

Electric Circuits

A torch, a doorbell and the lamp above your desk all work for the same reason: something pushes an electric current round a loop, and the loop is unbroken all the way round.

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6.1 Circuit diagrams and their symbols

Connect a lamp to a cell with two wires and the lamp lights. Take away one wire and it goes out at once. It does not fade and it does not dim: it stops. What matters is that the current has a **complete loop** to travel round — out of one terminal of the cell, through the wires and the lamp, and back into the other terminal. Break that loop anywhere at all and the current stops everywhere in it, not just at the break.

That is why a switch works. A switch is nothing more than a gap in the loop that you can close and open on purpose. It also means that where you put the switch makes no difference to whether it works — before the lamp or after it, the lamp goes out just the same.

Drawing the real wires and clips every time would be slow, and the drawing would be hard to read. So we draw a **circuit diagram** instead. In a circuit diagram the wires are straight lines, corners are square, and every component is replaced by an agreed symbol. Everybody uses the same symbols, which is the point: it means anyone can read anyone else's diagram. The symbols you need in this chapter are collected in Figure 6.1.

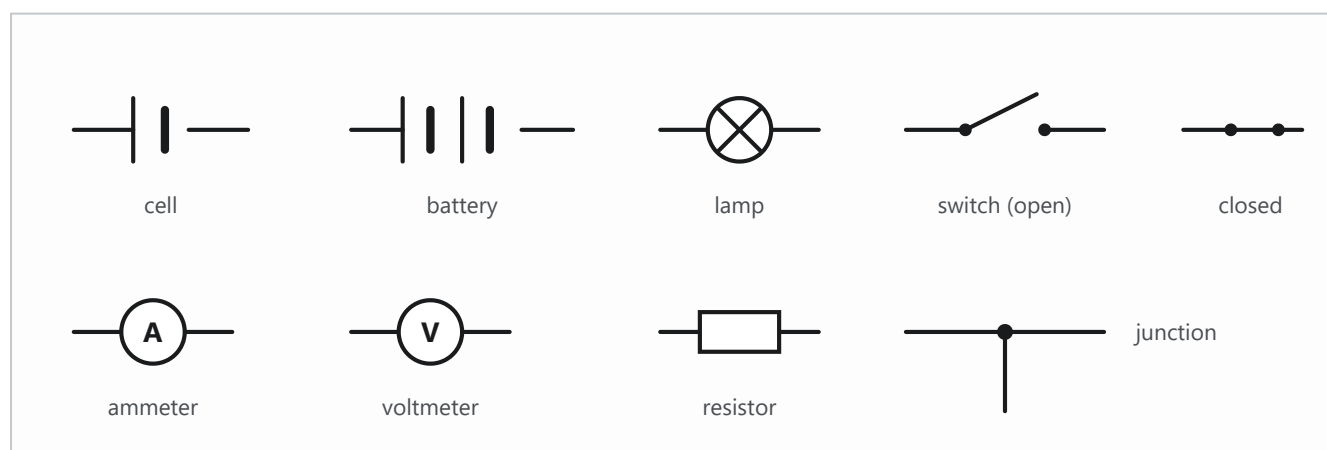


Figure 6.1 The circuit symbols used in this chapter.

Two conventions in Figure 6.1 are worth pausing over, because most of the mistakes people make in reading a diagram come from missing them.

The first is the **junction dot**. A dot is drawn wherever wires are joined together. It follows that two wires which cross *without* a dot are not connected at all — one simply passes over the other, like a road crossing a railway on a bridge. A single dot, or its absence, can therefore change what a diagram means completely, and it is the first thing to look for when a circuit does not behave as you expect.

The second is that the **shape of a diagram means nothing**. Only the connections matter. A loop drawn as a tall thin rectangle and the same loop drawn as a wide flat one are the same circuit, and a wire drawn as a long detour round three sides of the page is no different from a short straight one. Corners are drawn square purely to keep diagrams tidy. When you compare two diagrams, then, do not compare their shapes; trace the connections and compare those.

Figure 6.2 shows the same circuit drawn both ways. On the left is a picture of what is actually on the bench: a battery in its holder, a lamp in a lamp holder, a switch, and four wires with crocodile clips on their ends. On the right is the circuit diagram of the very same arrangement. Nothing has been changed except the way it is drawn — and the diagram is far quicker to read.

