\,\mathrm{mA}$ RCD. State and explain what happens when the person touches the case.

Working	Comment
$V = 230\,\mathrm{V}$, $R = 2000\,\Omega$, find I.	The person completes the circuit between the live case and the ground.

Working	Comment
(a) $I = V / R = 230 / 2000 = 0.115\text{ A} = 115\text{ mA}$.	Ohm's law, $I = V / R$ (5A).
(b) 115 mA is above the top row of the table (above about 100 mA).	Compare the calculated current with the approximate danger thresholds.
Effect: severe shock, with cardiac arrest and severe burns likely; without help this current is likely to be fatal.	The current is far above the 30 mA level at which the risk of ventricular fibrillation begins.
(c) The person's body provides a leakage path to ground, so the current in the active wire exceeds the current in the neutral wire by 115 mA.	The RCD compares the two currents (6B for the active and neutral wires).
$115\text{ mA} \ge 30\text{ mA}$, so the RCD opens the circuit within 0.03 s.	The residual current exceeds the RCD's rated value, so the RCD trips.

The RCD does not prevent the shock, but it ends it within 0.03 s — before the current has lasted long enough to be most likely to disrupt the heart.

Example 2 — scaffolded

A 2400 W portable heater runs from a 230 V power point on a circuit protected by a 16 A circuit breaker and a 30 mA RCD. (a) Calculate the current the heater draws in normal operation. (b) A fault inside the heater allows a very large current of 30 A to flow. State which device responds and explain how it operates. (c) Instead, a person touching the heater leaks a current of 40 mA to ground through their body. State and explain which device responds.

Working	Comment
(a) $I = P / V = 2400 / 230 = 10.4\text{ A}$.	Power rating divided by supply voltage, $P = V\,I$ rearranged (5A, 6B).
$10.4\text{ A} < 16\text{ A}$, so the circuit operates normally.	The normal current is below the breaker's rated current.
(b) $30\text{ A} > 16\text{ A}$, so the **circuit breaker** opens the circuit.	The current exceeds the breaker's rated current.
The very large short-circuit current trips the breaker's magnetic mechanism almost immediately.	Large currents are cleared fast, before the wiring overheats.
The RCD does not respond: the current still flows out along the active and back along the neutral, so the two currents are equal.	No leakage to ground means no residual current.
(c) The leakage makes the active current exceed the neutral current by 40 mA.	The person provides a path to ground.
$40\text{ mA} \ge 30\text{ mA}$, so the **RCD** opens the circuit within 0.03 s.	The residual current reaches the RCD's rated value.
The breaker does not respond: the circuit current is about $10.4\text{ A} + 0.04\text{ A} \approx 10.4\text{ A}$, far below 16 A.	A breaker responds in amperes; a shock current is tens of milliamperes.

Example 3 — unscaffolded

In Example 1 the current through the person was 115 mA at 230 V. (a) Calculate the power transferred to the person's body. (b) Calculate the energy transferred if the shock lasts 0.03 s (an RCD trips) and if it lasts 2.0 s (no RCD, and the person cannot let go). (c) Explain why the difference matters.

The power follows from $P = V\,I$:

$$P = 230 \times 0.115 = 26.45\text{ W} \approx 26\text{ W}.$$

The energy is $E = P\,t$:

$$E = 26.45 \times 0.03 = 0.79\text{ J}\,(\text{RCD trips at } 0.03\text{ s}),$$

$$E = 26.45 \times 2.0 = 53\,\text{J}\,(\text{no RCD, shock lasts } 2.0\,\text{s}).$$

∴ the power is about $26\,\text{W}$; the energy transferred is $0.79\,\text{J}$ with an RCD and $53\,\text{J}$ without one.

(c) The two energies differ by a factor of about 67. The damage a current does grows with the energy it transfers and with the duration of the shock: the risk of ventricular fibrillation rises sharply once a shock lasts as long as a heartbeat (about $1\,\text{s}$). With the RCD, the shock lasts $0.03\,\text{s}$ — about one thirtieth of a heartbeat; without it, the $2.0\,\text{s}$ shock spans two full heartbeats and transfers 67 times as much energy. This is the quantitative reason why the speed of an RCD, not just its sensitivity, saves lives.

Example 4 — unscaffolded

A student finds a person gripping a damaged extension lead plugged into a $230\,\text{V}$ power point, unable to let go. (a) Explain why the person cannot let go. (b) Describe, in the correct order, what the student should do, justifying the first step. (c) Afterwards the person says they feel fine. Explain why they must still see a doctor.

(a) The current from the $230\,\text{V}$, $50\,\text{Hz}$ AC supply passes through the muscles of the person's hand and arm and causes them to contract. Because the current is above the let-go threshold (about $10\,\text{mA}$), the contraction is sustained: the muscles grip the conductor and the person cannot release it, so the shock continues for as long as the contact lasts.

(b) First, the student must not touch the person: the person is still in contact with the current, and touching them could pass the current on to the student as well. Instead: (1) switch off the supply — at the power point or at the switchboard — or unplug the lead; if the supply cannot be switched off, separate the person from the lead using a dry object that does not conduct, such as a dry wooden broom handle; (2) call triple zero (000) for an ambulance;

(3) check whether the person responds and is breathing, and start CPR if they are not breathing normally; (4) cool any burns under running water for at least 20 minutes.

(c) Even a shock that feels mild can have disrupted the rhythm of the heart, and heart problems can appear hours later; the current can also cause internal damage that cannot be seen from outside. Anyone who has received an electric shock should have their heart checked by a doctor.

Practice questions

Question 1 Copy and complete the table below, which compares the three safety devices in a household switchboard.

Device	Responds to	Protects	After it operates
Fuse	…	the wiring and appliances against overloads and short circuits	…
Circuit breaker	…	…	it can be reset once the fault is cleared
RCD	an imbalance between the active and neutral currents (a residual current) of $30\,\text{mA}$ or more	…	…

Question 2 A person touches a live part of the $230\,\text{V}$ household supply. Their body resistance along the current path is $50\,\text{k}\,\Omega$ with dry skin and $2.0\,\text{k}\,\Omega$ with wet skin. (a) Calculate the current in each case. (b) Use the danger-threshold table to describe the likely effect in each case. (c) State what this comparison shows about using appliances with wet hands.

Question 3 An appliance labelled $1500\,\text{W}$ runs from the $230\,\text{V}$ supply. The circuit is protected by a fuse, and the available fuse ratings are $5\,\text{A}$, $8\,\text{A}$ and $15\,\text{A}$. (a) Calculate the current the appliance draws in normal operation. (b) State which fuse rating should be used, and justify your choice by referring to the other two ratings.

Question 4 An RCD monitoring a circuit records a current of $3.60\ \text{A}$ in the active wire and $3.57\ \text{A}$ in the neutral wire. (a) Calculate the residual current. (b) The RCD's rated residual current is $30\ \text{mA}$. State whether the RCD opens the circuit, and justify your answer. (c) State one possible cause of the imbalance.

Question 5 A person receives an electric shock in which a current of $30\ \text{mA}$ leaks from a faulty appliance through their body to ground. The circuit is protected by a $16\ \text{A}$ circuit breaker and a $30\ \text{mA}$ RCD. (a) Explain why the circuit breaker does not respond. (b) Explain how the RCD detects the fault. (c) Explain why the RCD's operating time of $0.03\ \text{s}$ is important for the person's safety.

Question 6 The following actions are available after a person receives an electric shock: (i) call triple zero (000) for an ambulance; (ii) switch off the electricity supply or unplug the cord; (iii) check whether the person responds and is breathing, and start CPR if they are not breathing normally; (iv) touch the person and pull them away from the source; (v) cool any burns under running water for at least 20 minutes. (a) Arrange the actions (i), (ii), (iii) and (v) in the correct order. (b) Explain why action (iv) must never come first.

