In this chapter, you will find out:

- how to construct and interpret circuit diagrams
- how to predict currents and voltages in series and parallel circuits
- how to predict the effects of logic gates
- how to describe and explain electrical safety measures.

An international language

The technicians in the photograph (Figure 19.1) are checking the quality of some circuit boards. These boards carry many electrical components connected together in complex circuits.

Circuits like these are used in many different applications – in cars, radios, computers, washing machines and so on. They may be designed by electronic engineers in one country, constructed in another country, and put to use in a third country. Everyone involved in the process must understand what is required. That is why we have an internationally agreed set of circuit symbols to represent the different components used in circuits.

You should already have used circuits containing cells, lamps, resistors, switches, ammeters and voltmeters, and you should be familiar with their symbols. You will learn about other electrical components and their symbols in this and later chapters.

Figure 19.1 Checking circuit boards. The boards are placed on a light box or light table and technicians use magnifiers to see the fine detail.
19.1 Circuit components

Figure 19.2 shows the circuit symbols for the electrical components that you are most likely to meet in this course. You should try to remember them. A complete list is given in Appendix 2 at the end of the book.

Resistors

A resistor (Figure 19.3) can be used to control the amount of current flowing around a circuit. A resistor has two terminals, so that the current can flow in one end and out the other. They may be made from metal wire (usually an alloy – a mixture of two or more metals with a high resistance) or from carbon. Carbon (like the graphite ‘lead’ in a pencil) conducts electricity, but not as well as most metals. Hence high-resistance resistors tend to be made from graphite, particularly as it has a very high melting point.

A variable resistor (sometimes called a potentiometer) can be used to alter the current flowing in a circuit. Figure 19.4a shows the inside of a variable resistor – notice that it has three terminals. As the
control is turned, the contact slides over the resistive track. The current enters at one end and flows through the track until it reaches the contact, where it leaves the resistor. The amount of track that it flows through depends on the position of the contact. Variable resistors like this are often used for the volume control of a radio or stereo system. (You may have come across a rheostat, which is a lab version of a variable resistor.)

Figure 19.4b shows an example of a circuit that contains a variable resistor, and Figure 19.4c shows two different circuit symbols for a variable resistor. Note that the upper symbol has three terminals (like the resistor itself), but this circuit only makes use of two of them.

**Transducers**

We use many different electric circuits to make things happen automatically. For example, if the temperature falls, we may want a heater to come on automatically. If someone is moving around inside a bank at night, the burglar alarm must sound.

Electronic systems like these depend on devices described as **transducers**. A system might be represented like this:

\[
\text{input transducer} \rightarrow \text{circuit} \rightarrow \text{output transducer}
\]

**An input transducer** responds to a change in the environment (for example, a change in light or temperature) and produces a voltage. The electrical **circuit** to which the input transducer is connected then provides the voltage needed to operate the **output transducer**.

For a burglar alarm system, the input transducer might be a light sensor, and the output transducer could be a bell or flashing light:

light sensor \(\rightarrow\) circuit \(\rightarrow\) bell

We will now look at some devices that can act as input transducers.

**Study tip**

An input transducer is any device whose electrical properties change when its environment changes. For example, the resistance of a resistor increases when it gets hotter.

**Light-dependent resistors**

A **light-dependent resistor (LDR)** is a type of ‘variable resistor’ whose resistance depends on the amount of light falling on it (Figure 19.5). An LDR is made of a material that does not normally conduct well. In the
dark, an LDR has a high resistance, often over 1 MΩ. However, light can provide the energy needed to allow a current to flow. Shine light on an LDR and its resistance decreases. In bright light, its resistance may fall to 400 Ω.

LDRs are used in circuits to detect the level of light, for example in security lights that switch on automatically at night. Some digital clocks have one fitted. When the room is brightly lit, the display is automatically brightened so that it can be seen against its bright surroundings. In a darkened room, the display need only be dim.

**Thermistors**

A thermistor (Figure 19.6) is another type of resistor whose resistance depends on its environment. In this case, its resistance depends on its temperature. The resistance changes by a large amount over a narrow range of temperatures.

For some thermistors, the resistance decreases as they are heated – perhaps from 2 kΩ at room temperature to 20 Ω at 100 °C. These thermistors are thus useful for temperature probes – see the discussion of thermometers in section 10.1.

For other thermistors, the resistance increases over a similar temperature range. These are included in circuits where you want to prevent over-heating. If the current flowing is large, components may burn out. With a thermistor in the circuit, the resistance increases as the temperature rises, and the high current is reduced.

### Questions

19.1 a Draw the circuit symbol for a resistor.
   b Draw the circuit symbol for a variable resistor.

19.2 a What does LDR stand for?
   b Draw its circuit symbol.
   c What happens to the resistance of an LDR when light is shone on it?