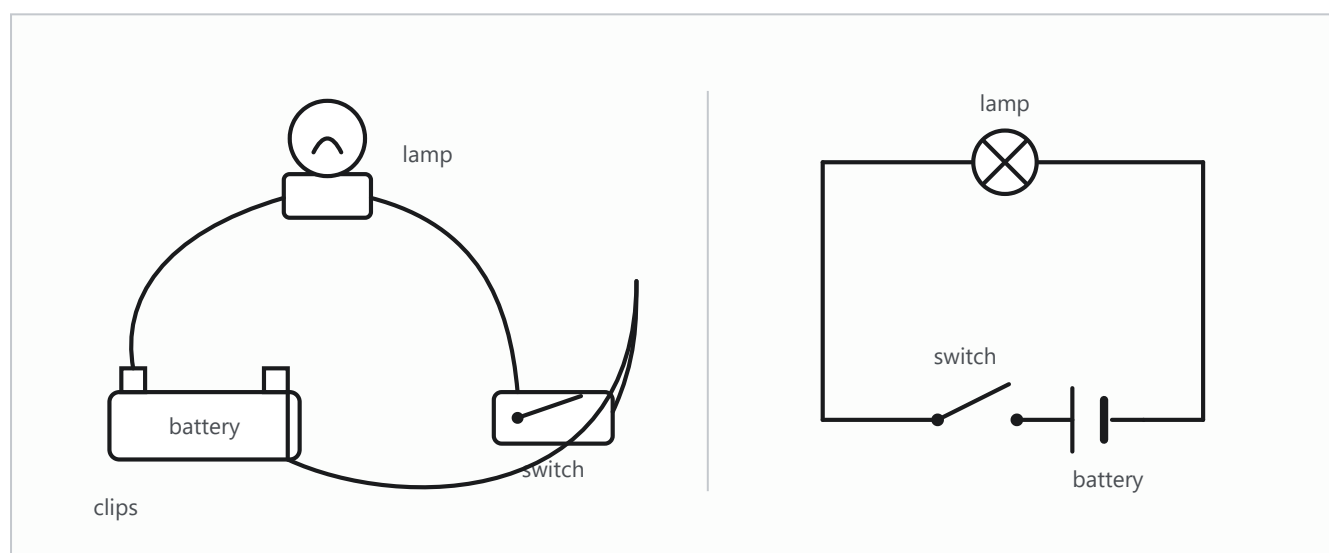


Figure 6.2 One circuit drawn two ways: the apparatus on the bench, and its circuit diagram. From here on we shall use diagrams only.

ACTIVITY 6.1 — FIND THE BREAK

Build the circuit in Figure 6.2 and check that the lamp lights. Now loosen one clip so that the wire is no longer gripped, leaving everything else exactly as it was. Does the lamp go dim, or does it go out? Tighten it, and this time loosen a clip on the other side of the lamp. Compare what happens in the two cases. Then write one sentence saying what a circuit needs in order to work at all.

You should have found that it made no difference which clip you loosened. A break anywhere stops the current everywhere in the loop — which is worth remembering when you are hunting for a fault in a circuit that will not light. The fault need not be anywhere near the component that has stopped working.

6.2 Components in series

Two lamps can be joined into a circuit in two quite different ways, and the difference matters so much that the rest of this chapter is really about telling them apart. The first way is called **series**. Components in series are joined one after another in a single loop, so that there is only **one path** for the current to take. On leaving the battery the current has no choice at all: it must pass through the first lamp, then through the second, and then back to the battery.

You have met series circuits already without necessarily naming them. The two cells inside a torch are in series, one stacked on top of the other. So is the fuse in a plug, and so were the older sort of decorative light strings, which is why a single dead lamp used to put out the whole string – something we come back to in Section 6.5.

Here is a quick test you can apply to any diagram. Put your finger on one terminal of the battery and trace the wire. If you can get back to the other terminal by exactly one route, everything you passed through on the way is in series.

Figure 6.3 shows two lamps in series with a 3.0 V battery. Three ammeters have been built into the loop at different places, so that we can compare the current at three points: before the first lamp, between the two lamps, and after the second lamp.