Question 7 A person with dry skin touches a live part of the $230\ \text{V}$ supply; the resistance of their body along the current path is $12\ \text{k}\,\Omega$. Calculate the current and use the danger-threshold table to describe the likely effect. Then show that if the skin is wet and the resistance falls to $1200\ \Omega$, the current exceeds $100\ \text{mA}$.

Question 8 A $2400\ \text{W}$ heater is plugged into a circuit protected by a $10\ \text{A}$ fuse, and connected to the $230\ \text{V}$ supply. (a) Calculate the current the heater draws in normal operation. (b) State what happens when the heater runs at full power, and justify your answer. (c) A short circuit in the heater then allows a current of $22\ \text{A}$ to flow. State how the fuse responds to this current compared with the current in part (b).

Question 9 Energy Safe Victoria states that safety switches are "an additional form of protection" to be used with circuit breakers and fuses, and that they "will not prevent all electric shocks". Explain why RCDs are additional to, rather than a replacement for, fuses and circuit breakers, and give one reason why an RCD cannot prevent every shock.

Question 10 A person touches the active and the neutral conductors of an appliance at the same time. Explain why the RCD on that circuit does not open, even though the person is receiving a shock.

Question 11 A person receives a shock in which a current of $60\ \text{mA}$ passes through their body at $230\ \text{V}$. (a) Calculate the power transferred to the body. (b) Calculate the energy transferred if the shock lasts $0.03\ \text{s}$ and if it lasts $1.0\ \text{s}$. (c) Use your answers to explain why the duration of a shock matters as much as its size.

Question 12 Energy Safe Victoria states that electric shocks near swimming pools "are more likely to be fatal than those received in other locations, as bare feet, minimum clothing and wet skin reduce your body's insulation and resistance". Explain this statement using the relationship between potential difference, current and resistance.

Question 13 Inside a metal-cased washing machine, the active wire comes loose and touches the case. The case is connected to the earth wire (6B), and the circuit is protected by a fuse and an RCD. Explain how the earth connection and the RCD each help to protect a person who later touches the case.

Question 14 A person touches a live part of the $230\ \text{V}$ supply. The resistance of their body along the current path is $4.6\ \text{k}\,\Omega$. (a) Calculate the current through the person. (b) Use the danger-threshold table to describe the risk. (c) State whether a $16\ \text{A}$ circuit breaker on the circuit responds, and whether a $30\ \text{mA}$ RCD responds, justifying each answer. (d) Calculate the energy transferred to the person if the RCD opens the circuit in $0.03\ \text{s}$.

Question 15 In Victoria, "All switchboards must have RCDs fitted", yet Energy Safe Victoria also warns that safety switches "will not prevent all electric shocks". Resolve this apparent contradiction: state what RCDs protect against, and state one situation in which an RCD will not protect a person.

Question 16 A person gripping a live conductor of the $230\ \text{V}$, $50\ \text{Hz}$ AC supply cannot let go. Explain how the current prevents them letting go, and explain why being unable to let go makes the shock more dangerous, making reference to duration and to the energy transferred.

Question 17 The $2400\ \text{W}$ heater of Worked Example 2 is running normally, drawing $10.4\ \text{A}$ from the $230\ \text{V}$ supply, when a fault causes a leakage current of $35\ \text{mA}$ through a person to ground. (a) Calculate the total current in the active wire. (b) Explain why the $16\,\mathrm{A}$ circuit breaker does not respond. (c) Explain why the $30\,\mathrm{mA}$ RCD does respond.

Question 18 A student writes: “A fuse protects you against electric shock, because it cuts the power when something goes wrong.” Identify the error in this statement and correct it, making reference to the currents involved.

Question 19 A person is in contact with a live conductor and is still being shocked. (a) Explain why a rescuer must not touch the person directly. (b) State two ways the rescuer can make the situation safe, one of which does not require switching off the supply.

Question 20 To stay below the let-go threshold, the current through a person’s body must be kept below about $10\,\mathrm{mA}$. (a) Calculate the smallest body resistance for which contact with the $230\,\mathrm{V}$ supply keeps the current below $10\,\mathrm{mA}$. (b) Dry, unbroken skin provides tens of thousands of ohms; wet skin may provide only a few thousand ohms. Use your answer to explain why wet hands make the household supply so much more dangerous.

Answers

Question 1 Fuse: a current above its rated value; it must be replaced by a fuse of the same rated current. Circuit breaker: a current above its rated value; the wiring and appliances against overloads and short circuits. RCD: people, against electric shock; it can be reset (and its test button checks it works). **Question 2** (a) dry: $4.6\,\text{mA}$, wet: $115\,\text{mA}$; (b) dry: felt, below the let-go threshold, the person can usually let go; wet: far above $30\,\text{mA}$, risk of ventricular fibrillation, likely to be fatal; (c) wet skin lowers the body's resistance and greatly increases the current. **Question 3** (a) $6.5\,\text{A}$; (b) the $8\,\text{A}$ fuse: the $5\,\text{A}$ fuse would blow in normal operation, and the $15\,\text{A}$ fuse would allow currents large enough to overheat the wiring. **Question 4** (a) $0.03\,\text{A} = 30\,\text{mA}$; (b) yes — the residual current reaches the rated value, so the RCD opens the circuit; (c) any one of: a person touching a live part; damaged insulation or moisture providing a leakage path to ground. **Question 5** (a) $30\,\text{mA} = 0.03\,\text{A}$ is far below the $16\,\text{A}$ rating; (b) the leakage makes the active current exceed the neutral current by $30\,\text{mA}$, reaching the RCD's rated residual current, so it opens the circuit; (c) the shock ends in about one thirtieth of a heartbeat, before the heart's rhythm is likely to be disrupted. **Question 6** (a) (ii), (i), (iii), (v); (b) the person may still be in contact with the current, and touching them could shock the rescuer too. **Question 7** $19\,\text{mA}$ — above the let-go threshold, so the person may be unable to let go; wet: $192\,\text{mA} > 100\,\text{mA}$. **Question 8** (a) $10.4\,\text{A}$; (b) the fuse blows — $10.4\,\text{A}$ exceeds the $10\,\text{A}$ rating; (c) $22\,\text{A}$ is a short-circuit current, so the fuse melts almost immediately rather than after a delay. **Question 9** RCDs respond to leakage currents of tens of milliamperes and protect people, while fuses and breakers respond to overcurrents of amperes and protect the wiring — both jobs are needed; limitation: any one of a person touching active and neutral at the same time, or no leakage path to ground. **Question 10** The current through the person flows out along the active and back along the neutral, so the two currents remain equal, the residual current is zero, and the RCD does not detect a fault. **Question 11** (a) $13.8\,\text{W}$; (b) $0.41\,\text{J}$ and $14\,\text{J}$; (c) the energy grows with time, and the risk of ventricular fibrillation rises sharply once a shock lasts about a heartbeat. **Question 12** Wet skin and bare feet lower the body's resistance; at the same potential difference, $I = V / R$ gives a larger current, so the shock is more severe. **Question 13** The earth wire gives the fault current a low-resistance path to ground, so a large current flows and the fuse melts (6B); the leaking current also makes the active and neutral currents unequal, so the RCD opens the circuit within $0.03\,\text{s}$. **Question 14** (a) $50\,\text{mA}$; (b) above $30\,\text{mA}$ — risk of ventricular fibrillation; (c) the breaker does not respond ($0.050\,\text{A} \ll 16\,\text{A}$); the RCD does ($50\,\text{mA} \geq 30\,\text{mA}$); (d) $0.35\,\text{J}$. **Question 15** RCDs protect people against shocks caused by leakage to ground; they cannot help when the currents stay balanced, for example when a person touches active and neutral at the same time. **Question 16** The $50\,\text{Hz}$ AC causes a sustained contraction of the muscles above the let-go threshold; the longer the shock lasts, the more energy is transferred ($E = P\,t$) and the greater the risk of ventricular fibrillation. **Question 17** (a) $10.4\,\text{A}$; (b) $10.4\,\text{A}$ is far below the $16\,\text{A}$ rating; (c) the leakage makes the residual current $35\,\text{mA} \geq 30\,\text{mA}$, so the RCD opens the circuit. **Question 18** A fuse responds to overcurrents of amperes and protects the wiring; a shock current is only tens of milliamperes, far below the fuse's rating — the device that protects people is the RCD. **Question 19** (a) the person is still in contact with the current, so the rescuer could be shocked too; (b) switch off the supply or unplug the cord; or separate the person with a dry object that does not conduct, such as a dry wooden broom handle. **Question 20** (a) $23\,\text{k}\,\Omega$; (b) dry skin can exceed $23\,\text{k}\,\Omega$, keeping the current below the let-go threshold, while wet skin is far below it, so the current rises into the danger range.