19.3 a Draw the circuit symbol for a thermistor.
   b Give one use for a thermistor.
   c Explain why a thermistor is suitable for this use.
Activity 19.1
Investigating resistive components

Skills
A03.1 Demonstrate knowledge of how to safely use techniques, apparatus and materials (including following a sequence of instructions where appropriate)
A03.2 Plan experiments and investigations
A03.3 Make and record observations, measurements and estimates
A03.4 Interpret and evaluate experimental observations and data

Find out more about thermistors and light-dependent resistors.

1 Design a circuit to measure the resistance of a thermistor. Check your design with your teacher before setting up your circuit.
2 Make measurements that will allow you to determine the thermistor’s resistance at room temperature.
3 Wrap your thermistor and its connecting wires in a plastic bag, so that it will not come into contact with the water in the water bath. Determine the resistance of the thermistor at different temperatures. Record your results in a table.
4 Draw a graph to show how the thermistor’s resistance depends on the temperature.
5 Connect an LDR in place of the resistor. Vary the brightness of the light falling on it. Observe how the current flowing through it varies.
6 You can use a light meter to determine the intensity of the light falling on the LDR. Place the light meter immediately next to the LDR. Design a method to vary the light level. Record your results in a table. Draw a graph to show how the resistance of the LDR depends on the intensity of the light.

Figure 19.7 A relay is used to link two circuits together. The relay is composed of a coil and a switch (shown in the blue dashed box).

When a current flows through the relay coil in the first circuit, it becomes magnetised. It pulls on the switch in the second circuit, causing it to close, and allowing a current to flow in the second circuit.

The second circuit often involves a large voltage, which would be dangerous for an operator to switch, or which could not be switched by a normal electronic circuit (because these work at low voltage).

Study tip
Remember: when a relay is used, there are two complete circuits.

Sensing circuits
A relay can be used in a circuit that senses changes in temperature or light level. Figure 19.8 shows a circuit that will set off a loud alarm when the temperature rises. This would be useful, for example, in an industrial freezer. If the freezer fails, a large quantity of frozen food could be ruined. Here is how the circuit in Figure 19.8 works:

1 When the temperature is low, the thermistor has a high resistance. The current in the left-hand circuit is small, so the relay remains open. There is no current in the right-hand circuit.

Relays
A relay is a type of switch that works using an electromagnet. Figure 19.7 shows that, when a relay is used, there are two circuits:

- the electromagnet coil of the relay (represented by a rectangle) is in one circuit
- the switch is in the other circuit.
When the temperature rises, the resistance of the thermistor decreases. The current through the relay coil increases, pulling the relay switch closed. Now a current flows in the right-hand circuit and this makes the bell ring. This circuit could be adapted to detect changes in light level. For example, the lights in a museum are switched off at night. A thief might use a torch and this could be detected using a light-dependent resistor in place of the thermistor.

**Question**

19.4

a) Redraw the circuit shown in Figure 19.8. Include a light-dependent resistor in place of the thermistor.

b) Explain why the bell would be silent when the LDR is in darkness.

c) Explain why the bell would ring when light shines on the LDR.

**Diodes**

A **diode** is a component that allows electric current to flow in one direction only. Its circuit symbol (Figure 19.9a) represents this by showing an arrow to indicate the direction in which current can flow. The bar shows that current is stopped if it tries to flow in the opposite direction. It can help to think of a diode as being a ‘waterfall’ in the circuit (Figure 19.9b). Charge can flow over the waterfall, but it cannot flow in the opposite direction, which would be uphill. Some diodes give out light when a current flows through them (Figure 19.9c). A diode that does this is called a **light-emitting diode** (LED). Again, it can help to think of the waterfall. As the charge flows over the waterfall, some of the energy it loses is given out as light.

Diodes are useful for converting alternating current (which varies back and forth) into direct current (which flows in one direction only). This process is known as **rectification** and the diode acts as a **rectifier**. Rectification is necessary, for example, in a radio that operates from the mains supply. Mains electricity is alternating current (a.c.) but the radio works using direct current (d.c.).

Light-emitting diodes are familiar in many pieces of electronic equipment. For example, they are used as the small indicator lights that show whether a stereo system or television is on. Modern traffic lights often use arrays of bright, energy-efficient LEDs in place of filament bulbs. These LED arrays use very little power, so they are much cheaper to run than traditional traffic lights. Also, they require little maintenance, because, if one LED fails, the remainder still emit light.

