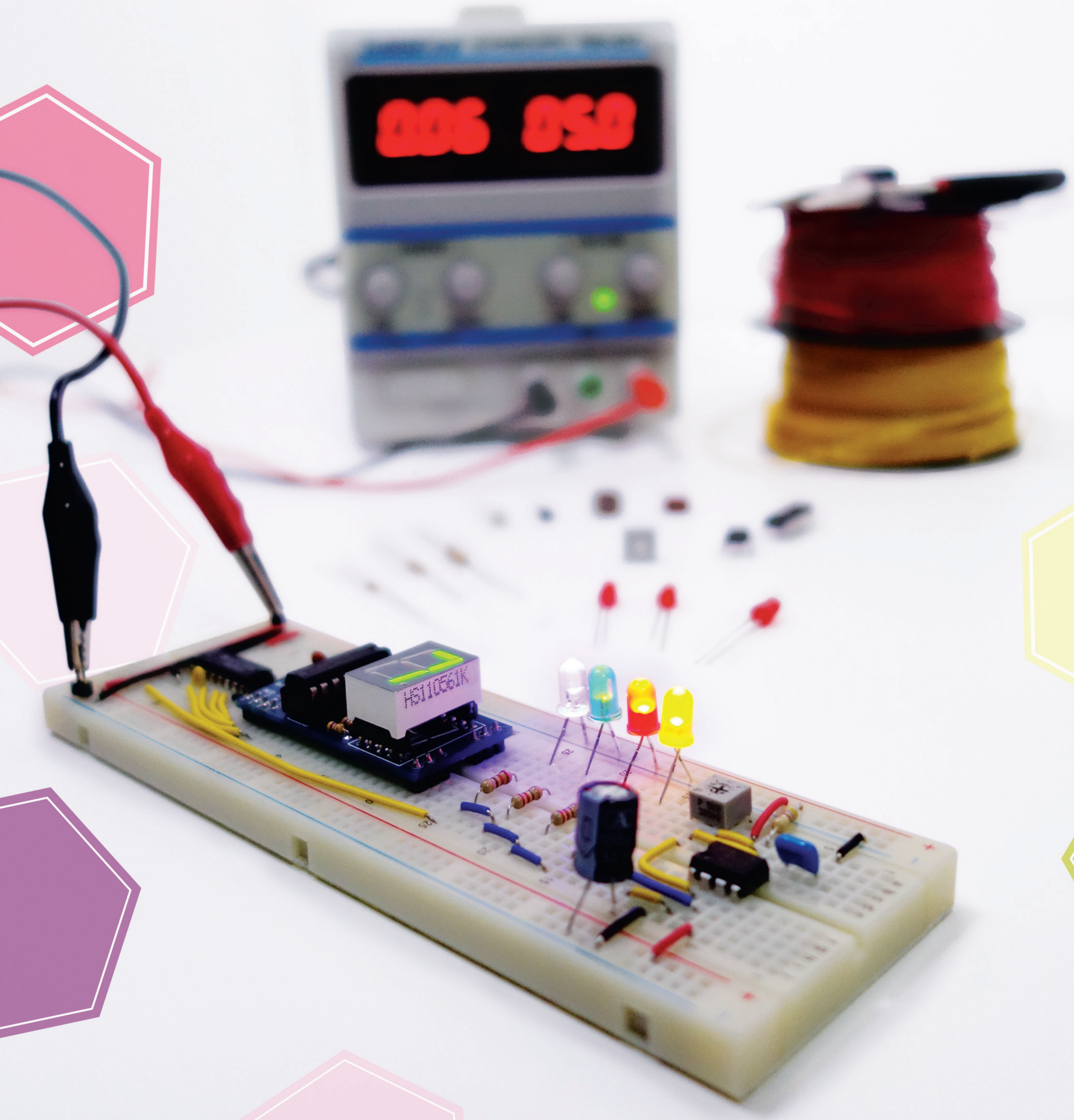
ESSENTIAL ELECTRONICS

A Textbook for GCE O-Level Electronics



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PREFACE

Essential Electronics – A Textbook for GCE O-Level Electronics is written to help upper secondary students build a strong, broad-based foundation in the study of electronics.

In alignment with the syllabus, the content is organised into the following five themes, each with a distinct colour scheme to help students identify the chapters under it.

- Electronic Systems
- Principles of Electricity
- Analogue Electronics
- Digital Electronics
- Engineering Design Process

Apart from the science of electronics, this textbook aims to equip students with practical knowledge of how to use electrical and electronic components correctly and safely. Detailed explanations are provided on the interpretation of data in component specification sheets. Furthermore, most of the circuits in this textbook have been built and tested to ensure that they are workable.

Another important aim of this textbook is to help students develop systems thinking – an essential skill in electronic engineering. By viewing electronic circuits as systems, students can break down larger systems into subsystems in order to analyse, design, build and test electronic circuits effectively.

As an introductory engineering course, GCE O-Level Electronics offers students multiple opportunities to develop 21st century competencies. For example, in Chapter 15, comprehensive explanations of the engineering design process help students develop the ability to specify a problem clearly, draft questions to guide their research and evaluate ideas. The importance of acknowledging sources of information used in one's work is also highlighted. These are key information and communication skills that are transferrable to other fields of study.

To achieve these aims, a number of useful features are included in this textbook:

- **Guiding questions**

  All chapters and sections start with an open-ended and thought-provoking guiding question which leads students towards a deeper understanding of the key ideas and helps them link the concepts in a meaningful and cohesive manner.

- **Block diagrams**

  Block diagrams are used extensively to highlight the inputs, processes and outputs of different types of systems.

- **Worked examples**

  Worked examples illustrate how concepts can be applied by providing models to guide students in solving problems.