Fully-worked solutions

Question 1 The fuse responds to a current above its rated value, and after it operates it must be replaced by a fuse of the same rated current. The circuit breaker also responds to a current above its rated value, and it protects the wiring and the appliances against overloads and short circuits. The RCD responds to a residual current of $30\,\text{mA}$ or more and protects people against electric shock; after it operates it can be reset, and its test button checks that it works. The pattern is that fuses and breakers respond in amperes and protect the wiring, while the RCD responds in milliamperes and protects people.

Question 2 (a) Using $I = V / R$ with $V = 230\,\text{V}$: dry skin: $I = 230 / 50\,000 = 0.0046\,\text{A} = 4.6\,\text{mA}$; wet skin: $I = 230 / 2000 = 0.115\,\text{A} = 115\,\text{mA}$. (b) At $4.6\,\text{mA}$ the shock is felt and may be unpleasant, but it is below the let-go threshold of about $10\,\text{mA}$, so the person can usually let go. At $115\,\text{mA}$ the current is above the top row of the table: there is a serious risk of ventricular fibrillation and the shock is likely to be fatal. (c) Wet skin greatly lowers the body's resistance, so the same $230\,\text{V}$ drives a current about 25 times larger. Appliances must never be touched with wet hands.

Question 3 (a) $I = P / V = 1500 / 230 = 6.5\ \text{A}$. (b) The $8\ \text{A}$ fuse should be used: it is the smallest available rating above the normal current of $6.5\ \text{A}$. The $5\ \text{A}$ fuse would blow in normal operation, since $6.5\ \text{A}$ exceeds its rating. The $15\ \text{A}$ fuse would carry currents large enough to overheat the circuit's wiring without melting, removing the protection the fuse is there to provide.

Question 4 (a) The residual current is the difference between the two currents: $3.60 - 3.57 = 0.03\ \text{A} = 30\ \text{mA}$. (b) The residual current has reached the RCD's rated residual current of $30\ \text{mA}$, so the RCD opens the circuit (within $0.03\ \text{s}$). (c) Any one of: a person touching a live part and providing a path to ground; damaged insulation or moisture allowing current to leak from the circuit to ground.

Question 5 (a) The shock current is $30\ \text{mA} = 0.03\ \text{A}$, which is far below the breaker's rated current of $16\ \text{A}$. The breaker responds to overcurrents measured in amperes, so it does not open. (b) The current leaking through the person does not return along the neutral wire, so the RCD detects an imbalance of $30\ \text{mA}$ between the active and neutral currents. This reaches the RCD's rated residual current, and the RCD opens the circuit within $0.03\ \text{s}$. (c) The risk of ventricular fibrillation rises sharply once a shock lasts as long as a heartbeat (about $1\ \text{s}$). At $0.03\ \text{s}$ the RCD ends the shock in about one thirtieth of a heartbeat, limiting both the energy transferred to the body and the chance that the heart's rhythm is disrupted.

Question 6 (a) The correct order is: (ii) switch off the electricity supply or unplug the cord; (i) call triple zero (000); (iii) check whether the person responds and is breathing, and start CPR if they are not breathing normally; (v) cool any burns under running water for at least 20 minutes. (b) The person may still be in contact with the electric current. A rescuer who touches them becomes part of the circuit and can receive a shock themselves — the rescuer must isolate the supply first (or use a dry object that does not conduct to separate the person from the source).

Question 7 Dry skin: $I = V / R = 230 / 12\,000 = 0.0192\ \text{A} = 19\ \text{mA}$ (to two significant figures). This is above the let-go threshold of about $10\ \text{mA}$: the muscles may contract and the person may be unable to let go. Wet skin: $I = 230 / 1200 = 0.192\ \text{A} = 192\ \text{mA}$, which exceeds $100\ \text{mA}$ — into the range of severe burns and cardiac arrest, likely to be fatal.

Question 8 (a) $I = P / V = 2400 / 230 = 10.4\ \text{A}$. (b) $10.4\ \text{A}$ exceeds the fuse's $10\ \text{A}$ rated current, so the fuse melts and the circuit is disconnected. The heater is too powerful for a $10\ \text{A}$ circuit and cannot run at full power on it. (c) A current of $22\ \text{A}$ is a short-circuit current: it exceeds the rating by far more than in part (b), so the fuse element melts almost immediately rather than after the delay of a small overload.

Question 9 Model answer. The three devices protect against different hazards. Fuses and circuit breakers respond to overcurrents — currents of amperes above a rated value — and they protect the wiring and appliances from overheating, overload and short circuit. An RCD responds to leakage currents of only tens of milliamperes, and it protects people from electric shock. Neither job replaces the other: an RCD does not stop a circuit from overloading, and a fuse cannot respond to the small current that harms a person. That is why an RCD is an additional form of protection, fitted alongside the other devices. An RCD cannot prevent every shock because it operates only when the active and neutral currents are unequal: if a person touches the active and the neutral conductors at the same time, the current through them still returns along the neutral wire, the currents stay balanced, and the RCD detects no residual current.

Question 10 Model answer. The RCD opens only when it detects a residual current — an imbalance between the current in the active wire and the current in the neutral wire. When a person touches active and neutral at the same time, the current through the person flows out along the active wire and back along the neutral wire, exactly like the current in an appliance. The two currents remain equal, the residual current is zero, and the RCD does not open, even though the person is receiving a shock. This is one reason why RCDs "will not prevent all electric shocks".

Question 11 (a) $P = VI = 230 \times 0.060 = 13.8\ \text{W}$. (b) $E = Pt$: for $0.03\ \text{s}$, $E = 13.8 \times 0.03 = 0.41\ \text{J}$; for $1.0\ \text{s}$, $E = 13.8 \times 1.0 = 14\ \text{J}$ (to two significant figures). (c) The same current transfers more than 30 times as much energy when it lasts $1.0\ \text{s}$ rather than $0.03\ \text{s}$. The damage a shock does grows with the energy transferred, and the risk of ventricular fibrillation rises sharply once the shock lasts as long as a heartbeat (about $1\ \text{s}$). The size of the current and the duration of the shock therefore matter equally: a smaller current held for a long time can be as dangerous as a larger current held briefly.

Question 12 Model answer. The current through the body is set by the potential difference and the body's resistance: $I = V / R$. Near a pool the skin is wet and the person is usually barefoot, and water on the skin greatly lowers the body's resistance. For the same potential difference, a lower resistance gives a larger current, so a fault that would give a startling shock with dry skin can drive a current into the danger range — above $30\,\text{mA}$, where there is a risk of ventricular fibrillation. Bare feet also give good contact with the ground, completing the path for the current.

Question 13 Model answer. When the active wire touches the case, the case becomes live. Because the case is connected to the earth wire, the fault provides a low-resistance path to ground: a large current flows, and the fuse melts and disconnects the appliance, as described in 6B. The RCD adds a second, faster layer of protection: the current flowing to ground through the earth wire does not return along the neutral wire, so the active current exceeds the neutral current. The RCD detects this residual current and opens the circuit within $0.03\,\text{s}$. Between them, the earth connection and the RCD ensure that anyone who touches the case meets either a disconnected appliance or a supply that is cut off within a fraction of a heartbeat.