**Study tip**

Remember that the arrow in the diode symbol shows the direction in which conventional current can flow through the diode.
19.2 Combinations of resistors

If you have two resistors, there are two ways they can be connected together in a circuit: in series and in parallel. This is illustrated for two 10 \( \Omega \) resistors in Figure 19.10. It is useful to be able to work out the total resistance of two resistors like this. What is their combined resistance or effective resistance?

a) For the two 10 \( \Omega \) resistors in series. The current has to flow through two resistors instead of one. The resistance in the circuit is doubled, so the combined resistance is 20 \( \Omega \).

b) For the two 10 \( \Omega \) resistors in parallel. There are two possible paths for the current to flow along, instead of just one. The resistance in the circuit is halved, so the effective resistance is 5 \( \Omega \).

(We have not really proved these values for the combined or effective resistance, but you should see that they are reasonable values.)

To recognise when two resistors are connected in series, trace the path of the current around the circuit. If all the current flows through one resistor and then through the other (as in Figure 19.10a), the resistors are connected in series. They are connected end-to-end. For resistors in parallel, the current flows differently.

It flows around the circuit until it reaches a point where the circuit divides (as at point X in Figure 19.10b). Then some of the current flows through one resistor, and some flows through the other. Then the two currents recombine (as at point Y in Figure 19.10b) and return to the cell. Resistors in parallel are connected side-by-side.

**Resistors in series**

If several resistors are connected in series, then the current must flow through them all, one after another. The combined resistance \( R \) in the circuit is simply the sum of all the separate resistances. For three resistors in series (Figure 19.11a), the formula for their combined resistance is:

\[
R = R_1 + R_2 + R_3
\]

Figure 19.11b shows the same current \( I \) flowing through three resistors — remember, current cannot be used up. We can calculate the combined resistance for this circuit:

combined resistance = 10 \( \Omega \) + 20 \( \Omega \) + 20 \( \Omega \) = 50 \( \Omega \)

So the three resistors could be replaced by a single 50 \( \Omega \) resistor and the current in the circuit would be the same.

So, for resistors in series:

- the combined resistance is equal to the sum of the resistances
- the current is the same at all points around the circuit.

Figure 19.10 Two ways of connecting two resistors in a circuit: a) in series and b) in parallel.

Figure 19.11 a) Three resistors connected in series. b) Values of current and p.d. in a series circuit. The same current \( I \) flows through each of the three resistors.
Resistors in parallel

The lights in a conventional house are connected in parallel with one another. The reason for this is that each one requires the full voltage of the mains supply to work properly. If they were connected in series, the p.d. would be shared between them and they would be dim. In parallel, each one can be provided with its own switch, so that it can be operated separately. If one bulb fails, the others remain lit.

The effective resistance of several resistors connected in parallel is less than that of any of the individual resistors. This is because it is easier for the current to flow. You can see this for three resistors in parallel in Figure 19.12a. The current flowing from the source divides up as it passes through the resistors. Figure 19.12b shows the current from the power supply splitting up and passing through three resistors in parallel.

So, for two resistors in parallel:
- the effective resistance is less than the resistance of either resistor
- the current from the source is greater than the current through either resistor.

Potential-divider circuits

Often, a power supply or a battery provides a fixed potential difference. To obtain a smaller p.d., or a variable p.d., this fixed p.d. must be split up using a circuit called a potential divider. Figure 19.13 shows two forms of potential divider.

In the circuit shown in Figure 19.13a, two resistors $R_A$ and $R_B$ are connected in series across the 6 V power supply. The p.d. across the pair is thus 6 V. (It helps to think of the bottom line as representing 0 V and the top line as 6 V.) The p.d. at point $X$, between the two resistors, will be part-way between 0 V and 6 V, depending on the values of the resistors. If the resistors are equal, the p.d. at $X$ will be 3 V. The p.d. of the supply will have been divided in half—hence the name potential divider.

To produce a variable output, we replace the two resistors with a variable resistor, as shown in Figure 19.13b. By altering the resistance of the variable resistor, the voltage at $X$ can have any value between 0 V and 6 V.

![Image](image_url)

**Figure 19.12** a Three resistors connected in parallel. b Values of current and p.d. in a parallel circuit. The current flowing from the supply is shared between the resistors.

**Figure 19.13** a A simple potential-divider circuit. The output voltage is a fraction of the input voltage. The input voltage is divided according to the relative values of the two resistors. b A variable resistor is used to create a potential-divider circuit, which gives an output voltage that can be varied.
Questions

19.5 What is the combined resistance of two 20 Ω resistors connected in series?
19.6 Three resistors are connected in series with a battery, as shown.

![Diagram of resistors A, B, C connected in series]

Resistor A has the greatest resistance of the three. The current through A is 1.4 A. What can you say about the currents through B and C?
19.7 What is the combined resistance of three 30 Ω resistors connected in series?
19.8 a Two resistors are to be connected to form a potential-divider circuit. Should they be connected in series or in parallel with each other?
b State briefly the function of a potential-divider circuit.