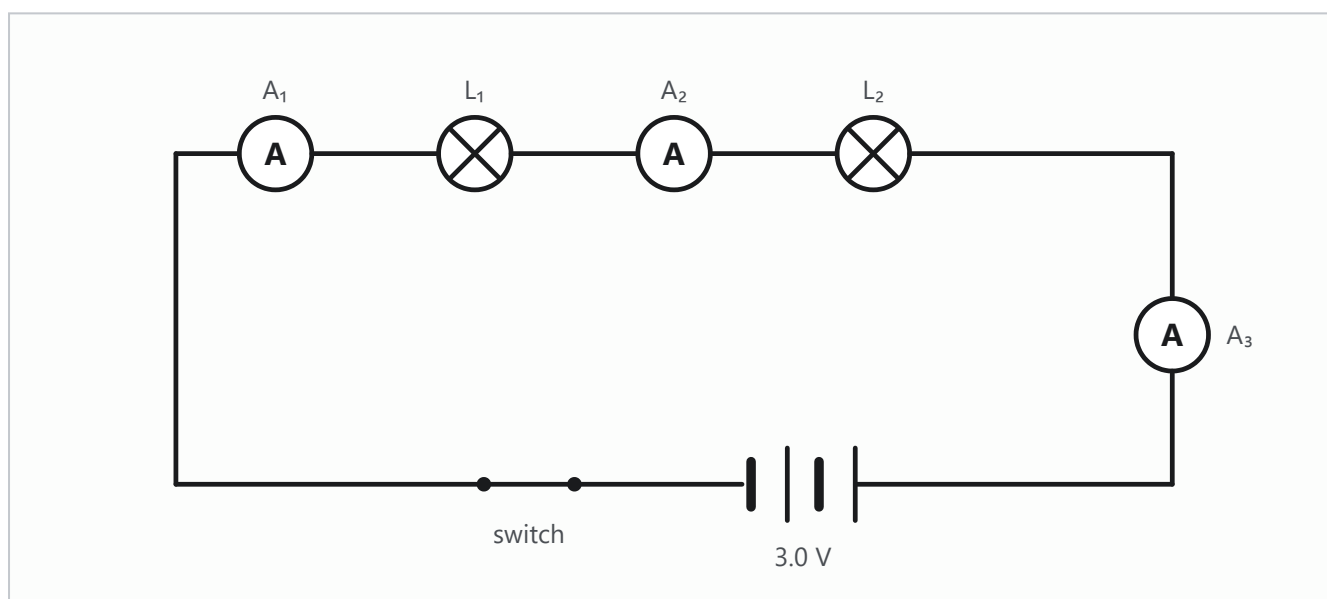


Figure 6.3 Two lamps in series with a 3.0 V battery. There is one path only, so every part of the circuit carries the same current. The three ammeters let you check that for yourself.

Before you read on, decide what you expect the three ammeters to read. Most people expect A₁ to read the most and A₃ the least, on the grounds that the two lamps have used some of the current up along the way. It is a thoroughly reasonable guess. It is also wrong, and the measured readings in Table 6.1 show why.

Table 6.1 Ammeter readings for the series circuit of Figure 6.3, and for the same circuit with a third identical lamp added to the loop.

Lamps in the loop	A ₁	A ₂	A ₃
two lamps	0.20 A	0.20 A	0.20 A
three lamps	0.14 A	0.14 A	0.14 A

Read the first row across. The three readings are the same. Read it again and be certain of it, because this is the most useful single fact in the chapter: **the current is the same at every point in a series circuit**. It is not used up, not shared out, and not weakened by passing through a lamp. Whatever leaves the battery arrives back at the battery.

WHY NOTHING IS USED UP

It is easy to muddle two different things here. The lamps certainly do take something out of the circuit — they take **energy**, which is why they become hot and give out light. What they do not take is current. Current is the movement of charge round the loop, and that charge has nowhere else to go: it cannot leak out through the wire and it cannot pile up inside a lamp. So energy is used up as you go round the loop, and current is not. Confusing the two is the commonest mistake made about circuits, and it is worth checking yourself against it whenever you predict an ammeter reading.

If you want a picture to hold on to, think of a bicycle chain. Pedal and the whole chain moves at once; every link moves at the same rate, including the links that have just come off the back sprocket. The chain delivers energy to the wheel, but no links are consumed in doing it, and you do not get fewer links arriving at the front than left it. A series circuit behaves in the same way, and for the same reason: the loop is continuous and nothing can escape from it.

Now read the second row of the table. Adding a third lamp made all three readings fall together, from 0.20 A to 0.14 A. They are still equal to one another, so the rule is holding good — but they are all smaller than before. Each extra lamp in the loop makes it harder for the battery to drive a current round, so the current everywhere in the loop drops. This is also the reason lamps in series grow dimmer as you add more of them, and it is the first hint that a series circuit shares out what the battery provides.