Question 14 (a) $I = V / R = 230 / 4600 = 0.050\ \text{A} = 50\,\text{mA}$. (b) $50\,\text{mA}$ is above about $30\,\text{mA}$, so there is a risk of ventricular fibrillation; the shock is dangerous. (c) The circuit breaker does not respond: the current is $0.050\ \text{A}$, far below its $16\ \text{A}$ rating. The RCD does respond: the person's body carries $50\,\text{mA}$ to ground, so the residual current is $50\,\text{mA} \geq 30\,\text{mA}$, and the RCD opens the circuit within $0.03\,\text{s}$. (d) $E = P\,t = V\,I\,t = 230 \times 0.050 \times 0.03 = 0.345\,\text{J} \approx 0.35\,\text{J}$.

Question 15 Model answer. There is no contradiction: the two statements are about different situations. RCDs are required on every switchboard because they protect people against the most common cause of serious shock — current leaking to ground through a fault or through a person — and they are the only switchboard device that can respond to currents as small as $30\,\text{mA}$. But an RCD works by detecting an imbalance between the active and neutral currents, so it cannot protect a person when no imbalance occurs: if a person touches the active and the neutral conductors at the same time, the currents stay balanced and the RCD does not open. The warning reminds people that an RCD reduces the risk of shock but does not remove the need for care.

Question 16 Model answer. The alternating current at $50\,\text{Hz}$ causes the muscles of the hand and arm to contract. Once the current is above the let-go threshold of about $10\,\text{mA}$, the contraction is sustained: the muscles grip the conductor and the person cannot release it. Being unable to let go makes the shock far more dangerous because the contact continues. The energy transferred to the body is $E = P\,t$, so the longer the shock lasts the more energy is deposited as damage; and the risk of ventricular fibrillation rises sharply once a shock lasts as long as a heartbeat. A shock that ends in $0.03\,\text{s}$ (an RCD) transfers only a small fraction of the energy of a shock that continues for seconds.

Question 17 (a) The active wire carries the heater's current plus the leakage: $10.4 + 0.035 = 10.435\ \text{A} = 10.4\ \text{A}$ (to three significant figures). (b) $10.4\ \text{A}$ is still far below the breaker's $16\ \text{A}$ rating — adding $35\,\text{mA}$ changes the total by less than half a percent — so the breaker does not respond. (c) The leaking current does not return along the neutral wire, so the RCD detects a residual current of $35\,\text{mA}$. This is greater than the RCD's rated residual current of $30\,\text{mA}$, so the RCD opens the circuit within $0.03\,\text{s}$.

Question 18 Model answer. The error is that a fuse does not respond to shock currents. A fuse melts when the current exceeds its rated current — a value of amperes, chosen to protect the circuit's wiring from overheating. The current that harms a person is only tens of milliamperes: $30\,\text{mA}$ is $0.03\ \text{A}$, hundreds of times smaller than a typical fuse rating, so a person could receive a fatal shock while the fuse carries the current without even warming noticeably. The device that protects people is the RCD, which detects the imbalance a shock current creates between the active and neutral wires and opens the circuit within $0.03\,\text{s}$.

Question 19 Model answer. (a) The person may still be in contact with the electric current. A rescuer who touches them directly can become part of the circuit and receive a shock themselves, turning one victim into two. (b) First, switch off the electricity supply — at the power point or the switchboard — or unplug the cord. If the supply cannot be switched off, the rescuer can separate the person from the conductor using a dry object that does not conduct, such as a dry wooden broom handle.

Question 20 (a) From $I = V / R$ rearranged as $R = V / I$, the smallest resistance that keeps the current below $10\,\text{mA}$ is

$$R = \frac{230}{0.010} = 23\,000\,\Omega = 23\,\text{k}\,\Omega\,.$$

(b) Dry, unbroken skin provides tens of thousands of ohms, which can exceed $23\,\mathrm{k}\,\Omega$ and keep the current below the let-go threshold of $10\,\mathrm{mA}$. Wet skin provides only a few thousand ohms — well below $23\,\mathrm{k}\,\Omega$ — so the current rises to tens or hundreds of milliamperes, into the range where the person cannot let go and the heart's rhythm is at risk. This is why the same $230\,\mathrm{V}$ supply that might only tingle with dry hands can kill with wet ones.

Topic 3 Test A — Modelling and using electricity (multiple choice)

Time allowed: 25 minutes · 20 marks · One scientific calculator permitted · The formula sheet (back of the Practice Examinations booklet) may be used.

Choose the response that is correct or that best answers the question. A correct answer scores 1 mark; an incorrect answer scores 0. Marks are not deducted for incorrect answers. No marks are given if more than one answer is completed for any question. Unless otherwise indicated, the diagrams in this test are not drawn to scale. The relations $I=\frac{Q}{t}$, $V=\frac{E}{Q}$, $P=\frac{E}{t}=VI$, $I=\frac{V}{R}$, $R_{\text{equivalent}}=R_1+R_2+\ldots$ *(series),* $\frac{1}{R_{\text{equivalent}}}=\frac{1}{R_1}+\frac{1}{R_2}+\ldots$ *(parallel) and* $1\,\text{kW h}=3.6\times10^{6}\,\text{J}$ *are provided on the formula sheet.*

Marks and time allowances are house convention: the VCE Physics Study Design fixes no mark allocations for Units 1 & 2 (assessment is a matter for school decision), and nothing in this test is a VCAA requirement.

Question 1

A $9.0\,\text{V}$ battery drives a steady current of $2.0\,\text{A}$ through a heating element for 3.0 minutes. Which one of the following is closest to the charge that passes through the element in this time?

A. $6.0\,\text{C}$

B. $27\,\text{C}$

C. $360\,\text{C}$

D. $3240\,\text{C}$

Question 2

When $40\,\text{C}$ of charge passes through a small electric motor, $480\,\text{J}$ of energy is transferred to the motor. Which one of the following is closest to the potential difference across the motor?

A. $19\,200\,\text{V}$

B. $12\,\text{V}$

C. $0.083\,\text{V}$

D. $520\,\text{V}$

Question 3

A small fan is connected to a $4.0\,\text{V}$ battery and carries a current of $1.2\,\text{A}$. Which one of the following is closest to the power of the fan?

A. $4.8\,\text{W}$

B. $3.3\,\text{W}$

C. $5.2\,\text{W}$

D. $0.30\,\text{W}$

Question 4

A teacher models an electric circuit with a water circuit: a pump, pipes and a water wheel. Which one of the following gives correct correspondences for this analogy?

A. The pump creates the water in the pipes, in the same way that a cell creates the charge in the wires.

B. The flow of water is smaller after the water has passed through the wheel, in the same way that current is used up in a component.

C. The pump stores water until the circuit is complete, in the same way that a cell stores charge until the circuit is closed.

D. The pump corresponds to the cell, the pressure difference produced by the pump corresponds to the potential difference, and the water already in the pipes corresponds to the charge already in the wires.

Question 5

A student wants to measure the current in a resistor. Which one of the following describes the correct meter and connection, with the reason for it?

A. A voltmeter connected in parallel across the resistor, with a resistance as high as possible.

B. A voltmeter connected in series with the resistor, with a resistance as high as possible.

C. An ammeter connected in series with the resistor, with a resistance as low as possible.

D. An ammeter connected in parallel across the resistor, with a resistance as low as possible.

Question 6

A $2.0\,\text{kW}$ heater in a Victorian home runs for 36 minutes. Which one of the following is closest to the energy it transfers in this time?

A. $1.2\,\text{kW h}$

B. $72\,\text{kW h}$

C. $0.60\,\text{kW h}$

D. $3.6\,\text{kW h}$

Question 7

Which one of the following best describes the kilowatt-hour (kW h)?