Worked example 19.1

Three 5.0 Ω resistors are connected in series with a 12 V power supply. Calculate their combined resistance, the current that flows in the circuit, and the p.d. across each resistor.

Step 1: Draw a circuit diagram and mark on it all the quantities you know. Add arrows to show how the current flows.

![Circuit diagram with 5.0 Ω resistors in series]

Step 2: Calculate the combined resistance.
\[
R = R_1 + R_2 + R_3 \\
R = 5.0 \Omega + 5.0 \Omega + 5.0 \Omega \\
R = 15 \Omega
\]

Step 3: Calculate the current flowing. A p.d. of 12 V is pushing current through a resistor of 15 Ω total resistance. So:
\[
current \ I = \frac{V}{R} = \frac{12 \text{ V}}{15 \Omega} = 0.8 \text{ A}
\]

Step 4: Calculate the p.d. across an individual 5.0 Ω resistor when a current of 0.8 A flows through it.
\[
p.d. \ V = IR = 0.8 \text{ A} \times 5 \Omega = 4.0 \text{ V}
\]

Festive lights, such as those used on Christmas trees, are often wired together in series. This is because each bulb works on a small voltage. If a single bulb was connected to the mains supply, the p.d. across it would be too great. By connecting them in series, the mains voltage is shared out between them. The disadvantage of this is that, if one bulb fails (its filament breaks), they all go out because there is no longer a complete circuit for the current to flow around.
Current and resistance in parallel circuits

From Figure 19.12b, you can see that the current divides up to pass through the branches of a parallel circuit. Adding up the currents through the three separate resistors gives the current flowing out of the power supply.

In other words, the current from the supply is the sum of the currents flowing through the resistors:

\[ I = I_1 + I_2 + I_3 \]

Because the resistors are connected side by side, each feels the full push of the supply.

To calculate the effective resistance \( R \) for three resistors in parallel, we use this formula:

\[ \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \]

There are two ways to calculate this type of sum: either use a calculator, or add up the fractions by finding their lowest common denominator. Worked example 19.2

Worked example 19.2

Two 40 \( \Omega \) resistors and a 20 \( \Omega \) resistor are all connected in parallel with a 12 V power supply. Calculate their effective resistance, and the current through each. What current flows from the supply?

**Step 1:** Draw a circuit diagram and mark on it all the quantities you know (see Figure 19.15). Add arrows to show how the current flows.

![Circuit Diagram](image)

**Step 2:** Calculate the effective resistance.

\[
\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \\
\frac{1}{R} = \frac{1}{40 \Omega} + \frac{1}{40 \Omega} + \frac{1}{20 \Omega} \\
\frac{1}{R} = \frac{1}{40 \Omega} + \frac{1}{20 \Omega} \\
\frac{1}{R} = \frac{4}{40 \Omega} + \frac{2}{40 \Omega} \\
\frac{1}{R} = \frac{4}{40 \Omega} \\
R = \frac{40 \Omega}{4} \\
R = 10 \Omega
\]

So the three resistors together have an effective resistance of 10 \( \Omega \).

**Step 3:** Each resistor has a p.d. of 12 V across it.

Now we can calculate the currents using the equation:

\[ I = \frac{V}{R} \]

We get the following results for the currents:

- Current through 12 V 20 \( \Omega \) resistor = \( \frac{12 V}{20 \Omega} = 0.60 \) A
- Current through 12 V 40 \( \Omega \) resistor = \( \frac{12 V}{40 \Omega} = 0.30 \) A

These values have been marked on the diagram. Notice that, as you might expect, the smaller (20 \( \Omega \)) resistor has a bigger current flowing through it than the larger (40 \( \Omega \)) resistors.

**Step 4:** The current \( I \) flowing from the supply is the sum of the currents flowing through the individual resistors.

\[ I = 0.6 \text{ A} + 0.3 \text{ A} + 0.3 \text{ A} = 1.2 \text{ A} \]

We could have reached the same result using the effective resistance (10 \( \Omega \)) of the circuit that we found in Step 2:

\[ I = \frac{12 V}{10 \Omega} = 1.2 \text{ A} \]

This is a useful way to check that you have calculated the effective resistance correctly.
shows how to use this formula, and how to work out the sum by finding the lowest common denominator.

**Study tip**

Current divides in a parallel circuit, but the total amount must remain the same – electrons cannot just disappear.

### Activity 19.2

**Resistor combinations**

**Skills**

- A03.1 Demonstrate knowledge of how to safely use techniques, apparatus and materials (including following a sequence of instructions where appropriate)
- A03.2 Plan experiments and investigations
- A03.3 Make and record observations, measurements and estimates
- A03.4 Interpret and evaluate experimental observations and data

Connect up some combinations of resistors in series and in parallel. Measure their combined or effective resistances and compare them with calculated values.