WORKED EXAMPLE

Question. Three identical lamps are connected in series with a 4.5 V battery. An ammeter placed between the second and third lamps reads 0.14 A. What would an ammeter read if it were moved to sit between the battery and the first lamp?

Answer. 0.14 A. The lamps are in series, so there is one path and the current is the same at every point in it. Moving the ammeter to a different place in the same loop cannot change the reading. Notice that the question tells you the number of lamps and the battery voltage, and that you need neither of them.

6.3 Components in parallel

The second way of joining two lamps is called **parallel**. Components in parallel are placed on separate branches side by side, so that the current leaving the battery arrives at a junction and **splits** between them. Each lamp sits on a path of its own. The two branch currents then meet at a second junction and join together again before returning to the battery.

Apply the finger test from the last section and the difference is immediate. Trace from one terminal of the battery and you find not one route back but two, and you have to choose. Everything on one of those routes is in parallel with everything on the other. The junction dots are where the choice appears and where it closes up again, which is why Figure 6.1 made a point of them.

Figure 6.4 shows two lamps in parallel with the same 3.0 V battery as before. An ammeter has been put in each branch, and a third one, A_0 , in the part of the circuit that every bit of the current must pass through on its way back to the battery.

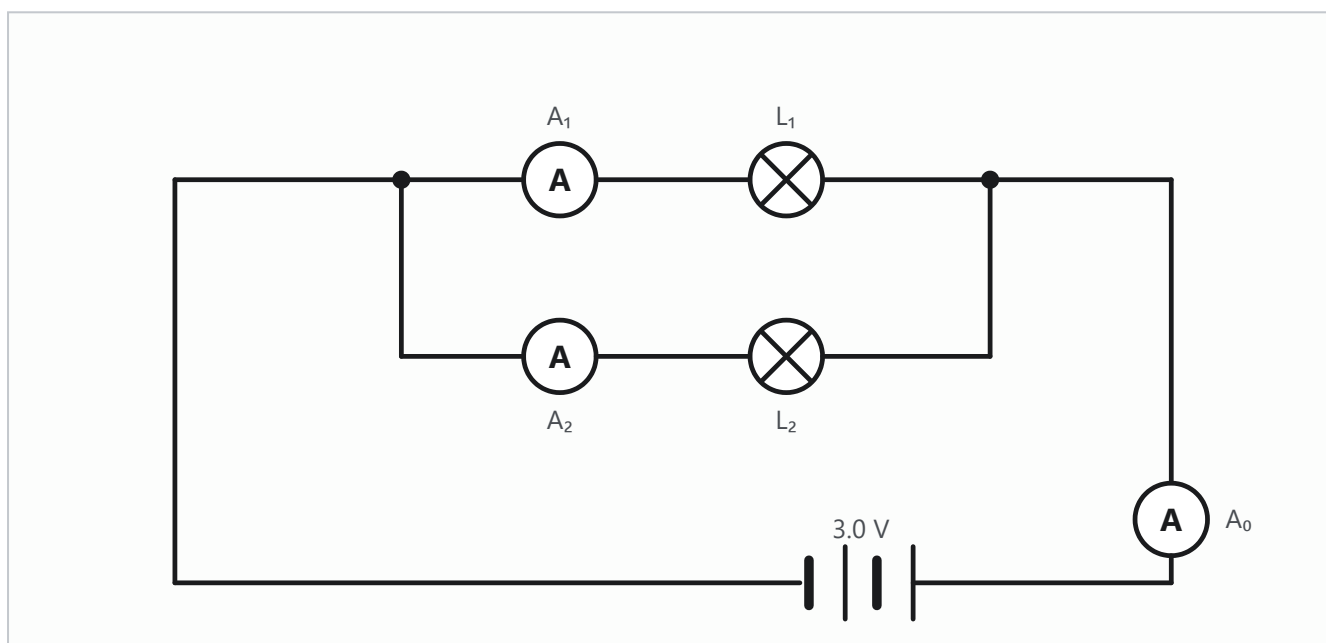


Figure 6.4 Two lamps in parallel with a 3.0 V battery. The junction dots mark where the current splits and where it rejoins. A_0 sits in the single part of the circuit, so it measures the whole current leaving the battery.

Parallel wiring is much the commoner of the two arrangements in everyday life. The sockets around the walls of a room are in parallel with one another, and so are the two headlamps of a car, and so are all the lamps in a house. The reasons are worth understanding rather than memorising, and they will fall out of the next two sections once we know what a parallel branch does to the current and to the potential difference.