A. The power used by an appliance rated at $1\,\text{kW}$.

B. A unit of energy: the energy transferred by a $1\,\text{kW}$ appliance running for 1 hour, equal to $3.6 \times 10^6\,\text{J}$.

C. The time for which a $1\,\text{kW}$ appliance must run to transfer $1\,\text{J}$ of energy.

D. The current drawn by a $1\,\text{kW}$ appliance from the household supply.

Question 8

A component in a circuit has a potential difference of $6.0\,\mathrm{V}$ across it and carries a current of $0.25\,\mathrm{A}$. Which one of the following is closest to the resistance of the component?

A. $1.5\,\Omega$

B. $0.042\,\Omega$

C. $6.0\,\Omega$

D. $24\,\Omega$

Question 9

A student measures the current in a device: at $5.0\,\mathrm{V}$ the current is $1.0\,\mathrm{A}$, and at $10\,\mathrm{V}$ the current is $2.0\,\mathrm{A}$. Which one of the following conclusions is correct?

A. The device is ohmic and its resistance is $0.20\,\Omega$.

B. The device is non-ohmic because its resistance is changing.

C. The device is ohmic and its resistance is $5.0\,\Omega$.

D. The device is non-ohmic because its resistance increases as the potential difference increases.

Question 10

Two resistors, of $12\,\Omega$ and $4.0\,\Omega$, are connected in parallel. Which one of the following is closest to their equivalent resistance?

A. $16\,\Omega$

B. $3.0\,\Omega$

C. $8.0\,\Omega$

D. $48\,\Omega$

Question 11

Two resistors, of $3.0\,\Omega$ and $5.0\,\Omega$, are connected in series. Which one of the following is closest to their equivalent resistance?

A. $8.0\,\Omega$

B. $15\,\Omega$

C. $1.9\,\Omega$

D. $0.53\,\Omega$

Question 12

A $12\,\mathrm{V}$ battery is connected to a circuit containing a $2.0\,\Omega$ resistor in series with a parallel pair of two $6.0\,\Omega$ resistors. Which one of the following is closest to the current delivered by the battery?

A. $0.86\,\mathrm{A}$

B. $1.5\,\mathrm{A}$

C. $2.4\,\mathrm{A}$

D. $4.0\,\mathrm{A}$

Question 13

A voltage divider is made from a $5.0\,k\,\Omega$ resistor and a $3.0\,k\,\Omega$ resistor connected in series across a $12\,V$ supply, with the output taken across the $3.0\,k\,\Omega$ resistor. Which one of the following is closest to the output potential difference?

A. $7.5\,V$

B. $4.5\,V$

C. $6.0\,V$

D. $12\,V$

Question 14

Two resistors, R_1 and R_2, are connected in series across a supply of potential difference V_{in} to make a voltage divider, with the output V_{out} taken across R_2. Which one of the following statements is correct?

A. The output is always less than the supply potential difference, and the larger resistor takes the larger share of the potential difference.

B. The output can be greater than the supply potential difference if R_2 is larger than R_1.

C. If the two resistors are equal, the output equals the supply potential difference.

D. The output is given by $V_{out} = V_{in} \times \frac{R_1}{R_1 + R_2}$.

Question 15

Two identical lamps are connected to a battery, first in series and then in parallel. Which one of the following best describes their brightness?

A. In series, each lamp glows at full brightness because the same current passes through both lamps.

B. In parallel, each lamp takes half the supply potential difference, so both glow dimly.

C. The lamps glow with the same brightness in both arrangements because they are identical.

D. In parallel, each lamp has the full supply potential difference across it and glows at full brightness; in series, the supply potential difference is shared and each lamp glows dimly.

Question 16

In Australian homes, appliances are connected in parallel across the $230\,V$ supply rather than in series. Which one of the following is the main reason for this?

A. Parallel circuits draw less current than series circuits, so the wiring does not overheat.

B. The parallel arrangement raises the potential difference supplied to each appliance above $230\,V$.

C. Every appliance receives the full $230\,V$ and can be switched on and off independently of the others.

D. Appliances connected in series would each receive $230\,V$ but would have to share the current.

Question 17

A $1380\,\mathrm{W}$ vacuum cleaner and a $1150\,\mathrm{W}$ iron are both running on a household circuit protected by a $10\,\mathrm{A}$ circuit breaker. The supply is $230\,\mathrm{V}$. Which one of the following best describes what happens?

A. Both appliances run normally, because their combined power rating is less than $2300\,\mathrm{W}$.

B. The total current drawn is $11\,\mathrm{A}$, which exceeds the $10\,\mathrm{A}$ rating, so the circuit breaker opens the circuit.

C. The residual current device (RCD) opens the circuit, because the current in the active wire differs from the current in the neutral wire.

D. Each appliance receives $115\,\mathrm{V}$ because the two appliances share the supply, so both run below their rated power.

Question 18

A silicon diode is connected in series with a resistor and a variable DC supply. Which one of the following best describes when the diode conducts?

A. Once the potential difference across it exceeds about $0.6\,\mathrm{V}$ in the forward direction; above this, the current rises rapidly.

B. As soon as any potential difference is applied across it.

C. Equally well in both directions.

D. Only when it is reverse-biased.

Question 19

Which one of the following safety devices is designed primarily to protect people from electric shock?

A. A fuse — it melts when the current through a person exceeds its rating.

B. A circuit breaker — it opens when the current in the circuit exceeds its rating.

C. The earth wire alone — it carries the shock current safely to ground.

D. A residual current device (RCD) — it opens the circuit when the currents in the active and neutral wires become unequal.

Question 20

For $50\,\mathrm{Hz}$ alternating current on a hand-to-foot path, which one of the following best describes the effects of current through the human body?

A. Currents below about $1\,\mathrm{mA}$ cause ventricular fibrillation.

B. The current through the body is set by the supply voltage alone and does not depend on the body’s resistance.

C. Currents above about $100\,\mathrm{mA}$ cause only a tingling sensation.

D. At and above about $10\,\mathrm{mA}$ a person gripping a conductor may be unable to let go, and currents above about $30\,\mathrm{mA}$ carry a risk of ventricular fibrillation.

End of Topic 3 Test A

Topic 3 Test A — solutions

Question	Answer	Question	Answer
1	C	11	A
2	B	12	C
3	A	13	B
4	D	14	A
5	C	15	D
6	A	16	C
7	B	17	B
8	D	18	A
9	C	19	D
10	B	20	D

Question 1 — C. $Q = I\,t = 2.0 \times (3.0 \times 60) = 2.0 \times 180 = 360\,\text{C}$ — the time must be converted to seconds first. **A** (6.0) multiplies the current by the time in minutes; **B** (27) multiplies the voltage by the time in minutes; **D** (3240) multiplies the voltage by the time in seconds, which would give an energy, not a charge.

Question 2 — B. $V = \frac{E}{Q} = \frac{480}{40} = 12\,\text{V}$: each coulomb transfers $12\,\text{J}$. **A** (19 200) multiplies E by Q; **C** (0.083) divides Q by E; **D** (520) adds the two numbers.

Question 3 — A. $P = V\,I = 4.0 \times 1.2 = 4.8\,\text{W}$. **B** (3.3) divides V by I, which gives a resistance; **C** (5.2) adds the two numbers; **D** (0.30) divides I by V.

Question 4 — D. The correspondences in **D** are correct and match the facts any analogy must reproduce: the cell does work on the charges (as the pump does work on the water), the potential difference is the "push" per coulomb (as the pressure difference is the push on the water), and the charges are already present in the wires (as the water is already in the pipes). **A** and **C** repeat the misconception that a cell creates or stores charge — charges are already in the wires; **B** repeats the misconception that current is used up — the flow (current) is the same at every point of a single loop.