1. Set up a circuit that will allow you to determine the resistance of a single resistor, or of two or more resistors.
2. Select four resistors with similar values of resistance. For each, make measurements to determine its resistance.
3. Connect two of the resistors in series. Calculate their combined resistance in series. Measure their combined resistance and compare it with your calculated value.
4. Repeat step 3 with other combinations of resistors (up to four) connected in series.
5. The effective resistance of two resistors in parallel is less than either of their individual resistances. Check this statement by measuring the effective resistance of two resistors in parallel.
6. If you know how to calculate the effective resistance of resistors in parallel, check whether your measured value is the same as the calculated value.

### Questions

- **19.9** Use the idea of resistors in series to explain why a long wire has more resistance than a short wire (of the same thickness and material).
- **19.10** Use the idea of resistors in parallel to explain why a thick wire has less resistance than a thin wire (of the same length and material).
- **19.11** A 10.0 Ω resistor is connected in series with a 20.0 Ω resistor and a 15.0 V power supply.
  a. Calculate the current flowing around the circuit.
  b. Which resistor will have the larger share of the p.d. across it?
- **19.12** What will be the effective resistance of three 60 Ω resistors connected together in parallel?
- **19.13** Two resistors of values 30 Ω and 60 Ω are connected in parallel. Calculate their effective resistance.

### 19.3 Electronic circuits

Electronic circuits (such as those found in phones, radios, mp3 players and television sets) make use of a number of other components to control the way that current flows in a circuit. In this section, we will look at logic gates.

**Analogue and digital**

In most of the circuits we have looked at so far, we could imagine choosing any value of voltage, for example, by changing a power supply or by altering a variable resistor. Many electronic circuits are different from this. They give an output voltage that can be either high (usually close to 6 V) or low (close to 0 V). (The relay circuits you studied above are like this – either the relay is open or closed, so the alarm bell rings or is silent – a relay cannot be half-way on.)

Circuits like this are described as digital. The output of the circuit is either ON or OFF – there is no in-between state. Digital electronic systems are very useful for storing and transferring information. Computers, mobile phones and mp3 players all work digitally.

In digital systems, each piece of information (such as a number or a letter) is represented in binary form as a sequence of 1s (ones) and 0s (zeros). In a circuit, a 1 corresponds to a high voltage (perhaps 6 V). A 0 corresponds to a low voltage (close to 0 V).
The opposite of a digital system is an analogue system. In an analogue system, voltages can have any value, positive or negative.

**Logic gates**

Logic gates are digital electronic components that engineers use as simple building blocks when they design electronic circuits. Each logic gate has a specific function, and many can be combined together to produce complex effects. Inside each logic gate there are a number of different components, but we do not need to think about these – we need only think about what goes in to the logic gate and what comes out as a result.

A logic gate is a device that receives one or more electrical input signals, and produces an output signal that depends on those input signals. These signals are voltages:
- high voltage is referred to as ON, and is represented by the symbol 1
- a low voltage is referred to as OFF, and is represented by the symbol 0.

In order to do this, a logic gate needs its own power supply, but this is not usually shown when circuit diagrams are drawn. It is easiest to understand how logic gates operate by looking at three specific examples: the AND, OR and NOT gates, whose circuit symbols are shown in Figure 19.14. The first two symbols have two inputs on the left and a single output on the right. The third one has one input on the left and one output on the right.

**a** An AND gate functions like this: its output is ON if both input 1 and input 2 are ON.

**b** An OR gate functions like this: its output is ON if either input 1 or input 2 or both is ON.

**c** A NOT gate functions like this: its output is ON if its input is not ON.

Let us look at a practical example. An OR gate might be useful in a heating system for the rooms in a house.

There might be temperature sensors in two rooms. If a room was cold, the sensor would send an ON signal to the OR gate. If either room was cold, the output of the gate would be ON, and this would switch on the heaters.

The way in which these three gates operate is clear from their names. Another way to remember how they operate is by learning their truth tables, shown in Figure 19.15. In a truth table, we use 0 and 1 to stand for OFF and ON.

![Figure 19.14](image)

**Figure 19.14** Circuit symbols for three logic gates: **a** AND, **b** OR and **c** NOT. In a truth table, 0 stands for OFF or a low voltage; and 1 stands for ON or a high voltage.