One more thing before the readings. The order of the branches does not matter, and neither does which branch is drawn on top. Swap L_1 and L_2 over and you have not changed the circuit at all — each is still on its own path between the same two junctions. This is quite unlike a series circuit, where the components sit in a definite order along the loop, even though, as we have just seen, that order makes no difference to the current either.

Table 6.2 Ammeter readings for the parallel circuit of Figure 6.4, first with two identical lamps and then with L_2 replaced by a lamp of a different kind.

Lamps	A_1 (branch 1)	A_2 (branch 2)	A_0 (single part)
two identical lamps	0.30 A	0.30 A	0.60 A
L_2 replaced by a dimmer lamp	0.30 A	0.18 A	0.48 A

Take the first row. The two branches carry 0.30 A each, and the single part of the circuit carries 0.60 A. In other words, **the branch currents add up to the current through the battery**. That is exactly what "splits" means: the 0.60 A leaving the battery divides at the junction into two lots of 0.30 A, and the two lots join up again at the far junction to make 0.60 A once more. Nothing is lost at a junction and nothing is created there.

The second row makes the same point in a way that is harder to explain away. Here the branches are not equal, so the current does not divide equally: one branch takes 0.30 A and the other 0.18 A. But $0.30 + 0.18 = 0.48$, which is precisely what A_0 reads. The branch currents still add up to the current through the battery, whether or not the branches are alike.

Now compare Table 6.2 with Table 6.1, because one more thing stands out. In series, each of the two identical lamps had 0.20 A through it. In parallel, each has 0.30 A. The parallel lamps are carrying half again as much current, and if you build both circuits you will see the consequence plainly: two lamps in parallel are noticeably brighter than the same two lamps in series. Section 6.4 explains where that difference comes from.

There is a price for that brightness, and the ammeter A_0 has already told us what it is. The battery in the parallel circuit is supplying 0.60 A, three times the 0.20 A it supplied in series. Adding another branch would raise the total again, because the new branch takes its own current without reducing what the existing branches take. A battery driving lamps in parallel therefore runs down faster than the same battery driving the same lamps in series — which is the other half of the bargain, and the reason a torch designer does not simply put everything in parallel and have done with it.

ACTIVITY 6.2 — SERIES OR PARALLEL?

Build the circuit in Figure 6.4 and check that both lamps light. Now, without rebuilding it from scratch, move a single wire so that the two lamps end up in series instead, as in Figure 6.3. Which wire did you have to move? Sketch what you had before and after, and mark on each sketch where the junctions are. Finally, say which of the two circuits gave the brighter lamps, and predict what a third lamp would do to each.

SPOTTING THE DIFFERENCE IN A DIAGRAM

You do not have to trace anything if you know what to look for. Ask: starting at the battery, is there more than one route back? Exactly one route means the components on it are in series. A route that divides means the components on the separate branches are in parallel. Junction dots are the giveaway, and a diagram drawn in an unfamiliar shape is still answered by the same question.

6.4 Measuring current and potential difference

Two different meters are used on circuits, and they are connected in two different ways. Getting them the wrong way round is the most common practical mistake made in the laboratory, so it is worth learning the pair together rather than one at a time.

An **ammeter** measures the current through a component. Current has to pass through the meter for the meter to measure it, so an ammeter is connected **in series** — it goes into the loop itself, in line with the component, exactly as the ammeters in Figures 6.3 and 6.4 do. You have to break the circuit open to put one in.

A **voltmeter** measures the potential difference across a component: how much energy the current gives up in passing through it. That is a comparison between one side of the component and the other, so a voltmeter is connected **in parallel** — it goes across the component, touching the circuit at two points, and the circuit does not have to be broken to add one. Figure 6.5 shows both meters at work on the same lamp.