Question 5 — C. Current is the rate of flow of charge, so the meter that measures it must sit in the path of the flow: an ammeter is connected in series with the component. Its resistance must be as low as possible so that it does not change the current it is measuring. **A** and **D** use the wrong meter or the wrong connection (a parallel ammeter would short the component); **B** places a high-resistance voltmeter in series, which would almost stop the current.

Question 6 — A. Convert the time first: $36\,\text{min} = 0.60\,\text{h}$, then $E = P\,t = 2.0 \times 0.60 = 1.2\,\text{kW h}$. **B** (72) multiplies by the time in minutes; **C** (0.60) quotes the time as if it were the energy; **D** (3.6) brings in the 3.6×10^6 joule conversion factor where it is not needed.

Question 7 — B. The kilowatt-hour is a unit of energy: $1\,\text{kW h} = 1000\,\text{W} \times 3600\,\text{s} = 3.6 \times 10^6\,\text{J}$, the energy transferred by a $1\,\text{kW}$ device running for 1 hour. **A** describes a power; **C** garbles the definition into a time; **D** describes a current.

Question 8 — D. $R = \frac{V}{I} = \frac{6.0}{0.25} = 24\,\Omega$. **A** (1.5) multiplies V by I; **B** (0.042) divides I by V; **C** (6.0) quotes the potential difference as if it were the resistance.

Question 9 — C. The ratio V / I is the same at both readings: $5.0 / 1.0 = 5.0\,\Omega$ and $10 / 2.0 = 5.0\,\Omega$. A constant resistance means the device is ohmic, with $R = 5.0\,\Omega$. **A** uses the inverted ratio I / V; **B** and **D** claim the resistance is changing when the data show it is constant.

Question 10 — B. For two resistors in parallel, $R_{\text{equivalent}} = \dfrac{R_1 R_2}{R_1 + R_2} = \dfrac{12 \times 4.0}{12 + 4.0} = \dfrac{48}{16} = 3.0\,\Omega$. **A** (16) adds the resistances as if they were in series; **C** (8.0) averages them; **D** (48) multiplies them. The equivalent resistance of a parallel group is always smaller than the smallest member.

Question 11 — A. In series, resistances add: $R_{\text{equivalent}} = 3.0 + 5.0 = 8.0\,\Omega$. **B** (15) multiplies them; **C** (1.9) applies the parallel rule; **D** (0.53) inverts the parallel sum incorrectly.

Question 12 — C. The parallel pair gives $\dfrac{6.0 \times 6.0}{6.0 + 6.0} = 3.0\,\Omega$, so the total resistance is $2.0 + 3.0 = 5.0\,\Omega$ and $I = \dfrac{V}{R} = \dfrac{12}{5.0} = 2.4\text{ A}$. **A** (0.86) adds all three resistors as if they were in series ($14\,\Omega$); **B** (1.5) leaves the parallel pair at $6.0\,\Omega$; **D** (4.0) ignores the series resistor ($12/3.0$).

Question 13 — B. $V_{\text{out}} = V_{\text{in}} \times \dfrac{R_2}{R_1 + R_2} = 12 \times \dfrac{3000}{5000 + 3000} = 12 \times \dfrac{3}{8} = 4.5\text{ V}$. **A** (7.5) is the share across the $5.0\text{ k}\Omega$ resistor; **C** (6.0) halves the supply, which only holds for equal resistors; **D** (12) treats the output as the full supply.

Question 14 — A. Because $\dfrac{R_2}{R_1 + R_2}$ is always less than 1, the output is always less than the supply, and in a series circuit the larger resistance takes the larger share of the potential difference. **B** contradicts the first fact; **C** is wrong — equal resistors halve the supply, $V_{\text{out}} = V_{\text{in}}/2$; **D** gives the share across R_1, not the output across R_2.

Question 15 — D. In parallel, each lamp is connected directly across the battery and receives the full supply potential difference, so each glows at full brightness. In series, the supply potential difference is shared between the two lamps, so each receives half and glows dimly. **A** wrongly claims full brightness in series; **B** reverses the parallel behaviour (parallel branches each receive the full supply, not half); **C** ignores that the potential difference across each lamp differs between the two arrangements.

Question 16 — C. In a parallel arrangement every appliance is connected directly across the supply, so each receives the full 230 V it is designed for, and each can be switched independently. **A** is false — parallel circuits draw more total current, not less; **B** is false — the supply stays at 230 V; **D** describes series, not parallel, behaviour, and series appliances would share the voltage, not each receive 230 V.

Question 17 — B. $I = P/V$ for each appliance: the vacuum cleaner draws $1380/230 = 6.0\text{ A}$ and the iron draws $1150/230 = 5.0\text{ A}$. Parallel currents add, so the circuit draws 11 A, which exceeds the breaker's 10 A rating — an overload — and the breaker opens. **A** compares powers when the breaker responds to current; **C** is wrong because there is no imbalance — all the current that leaves on the active wire returns on the neutral; **D** treats the appliances as a series circuit, but household loads are in parallel and each receives the full 230 V.

Question 18 — A. A silicon diode conducts in the forward direction only once the potential difference across it exceeds its threshold of about 0.6 V; above the threshold the current rises rapidly. **B** ignores the threshold; **C** is false — a diode is a one-way device; **D** reverses the condition (a reverse-biased diode does not conduct).

Question 19 — D. An RCD compares the current in the active wire with the current in the neutral wire. If some of the current finds another path to ground — for example through a person — the two currents become unequal, and the RCD opens the circuit within about 0.03 s at its 30 mA rating. It is the device designed to protect people. **A** and **B** are wrong because a fuse or circuit breaker responds to currents of many amperes — far above a shock current — and protects the wiring, not the person; **C** is wrong because the earth wire normally carries no current: it keeps metal cases from becoming live but does not carry a shock current through a person.

Question 20 — D. These are the approximate danger thresholds for 50 Hz AC on a hand-to-foot path: below about 10 mA a person can usually let go; at and above about 10 mA (the let-go threshold) the muscles may contract so a person gripping a conductor cannot release it; above about 30 mA there is a risk of ventricular fibrillation, growing with both current and duration. **A** is wrong — currents below about 1 mA are the threshold of perception (a tingle); **B**

is wrong — by $I = V / R$ the current depends on the body's resistance, which varies with the condition of the skin; **C** is wrong — currents above about $100\,\text{mA}$ cause severe burns and cardiac arrest and are likely to be fatal.

Source: International Electrotechnical Commission, IEC 60479-1, Effects of current on human beings and livestock — Part 1: General aspects, retrieved 2026-08-18. The values are approximate, for $50\,\text{Hz}$ *AC on a hand-to-foot path.*

Topic 3 Test B — Modelling and using electricity (written responses)

Time allowed: 50 minutes · 40 marks · One scientific calculator permitted · The formula sheet (back of the Practice Examinations booklet) may be used. In questions where more than one mark is available, appropriate working must be shown.

Answer all questions in the spaces provided. Where a final answer has a required unit, give your answer in that unit. Unless otherwise indicated, the diagrams in this test are not drawn to scale.

Marks and time allowances are house convention: the VCE Physics Study Design fixes no mark allocations for Units 1 & 2 (assessment is a matter for school decision), and nothing in this test is a VCAA requirement.