![Figure 19.15](image)

**Figure 19.15** Truth tables for three logic gates: **a** AND, **b** OR and **c** NOT. In a truth table, 0 stands for OFF or a low voltage; and 1 stands for ON or a high voltage.
A **truth table** shows all the possible combinations of inputs, and the output that results from each combination. The NOT gate (Figure 19.15c) has only one input, which can be ON or OFF, so this is the simplest table. The AND gate (Figure 19.15a) and OR gate (Figure 19.15b) both have two inputs. So there are four possible combinations of inputs, and there is a corresponding output for each. For example, you can see from the last line in the truth table for the AND gate that two input 1s give an output 1. For all other combinations of inputs, the output is 0. You should check that you understand how these truth tables represent the same information as in the sentences above that describe these gates.

**Combining logic gates**

Computer chips (microprocessors) are made up of many millions of logic gates. They combine together to produce outputs that depend on many different inputs. We will restrict ourselves to some simple examples involving just a few gates, to illustrate the principles involved.

Figure 19.16a shows an AND gate with a NOT gate connected to its output. We can work out the truth table for this combination by realising that the output of the AND gate is the input of the NOT gate. When the AND gate output is 1, the NOT gate turns this into a 0.

Figure 19.16b shows the same gates but connected together differently, along with the resulting truth table. This shows that the order in which gates are connected together is important. By combining the same gates in different orders, we can achieve different effects.

Figure 19.17 shows a combination of three OR gates. Let us look at a practical example of how this might function. A building has smoke detectors in four different places. Their outputs are connected via this combination of OR gates to a single alarm siren. If any detector gives an ON signal, the siren will be switched on. This saves the expense of a separate siren for each detector.

**Two more logic gates**

Figure 19.18 shows the symbols for two more logic gates, the NAND and NOR gates, each of which has two inputs and a single output. Their truth tables are also shown. From the truth tables, you should see that these gates can be described as follows.

a A NAND gate functions like this: its output is OFF if both input 1 and input 2 are ON.

b A NOR gate functions like this: its output is ON if neither input 1 nor input 2 is ON.

You could construct a NAND gate by connecting a NOT gate to the output of an AND gate, so AND + NOT = NAND. Similarly, you could construct a NOR...
gate by connecting a NOT gate to the output of an OR gate, so OR + NOT = NOR.

19.4 Electrical safety
Mains electricity is hazardous, because of the large voltages involved. If you come into contact with a bare wire at 230 V, you could get a fatal electric shock. Here, we will look at some aspects of the design of electrical systems and see how they can be used safely.

Electrical cables
The cables that carry electric current around a house are carefully chosen. Figure 19.19 shows some examples. For each, there is a maximum current that it is designed to carry. A 5 A cable (Figure 19.19a) is relatively thin. This might be used for a lighting circuit, since lights do not require much power, so the current flowing is relatively small. The wires in a 30 A cable (Figure 19.19c) are much thicker. This might be used for an electric cooker, which requires much bigger currents than a lighting circuit.

The wires in each cable are insulated from one another, and the whole cable has more protective insulation around the outside. If this insulation is damaged, there is a chance that the user will touch the bare wire and get an electric shock. There is also a chance that current will flow between two bare wires, or from one bare wire and any piece of metal it comes into contact with. Often, the metal case of an electrical appliance is earthed by connecting it to the earth wire to reduce the chances of a fatal electric shock.

Questions

19.14 The output of a NOT gate is connected to the input of another NOT gate.
   a) Draw up a truth table for this arrangement.
   b) Write a sentence to describe its effect.

19.15 a) Draw the symbol for a NOR gate.
   b) Draw a truth table to represent the operation of this gate.
   c) Write a sentence summarising its operation.

19.16 Look at the combination of gates shown in Figure 19.16b, together with its truth table.
   a) Draw the same combination of gates, but with the NOT gate connected to the other input of the AND gate.
   b) Draw up the corresponding truth table for this new arrangement.

19.17 The outputs of two AND gates are connected to the inputs of a third AND gate.
   a) Using the correct symbols, show that arrangement of gates.
   b) When is the output of this third gate ON?
   c) Suggest a use for this combination of gates.
Another hazard can arise if an excessive current flows in the wires. They will heat up and the insulation may melt, causing it to emit poisonous fumes or even catch fire. Thus it is vital to avoid using appliances that draw too much current from the supply. Fuses help to prevent this from happening – see below.

When using electricity, it is important to avoid damp or wet conditions. Recall that water is an electrical conductor (see section 18.1). So, for example, if your hands are wet when you touch an electrical appliance, the water may provide a conductive path for current to flow from a live wire through you to earth. That could prove fatal.

**Fuses**

Fuses are included in circuits to stop excessive currents from flowing. If the current gets too high, cables can burn out and fires can start. A fuse contains a thin section of wire, designed to melt and break if the current gets above a certain value. Usually, fuses are contained in cartridges, which make it easy to replace them, but some fuses use fuse wire, as shown in Figure 19.20. The thicker the wire, the higher the current that is needed to make it ‘blow’. A fuse represents a weak link in the electricity supply chain. Replacing a fuse is preferable to having to rewire a whole house.