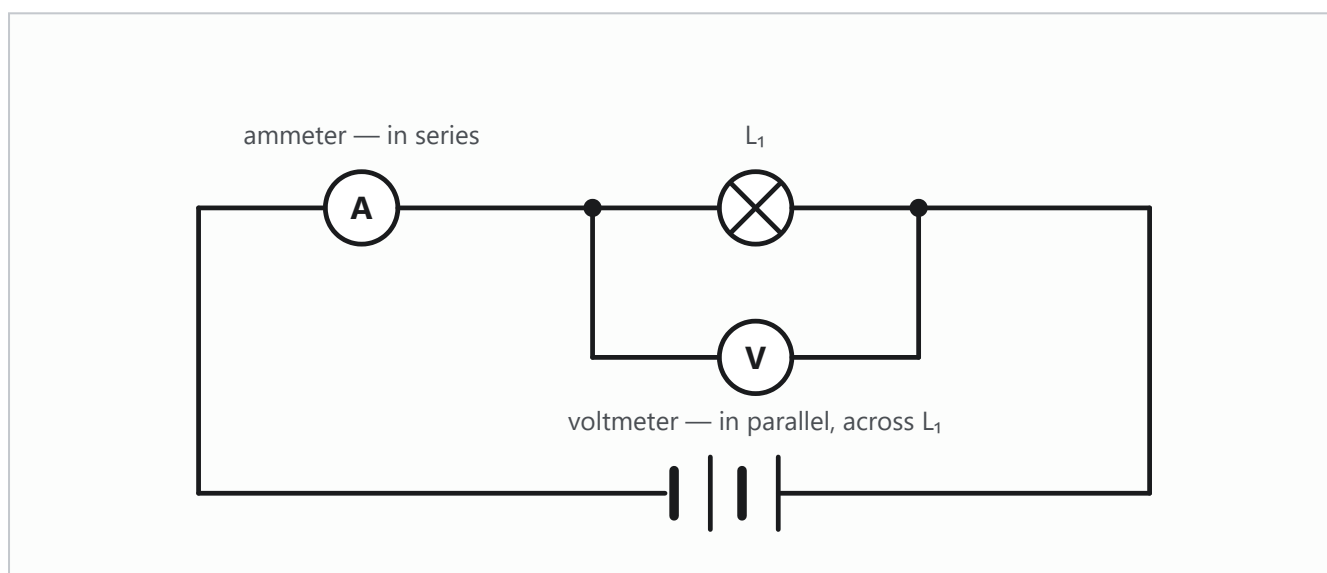


Figure 6.5 How the two meters go into a circuit. The ammeter is part of the loop; the voltmeter bridges across the lamp. Only the ammeter requires the circuit to be opened up.

It is worth knowing what happens if you swap them over, both because it explains the rule and because it will save a meter. Figure 6.6 shows the two wrong connections.

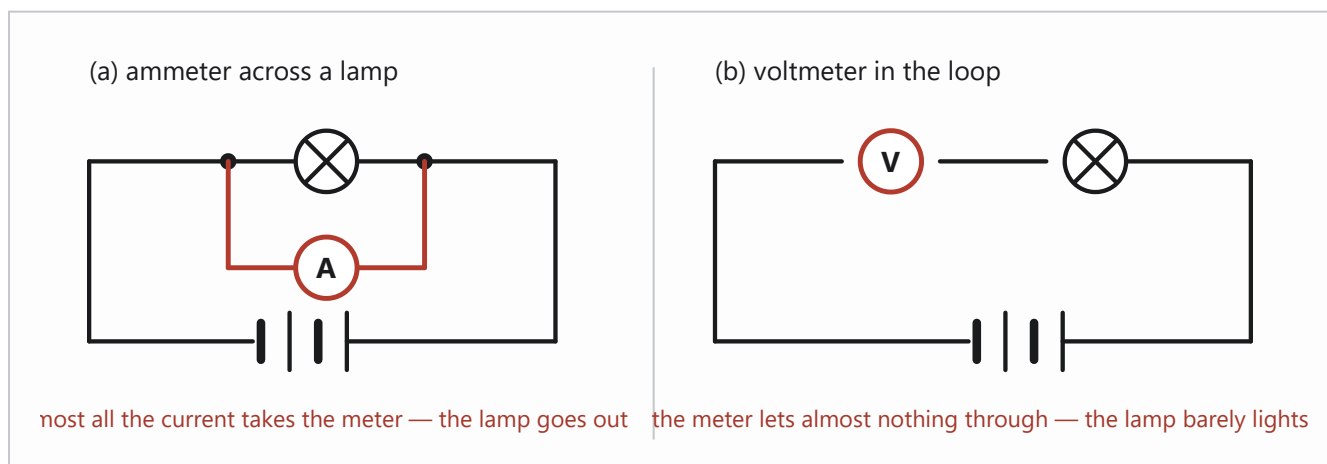


Figure 6.6 The two wrong connections. Neither is a good idea; (a) can damage the ammeter.