Question 1 (6 marks)

A portable radio runs from a $9.0\,\text{V}$ battery. When the radio is playing, the current in its circuit is a steady $0.40\,\text{A}$.

a. Show that the charge that passes through the radio in 30 minutes of playing is $720\,\text{C}$. 2 marks

b. Calculate the energy transferred to the radio in this time. Give your answer in J. 2 marks

c. Calculate the power of the radio. Give your answer in W. 1 mark

d. The radio's circuit is a single loop. Explain why the current is the same at every point in the loop. 1 mark

Question 2 (7 marks)

A bedroom circuit in a Victorian home is modelled as a $230\,\text{V}$ supply protected by a $10\,\text{A}$ circuit breaker, with the appliances connected in parallel. A $920\,\text{W}$ iron and a $1380\,\text{W}$ vacuum cleaner are running on the circuit.

a. Calculate the current in the iron. Give your answer in A. 1 mark

b. Calculate the current in the vacuum cleaner, and the total current drawn from the supply. Give your answers in A. 2 marks

c. A $230\,\text{W}$ lamp is then plugged into the same circuit. State what happens, and justify your answer. 1 mark

d. Explain why the circuit breaker is placed in the active wire rather than in the neutral wire. 1 mark

e. State the purpose of the earth wire in a household circuit. 2 marks

Question 3 (7 marks)

Students design a temperature-sensing circuit to switch a heater on in a greenhouse. The circuit is a voltage divider: a fixed resistor $R_1 = 1200\,\Omega$ and an NTC thermistor R_2 are connected in series across a $6.0\,\text{V}$ battery, and the output V_{out} is measured across the thermistor. At $20\,°\text{C}$ the thermistor's resistance is $800\,\Omega$.

a. At $20\,°\text{C}$, calculate the current in the divider and the output potential difference V_{out}. Give your answers in mA and in V. 2 marks

b. As the greenhouse warms up, state what happens to the resistance of the thermistor and to V_{out}. 1 mark

c. The heater is to switch on when the greenhouse cools down. Explain why V_{out} rises as the temperature falls. 1 mark

d. Suppose R_2 were replaced by a light-dependent resistor (LDR). State one change in conditions that would make V_{out} rise in the same way. 1 mark

e. The heater's switch closes when V_{out} reaches $3.6\,\text{V}$. On a cold morning the thermistor's resistance is $2400\,\Omega$. Determine whether the heater switches on. 2 marks

Question 4 (6 marks)

A $12\,\text{V}$ battery is connected to a circuit containing a $4.0\,\Omega$ resistor and a $12\,\Omega$ resistor connected in parallel, and this combination in series with a $7.0\,\Omega$ resistor.

a. Show that the equivalent resistance of the parallel pair is $3.0\,\Omega$. 1 mark

b. Calculate the total resistance of the circuit. Give your answer in Ω. 1 mark

c. Calculate the current delivered by the battery. Give your answer in A. 1 mark

d. Calculate the potential difference across the parallel pair. Give your answer in V. 1 mark

e. Calculate the power dissipated in the $7.0\,\Omega$ resistor. Give your answer in W. 1 mark

f. Calculate the current in the $4.0\,\Omega$ resistor. Give your answer in A. 1 mark

Question 5 (8 marks)

A washing machine with a metal case is labelled $1610\,\text{W}$. It is connected to a $230\,\text{V}$ household circuit protected by a $10\,\text{A}$ circuit breaker and a $30\,\text{mA}$ residual current device (RCD). The metal case is connected to the earth wire.

a. Calculate the current in the washing machine when it is running at full power. Give your answer in A. 2 marks

b. Inside the washing machine, the active wire comes loose and touches the metal case. Describe what happens, and explain how the earth wire protects a person who touches the machine. 2 marks

c. Explain how the RCD protects a person who touches a live part of the circuit, even though the current through the person is far below the circuit breaker's rating. 2 marks

d. Explain why the $10\,\text{A}$ circuit breaker cannot protect a person from electric shock. 1 mark

e. State the first two actions you should take if you see someone receiving an electric shock. 1 mark

Question 6 (6 marks)

A student investigates the behaviour of an unknown component X. She connects X in series with an ammeter and a variable resistor to a low-voltage DC power supply, and connects a voltmeter across X. She adjusts the supply and records the readings in her logbook:

Potential difference across X, V (V)	0.0	1.0	2.0	3.0	4.0	5.0	6.0
Current through X, I (A)	0.00	0.30	0.50	0.63	0.73	0.81	0.88

a. Identify the independent variable, the dependent variable and one variable that the student should hold constant. 2 marks

b. Calculate the resistance of X at $V = 2.0\,\text{V}$ and at $V = 6.0\,\text{V}$. Give your answers in Ω. 2 marks

c. State whether X is ohmic or non-ohmic, using your answers to part **b** to justify your answer. 1 mark

d. X is one of a fixed resistor, a filament lamp or a diode. Identify X and explain your choice. 1 mark

End of Topic 3 Test B

Topic 3 Test B — solutions

Question 1 $V = 9.0\,\text{V}$, $I = 0.40\,\text{A}$, $t = 30\,\text{min}$.

(a) Convert the time first: $t = 30 \times 60 = 1800\,\text{s}$. Then

$$Q = I\,t = 0.40 \times 1800 = 720\,\text{C},$$

as required. **(1 mark** converts the time to seconds and uses $Q = I\,t$; **1 mark** correct value $720\,\text{C}$.)

(b) $E = V\,Q = 9.0 \times 720 = 6480\,\text{J}$ (equivalently $E = P\,t$, using the power from part **c**: $3.6 \times 1800 = 6480\,\text{J}$). **(1 mark** uses $E = V\,Q$ or $E = P\,t$; **1 mark** correct value $6480\,\text{J}$.)

(c) $P = V\,I = 9.0 \times 0.40 = 3.6\,\text{W}$. **(1 mark: correct value $3.6\,\text{W}$.)**

(d) Charge is not used up as it moves around the circuit — it is conserved — and there is only one path for it to take. So the rate of flow of charge is the same past every point in the loop, and the current is the same everywhere. **(1 mark: charge is conserved/not used up in a single loop, so the rate of flow is the same everywhere.)**

Question 2 $V = 230\,\text{V}$; breaker rating $10\,\text{A}$; loads in parallel.

(a) $I = \dfrac{P}{V} = \dfrac{920}{230} = 4.0\,\text{A}$. **(1 mark: correct value $4.0\,\text{A}$.)**

(b) Vacuum cleaner: $I = \dfrac{1380}{230} = 6.0\,\text{A}$. Total: $I_{\text{total}} = 4.0 + 6.0 = 10\,\text{A}$. **(1 mark** $6.0\,\text{A}$; **1 mark** total $10\,\text{A}$ — parallel currents add.)

(c) The lamp draws $\dfrac{230}{230} = 1.0\,\text{A}$, so the circuit now draws $10 + 1.0 = 11\,\text{A}$, which exceeds the breaker's $10\,\text{A}$ rating. The circuit breaker opens the circuit (an overload). **(1 mark: total becomes $11\,\text{A} > 10\,\text{A}$, so the breaker opens.)**

(d) Opening the active wire disconnects the appliances from the supply. A switch placed in the neutral wire would stop an appliance working, but the appliance would remain connected to the supply — still live. **(1 mark: the active wire is the supply side; opening it disconnects the load, whereas opening the neutral leaves it live.)**

(e) The earth wire connects the metal cases of appliances to ground; it normally carries no current. If the active wire touches a case (an earth fault), the earth wire provides a low-resistance path, so a large fault current flows and the fuse or circuit breaker opens the circuit before the case can remain live and shock someone. **(1 mark** the earth wire connects metal cases to ground and normally carries no current; **1 mark** during an earth fault it carries a large fault current so the protective device opens / the case is not left live.)

Question 3 $V_{\text{in}} = 6.0\,\text{V}$, $R_1 = 1200\,\Omega$, $R_2 = 800\,\Omega$ at $20\,°\text{C}$.

(a) One series path, so

$$I = \frac{V_{\text{in}}}{R_1 + R_2} = \frac{6.0}{1200 + 800} = \frac{6.0}{2000} = 0.0030\,\text{A} = 3.0\,\text{mA}.$$

The output across the thermistor is

$$V_{\text{out}} = I\,R_2 = 0.0030 \times 800 = 2.4\,\text{V} \left(\text{or } 6.0 \times \frac{800}{2000} = 2.4\,\text{V} \right).$$

(1 mark current $3.0\,\text{mA}$; **1 mark** $V_{\text{out}} = 2.4\,\text{V}$.)