**Figure 19.19** Cables of different thicknesses are chosen according to the maximum current that they are likely to have flowing through them: a 5 A, b 15 A and c 30 A. Each cable has live, neutral and earth wires, which are colour coded. In these cables, the earth wire does not have its own insulation.

**Figure 19.20** a Cartridge fuses and fuse wire. The thicker the wire, the higher the current that causes it to blow. b The circuit symbol for a fuse.

It is important to choose a fuse of the correct value in order to protect an appliance. The current rating of the fuse should be just above the value of the current that flows when the appliance is operating normally (see Worked example 19.3).

**Worked example 19.3**

A 2 kW heater works on a 230 V mains supply. The current flowing through it in normal use is 8.7 A. What current rating would a suitable fuse have? Choose from 3 A, 13 A and 30 A.

**Step 1:** The 3 A fuse has a current rating that is too low, and it would blow as soon as the heater was switched on.

**Step 2:** The 30 A fuse would not blow, but it is unsuitable because it would allow an excessive current (say, 20 A) to flow, which could cause the heater to overheat.

**Step 3:** The 13 A fuse is the correct choice, because it has the lowest rating above the normal operating current.
Circuit breakers

There are two types of circuit breaker used in electrical safety – try not to confuse them. Both work using electromagnets, but we will not consider the detail of their construction here.

A trip switch can replace a fuse. When the current flowing through the trip switch exceeds a certain value, the switch 'rips', breaking the circuit. Some modern house wiring systems use trip switches instead of fuses in the fuse box (Figure 19.21). You have probably come across trip switches on lab power supplies. If too much current starts to flow, the supply itself might overheat and be damaged. The trip switch jumps out, and you may have to wait a short while before you can reset it.

A residual-current device (RCD) protects the user rather than an appliance or cable. In normal circumstances, the currents flowing in the live and neutral wires are the same, because they form part of a series circuit. However, suppose that there is a fault.

Someone cutting the lawn with an electric lawnmower has accidentally damaged the live wire, by running over the flex with the mower. Some current then flows through the user, rather than along the neutral wire. Now more current is flowing in the live wire than in the neutral. The RCD detects this and switches off the supply. Houses often have RCDs fitted next to the fuse box. School labs usually have one too, to protect students and teachers.

Study tip

Remember that, if someone is to get a shock, they have to be part of a circuit. Current may flow through them and down into the ground.

Activity 19.3
Electrical safety

Find out more about electrical hazards.

Questions

19.18 In normal use, a current of 3.5 A flows through a hairdryer. Choose a suitable fuse from the following: 3 A, 5 A, 13 A, 30 A. Explain your choice.

19.19 a Why are fuses fitted in the fuse box of a domestic electricity supply?
b What device could be used in place of the fuses?

19.20 What hazards can arise when the current flowing in an electrical wire is too high?
Summary

You should know:

- how these circuit components behave – light-dependent resistor, thermistor, relay
- how these circuit components behave – diode, logic gates
- the current, voltage and effective resistance of resistors in series
- the current, voltage and effective resistance of resistors in parallel
- the formula for the effective resistance of resistors in parallel
- about potential-divider circuits
- how logic gates are used in digital control circuits
- about electrical safety devices: fuses and circuit breakers.

End-of-chapter questions

1. Copy the table and complete it by adding the names and symbols of the devices described.

<table>
<thead>
<tr>
<th>Name of device</th>
<th>Circuit symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>resistance decreases when light falls on it</td>
</tr>
<tr>
<td></td>
<td></td>
<td>resistance changes when temperature changes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>an electromagnetic switch</td>
</tr>
</tbody>
</table>

2. Copy and complete the following sentences about resistors connected in series. Fill the gaps with suitable words.
   a. Resistors in series have the same ...... in them.
   b. The effective resistance of resistors in series is the ...... of their resistances.

3. Copy and complete the following sentences about resistors connected in parallel. Fill the gaps with suitable words.
   a. Resistors in parallel have the same ...... across them.
   b. Current from the supply is ...... between resistors in parallel.
   c. The effective resistance of resistors in series is ...... than each of their individual resistances.

4. Copy and complete the following sentences about resistor combinations. Choose the correct word from each pair.
   a. When resistors are connected in series / parallel, the p.d. across the supply is shared between the resistors.
   b. When resistors are connected in series / parallel, the current from the supply is shared between the resistors.
   c. When resistors are connected in series / parallel, their effective resistance is given by \( R = R_1 + R_2 + R_3 \).
   d. When resistors are connected in series / parallel, their effective resistance is given by \( \frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \).
5 a Draw the circuit symbols for the following logic gates.
   i NOT
   ii AND
   iii OR
   iv NAND
   v NOR
b Write the truth table for each of these gates.