In Figure 6.6(a) the ammeter has been put across the lamp instead of in the loop. An ammeter is built to let current through very easily, so it offers the current a far easier route than the lamp does. Almost all of the current goes through the meter, the lamp goes out, and the meter may be damaged by a current larger than it was built for. In Figure 6.6(b) the voltmeter has been put into the loop instead of across the lamp. A voltmeter is built to let almost no current through, so putting one in the loop nearly stops the current altogether and the lamp barely lights. Each meter behaves badly in the other's place, and for a reason you can now state.

Now use a voltmeter properly, to find out where the difference in brightness came from. Table 6.3 gives the potential difference across each lamp, first for two lamps in series and then for two in parallel, in both cases with the same 3.0 V battery.

Table 6.3 Potential difference across each lamp, measured with the same 3.0 V battery in each circuit.

Circuit	across L_1	across L_2	across the battery
two identical lamps in series	1.5 V	1.5 V	3.0 V
two unlike lamps in series	2.0 V	1.0 V	3.0 V
two identical lamps in parallel	3.0 V	3.0 V	3.0 V

In the series circuit each identical lamp had 1.5 V across it, and the two add up to the 3.0 V of the battery. **In series the potential difference of the supply is shared between the components.** Each lamp received only half of what the battery offered, which is why both were dim. The second row shows that the sharing need not be equal — two unlike lamps took 2.0 V and 1.0 V — but that the shares still add up to 3.0 V. Sharing, not splitting equally, is the rule.

In the parallel circuit each lamp had the full 3.0 V across it. **In parallel each branch gets the whole potential difference of the supply.** Each lamp was being driven exactly as hard as if it were the only lamp in the circuit, which is why both were bright, and why each drew more current than the same lamp did in series.

It helps to read potential difference as a statement about energy. The battery offers each unit of charge a fixed amount of energy — 3.0 V worth — to spend on its way round. In series, a unit of charge must pass through both lamps on its single journey, so it spends part of its energy in the first and the rest in the second, and the two amounts have to add up to what it started with. In parallel, a unit of charge goes through one lamp only and then straight back to the battery, so it spends the whole of its energy in that one lamp. Nothing is being divided up in the parallel case, which is exactly why each branch gets the full 3.0 V.

WORKED EXAMPLE

Question. Three identical lamps are connected in series with a 4.5 V battery. What is the potential difference across each one?

Answer. 1.5 V. In series the supply is shared between the components, and the three lamps are identical, so each takes an equal share: $4.5 \text{ V} \div 3 = 1.5 \text{ V}$. As a check, the three shares add back up to the 4.5 V of the battery.

6.5 When one lamp fails

Lamps do not last for ever. Inside each one is a very thin wire, the **filament**, which is what glows when a current passes through it. It runs extremely hot in normal use, and in time it thins and breaks. A lamp with a broken filament is no longer something the current can pass through; it has become a gap in the wiring, no different from a snapped wire or an open switch.

What that gap does to the rest of the circuit depends entirely on whether the lamp was in series or in parallel — and this, more than anything else in the chapter, is why the distinction is worth knowing. Figure 6.7 shows the same failure in the two arrangements, side by side.