(b) The thermistor is NTC, so as the temperature rises its resistance **falls**. The thermistor's share $\frac{R_2}{R_1+R_2}$ of the total resistance becomes smaller, so V_{out} **falls**. **(1 mark: resistance falls and V_{out} falls.)**

(c) As the temperature falls, the NTC thermistor's resistance rises, so the thermistor takes a larger share of the total resistance. The potential difference is shared in proportion to the resistances, so a larger share of the supply potential difference appears across it: V_{out} rises. **(1 mark: cooling raises R_2, which raises the thermistor's share of the supply potential difference.)**

(d) The light intensity falling on the LDR decreases (for example, dusk or darkness). An LDR's resistance increases as the light level falls, so — like the cooling thermistor — it takes a larger share of the supply potential difference and V_{out} rises. **(1 mark: a decrease in light intensity.)**

(e) With $R_2 = 2400\,\Omega$:

$$V_{out} = V_{in} \times \frac{R_2}{R_1+R_2} = 6.0 \times \frac{2400}{1200+2400} = 6.0 \times \frac{2400}{3600} = 4.0\,\text{V}.$$

Since $4.0\,\text{V} \geq 3.6\,\text{V}$, the output reaches the closing value, the switch closes and the heater switches on. **(1 mark** $V_{out} = 4.0\,\text{V}$; **1 mark** $4.0\,\text{V}$ is at or above $3.6\,\text{V}$, so the heater switches on.)

Question 4 $V = 12\,\text{V}$; parallel pair $4.0\,\Omega$ and $12\,\Omega$; series resistor $7.0\,\Omega$.

(a) For two resistors in parallel,

$$R_{pair} = \frac{R_1 R_2}{R_1+R_2} = \frac{4.0 \times 12}{4.0+12} = \frac{48}{16} = 3.0\,\Omega,$$

as required (equivalently $\frac{1}{R_{pair}} = \frac{1}{4.0} + \frac{1}{12} = \frac{4}{12}$, giving $R_{pair} = 3.0\,\Omega$). **(1 mark: correct reduction to $3.0\,\Omega$.)**

(b) $R_{total} = 3.0 + 7.0 = 10\,\Omega$. **(1 mark: correct value $10\,\Omega$.)**

(c) $I = \frac{V}{R_{total}} = \frac{12}{10} = 1.2\,\text{A}$. **(1 mark: correct value $1.2\,\text{A}$.)**

(d) The battery current flows through the equivalent resistance of the pair, so

$$V_{pair} = I\,R_{pair} = 1.2 \times 3.0 = 3.6\,\text{V}.$$

(1 mark: correct value $3.6\,\text{V}$.)

(e) The full battery current flows through the $7.0\,\Omega$ resistor, so

$$P = I^2 R = 1.2^2 \times 7.0 = 1.44 \times 7.0 = 10\,\text{W}.$$

(Equivalently, the potential difference across it is $12 - 3.6 = 8.4\,\text{V}$, so $P = V\,I = 8.4 \times 1.2 = 10\,\text{W}$. Here $P = I^2 R$ follows from $P = V\,I$ and $V = I\,R$.) **(1 mark: correct value $10\,\text{W}$.)**

(f) The parallel pair has $3.6\,\text{V}$ across each branch, so the current in the $4.0\,\Omega$ resistor is

$$I_{4.0} = \frac{V_{pair}}{4.0} = \frac{3.6}{4.0} = 0.90\,\text{A}.$$

(1 mark: correct value $0.90\,\text{A}$. Check: $3.6/12 = 0.30\,\text{A}$ in the other branch, and $0.90 + 0.30 = 1.2\,\text{A}$, the battery current.)

Question 5 $V = 230\,\text{V}$; washing machine rated $1610\,\text{W}$; breaker $10\,\text{A}$; RCD $30\,\text{mA}$.

(a) $I = \frac{P}{V} = \frac{1610}{230} = 7.0\,\text{A}$. **(1 mark** uses $I = P/V$; **1 mark** correct value $7.0\,\text{A}$.)

(b) The loose wire connects the supply to the case. Because the case is connected to the earth wire, the fault provides a low-resistance path from the active wire to ground, so by $I = V / R$ a very large fault current flows. This exceeds the circuit breaker's rating, the breaker opens and the machine is disconnected. A person who touches the case is protected: before the breaker opens, almost all of the fault current takes the earth wire, whose resistance is far lower than a person's, and once the breaker opens the case is no longer live. (**1 mark** the earth wire gives a low-resistance path, so a large fault current flows and the breaker/fuse opens; **1 mark** the person is protected because the fault current takes the earth wire and the case is not left live.)

(c) The current through the person does not return through the neutral wire, so the current in the active wire becomes greater than the current in the neutral wire. The RCD senses this imbalance (the residual current) and opens the circuit — at its $30\,\text{mA}$ rating, within about $0.03\,\text{s}$. That is a current and a time the circuit breaker cannot respond to: the shock is over before it can do serious harm. (**1 mark** the RCD senses the imbalance between the active and neutral currents; **1 mark** it opens the circuit very quickly (at about $30\,\text{mA}$, within about $0.03\,\text{s}$).)

(d) A shock current through a person is of the order of milliamperes to tens of milliamperes — far below $10\,\text{A}$. The circuit breaker responds only to currents above its rating, so it never opens during a shock; it protects the wiring, not the person. **(1 mark: a shock current is far below the breaker's rating, so the breaker does not open.)**

(e) First: look, don't touch — do not put yourself in danger, because the person may still be in contact with the current. Second: isolate the supply before approaching — switch off at the mains or the power point and unplug the cord. **(1 mark: both first actions stated — do not touch until safe; isolate the supply.)**

Source: International Electrotechnical Commission, IEC 60479-1, Effects of current on human beings and livestock — Part 1: General aspects, retrieved 2026-08-18. The current thresholds are approximate, for $50\,\text{Hz}$ *AC on a hand-to-foot path. Source: Energy Safe Victoria, Household wiring, retrieved 2026-08-18.*

Question 6

(a) **Independent variable:** the potential difference V across component X (the quantity deliberately changed). **Dependent variable:** the current I through X (the quantity measured). **Controlled variable:** any one of the component itself (the same X throughout), the temperature of X, or the same meters and circuit arrangement. (**1 mark** IV and DV both correct; **1 mark** a valid controlled variable.)

(b) Resistance is the ratio of potential difference to current, $R = \frac{V}{I}$:

- at $V = 2.0\,\text{V}$: $R = \frac{2.0}{0.50} = 4.0\,\Omega$;
- at $V = 6.0\,\text{V}$: $R = \frac{6.0}{0.88} = 6.8\,\Omega$.

(**1 mark** $4.0\,\Omega$ at $2.0\,\text{V}$; **1 mark** $6.8\,\Omega$ at $6.0\,\text{V}$.)

(c) X is **non-ohmic**: its resistance is not constant — it rises from $4.0\,\Omega$ to $6.8\,\Omega$ as the potential difference increases. For an ohmic device the ratio V / I would be the same at every reading, and the I–V graph would be a straight line through the origin; here the current grows more slowly than the potential difference, so the graph is a curve. **(1 mark: non-ohmic, justified by the changing (rising) resistance.)**

(d) X is a **filament lamp**. As the current grows, the filament gets hotter, and the resistance of the hot metal is larger than when it is cool — so the resistance rises with potential difference, as the data show. X cannot be a fixed resistor (its resistance would be constant), and it cannot be a diode: a silicon diode carries almost no current below about $0.6\,\text{V}$, whereas X already carries $0.30\,\text{A}$ at $1.0\,\text{V}$. **(1 mark: filament lamp, with the heating-resistance reasoning and a reason for rejecting at least one of the alternatives.)**