6 A fuse can be used to protect an electrical circuit.
a What problems may arise if a high current flows in a circuit? [1]
b What happens in the fuse when a dangerously high current flows in the circuit? [1]
c What other device could be used to protect a circuit instead of a fuse? [1]
d Explain why a 13 A fuse is suitable for a circuit in which the greatest current is usually 10 A. [1]

7 Draw the circuit symbol for each of the following electrical components. [4]
a resistor
b lamp
c bell
d fuse

8 a Draw a circuit in which two resistors are connected in series with each other, and with a switch and a 6 V supply. [4]
b If the two resistors in part a have values of 10 Ω and 40 Ω, what will be their combined resistance? [2]
c If the current flowing from the supply is 0.12 A, what current will flow through the 10 Ω resistor? [1]
d What current will flow back to the supply? [1]

9 Name the following electrical components. [1]
a It stores energy in a circuit.
b Its resistance decreases when light shines on it.
c It acts as an electromagnetic switch.

10 An electric circuit is designed to carry a current of 10 A.
a What problem may arise if the current rises above this value? [1]
b Name two devices that could be fitted into the circuit to protect the circuit if the current becomes dangerously high. [2]
c If the circuit is required to carry a higher current, how should the wiring be changed? Explain your answer. [3]
11 The circuit diagram shows an electric circuit in which current flows from a 6 V battery through two resistors.

![Circuit Diagram]

a Are the resistors connected in series or in parallel with each other? [1]
b For each resistor, state the p.d. across it. [2]
c The current flowing from the battery is shared between the resistors. Which resistor will have a bigger share of the current? Explain your answer. [2]
d Calculate the effective resistance of the two resistors, and the current that flows from the battery. [5]

12 The circuit diagram shows a circuit that includes a diode.

![Circuit Diagram with Diode]

a Copy the diagram and label the diode. [1]
b On your diagram, between points A and B, add the symbol for a cell. The cell must be connected in such a way that a current flows through the resistor. [1]
c On your diagram, add a labelled arrow to show the direction in which electrons move through the resistor when the current flows. [1]

13 Logic gates are often used in electronic control circuits. The operation of a logic gate can be represented by a truth table.

a What logic gate is represented by the truth table shown? Write a sentence to describe its operation. [2]

<table>
<thead>
<tr>
<th>input 1</th>
<th>input 2</th>
<th>output</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Key: 0 = OFF
Key: 1 = ON

b The output of a gate called an 'exclusive OR' gate is ON if just one of its two inputs is ON. Otherwise, it is OFF. Draw a truth table to represent this. [4]
c Name the two logic gates shown in the diagram. [2]

\[
\text{input 1} \quad \text{gate} \quad \text{output}
\]
\[
\text{input 2}
\]

\[\text{output}\]

d What will be the output of the combination of gates shown in the diagram if both inputs are ON? [1]

14 The diagram represents the circuit that operates two of the lamps on a car.

\[
\text{switch} \quad \text{fuse} \quad \text{car battery} \quad \text{lamps}
\]

\[\text{L}_1 \quad \text{L}_2\]

a Draw the circuit diagram for this circuit, using conventional symbols. [3]

b The car battery has an e.m.f. of 12 V and, when the lamps are switched on, there is a current of 1.6 A in each lamp. Calculate the resistance of one of the lamps. [4]

c When the switch is turned on, both lamps should light up. On one occasion when the driver operates the switch, lamp L₂ fails to light up. Suggest a reason for this. [1]

d An amateur workman connects a length of wire across lamp L₂ and shorts it out. When the switch is closed for the first time after this, what happens, if anything, to:

i the fuse

ii lamp L₁

iii lamp L₂? [3]

[Cambridge IGCSE® Physics 0625/23, Question 8, October/November, 2012]
15 The figure shows a circuit containing a 12 V power supply, some resistors and an ammeter whose resistance is so small that it may be ignored.

![Circuit Diagram]

a. i. Determine the potential difference across the 2 Ω resistor. [1]
   ii. State the potential difference across the 3 Ω resistor. [1]

b. Calculate the effective resistance of:
   i. the 2 Ω and 4 Ω resistors connected in series [1]
   ii. the 3 Ω and 6 Ω resistors connected in parallel. [2]

c. Calculate the reading on the ammeter. [2]

d. Without further calculation, state what happens, if anything, to the ammeter reading if:
   i. the 2 Ω resistor is shorted out with a thick piece of wire [2]
   ii. the thick piece of wire from d i and the 3 Ω resistor are both removed.

[Cambridge IGCSE Physics 0625/33, Question 7, October/November, 2011]