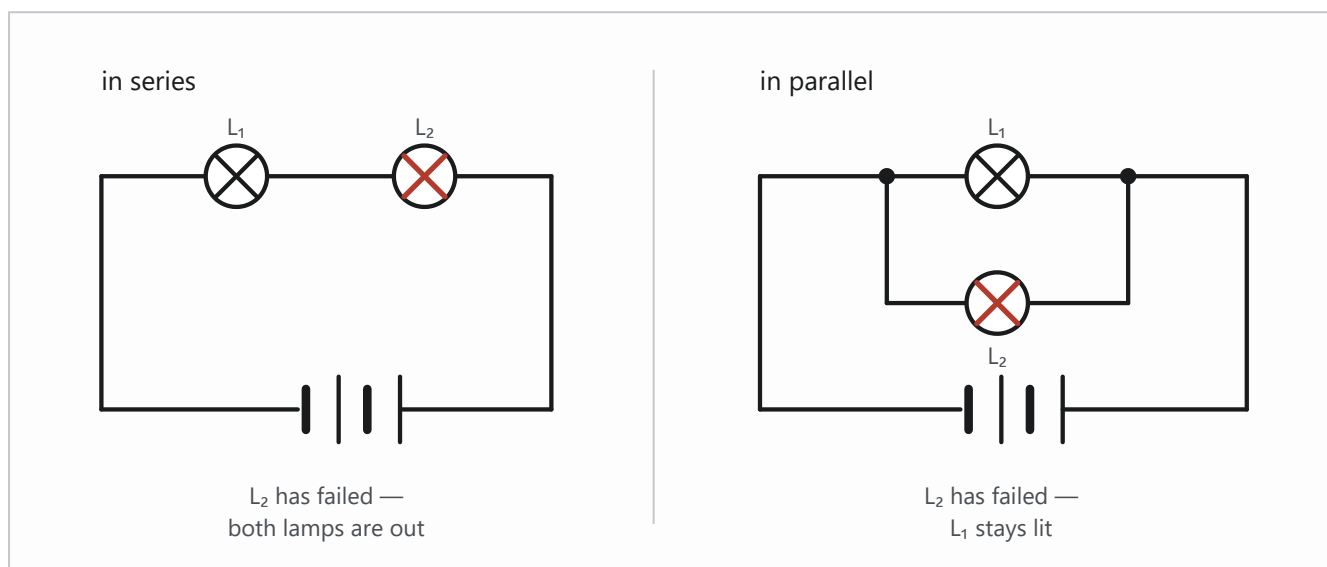


Figure 6.7 The same failure in the two arrangements. A broken filament is drawn in red. In series it breaks the only loop there is; in parallel it breaks only its own branch.

On the left, the two lamps are in series and L₂ has failed. There was only ever one loop, and the gap in L₂ has broken it, so no current flows anywhere in the circuit. **Both** lamps are out, including the one that is still perfectly good.

ACTIVITY 6.3 — PREDICT, THEN REMOVE A LAMP

Build the series circuit of Figure 6.3 and the parallel circuit of Figure 6.4, side by side on the bench, and light both. Before you touch anything, write down what you expect to happen in each circuit if one lamp is unscrewed from its holder. Now unscrew one lamp in the series circuit, and record what the other lamp does. Screw it back in, then unscrew one lamp in the parallel circuit and record what the other lamp does.

Unscrewing a lamp leaves a gap in exactly the way a broken filament does, so this is the same test as Figure 6.7 without having to wait for a lamp to fail. Which of your two predictions was right? If either was wrong, write down which arrangement misled you, and why.

That is the frustrating thing about a series string. A single failure anywhere puts the whole string out, and because every lamp is equally dark, every lamp looks equally guilty. There is no way to tell from looking which one has gone, and the only way to find it is to test or replace the lamps one at a time until the string lights again. Anyone who has dealt with an old set of decorative lights knows the feeling.

On the right of Figure 6.7, the two lamps are in parallel and L_2 has failed in exactly the same way. Its own branch is now broken, so no current passes through it and L_2 is out. But L_1 sits on a separate branch, and that branch is untouched: it still runs from one junction to the other without a gap. So L_1 stays lit — and stays lit at the same brightness as before, because it still has the full potential difference of the battery across it. The failure has been contained in the branch where it happened, and the faulty lamp is the only dark one, so it identifies itself.

6.6 Circuits in the home

The lamps in the rooms of a house are wired in parallel, and by now you can say why without being told. Each lamp is on a branch of its own, so each receives the full supply potential difference and burns at full brightness however many others happen to be switched on. Each branch can be broken by its own switch, which is what lets you light the kitchen without lighting every room in the building. And when one lamp finally fails, the other branches are still unbroken, so the rest of the house stays lit and the dark lamp tells you at once which one to replace.

Wire the same lamps in series instead and all three of those advantages disappear together. The supply would be shared out, so every lamp would be dim, and adding a lamp anywhere would make all the others dimmer still. One switch would control everything at once, because there would be only one loop to break. And the first filament to go would put out every light in the house, leaving you to hunt for it in the dark.

ONE THING THAT IS DELIBERATELY IN SERIES

Not everything should be in parallel. A fuse, and the main switch for a circuit, are put in series on purpose — precisely because anything in series with a circuit is able to break the whole loop. The same behaviour that makes series wiring a nuisance in a string of lamps is exactly what makes it the right choice for a safety device.

A last word on reading circuits. Almost every question in this chapter can be answered by asking the same two things: is there one path or more than one, and is the loop I care about unbroken? Those two questions will take you further than remembering which table had which number in it.

The unit of current, the ampere, is named after the French scientist André-Marie Ampère. The ammeters in most school laboratories have two ranges, 0–1 A and 0–5 A. All the readings in this chapter were taken on the 0–1 A range, which is the more sensitive of the two.