- **Review questions**

  Students are encouraged to attempt the review questions at the end of each section to check their understanding of key concepts. The answers to these questions are provided at the back of the book.

- **Further readings**

  Found at the end of some chapters, these readings take interested students beyond the scope of the syllabus to learn additional ideas about the applications of electronics.

- **Differentiated annotations**

  In the study of electronics, the same letter is often used to represent both a component and a quantity, which can be confusing for new learners. For example, 'R' can refer to a resistor in a circuit as well as its resistance. To help students, this textbook uses non-italic letters to represent components and italic letters to represent quantities. Thus, 'R' refers to a resistor and 'R' refers to its resistance.

ACKNOWLEDGEMENTS

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CONTENTS

1.1 What are the main parts of an electronic system?

Learning Outcomes

- Recognise and understand that a simple system consists of an input, a process and an output.
- Give examples of electronic systems encountered in daily life.
- Identify the inputs, processes (amplification, logic, memory, decoding, timing and counting) and outputs of an electronic system (e.g., an audio amplifier).
- Describe a subsystem as a system that obtains input from, or provides input to, another subsystem.

Key Ideas

- A system is a collection of parts that work together to perform one or more functions.
- A basic system consists of an input, a process and an output.
- A subsystem is part of a system that receives input from and/or provides input to another subsystem.
- Electronic systems can perform useful processes such as amplification, logic decision making, storing data, decoding, timing and counting.

Parts of a basic system

A **system** is a collection of parts that work together to perform one or more functions. A basic system consists of an **input**, a **process** and an **output**. An input is the information or energy that goes into a system. A process is an action performed by the system on an input to turn it into an output. An output is the information or energy that goes out of a system.

The relationship between inputs, processes and outputs can be represented using a block diagram like the one in Figure 1.2. The arrows represent the flow of information or energy.

Figure 1.2 Parts of a basic system

An example of a system is the electronic calculator shown in Figure 1.3. The main parts of the calculator are the buttons, processor (hidden inside) and display panel. The buttons allow the user to enter the numbers (input). The processor performs the calculation (process). The display panel shows the result (output).

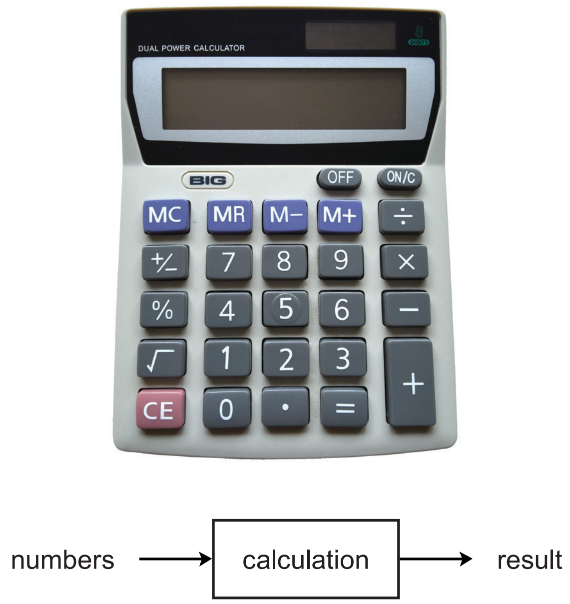


Figure 1.3 An electronic calculator is an example of a system

In electronics, it is common to use the parts of an electronic system to draw its block diagram. Figure 1.4 shows the block diagram of an electronic calculator which is made up of three blocks: the buttons, processor and display panel. Each block is called a **subsystem**. Notice that each subsystem takes in input from another subsystem or provides input into another subsystem or both.

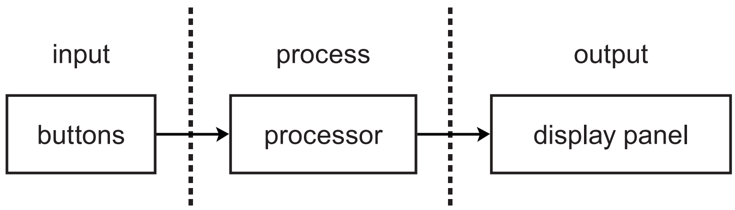


Figure 1.4 Block diagram of an electronic calculator

Besides the calculator, there are many other electronic systems that are used to perform different useful functions. The more complex an electronic system, the more complicated the processes involved. Computers and mobile phones are examples of complex electronic systems.

Simple electronic systems perform simpler functions. They are easier to understand and build. Figure 1.5 shows a digital tally counter, loudhailer and digital kitchen timer, which are some examples of simple electronic systems. In this course, we will learn about various electrical and electronic components that will enable us to design and build simple electronic systems.

digital tally counter


loudhailer

digital kitchen timer

Figure 1.5 Examples of simple electronic systems

Table 1.1 shows some common electronic systems and the processes they perform.

Table 1.1 Examples of electronic systems and the processes they perform

Electronic system	Process
audio amplifier	amplification
counter	counting
timer	timing
logic gate	decision making
decoder	decoding
memory circuit	storing data

Review Questions 1.1

1. State the three parts of a basic system.
2. Explain what is meant by a subsystem.
3. Give two examples of electronic systems and draw a block diagram for each system to describe its input, process and output.

1.2 How are electronic systems represented?

Learning Outcomes

- Represent complex systems in terms of subsystems using block diagrams.
- Use the symbols of common electrical and electronic components to represent an electrical/electronic system.

Key Ideas

- Block diagrams are commonly used to provide an overview of an electronic system.
- Circuit diagrams are used to describe how the components in electronic circuits are electrically connected together.

Electronic systems are commonly represented in the form of block diagrams and circuit diagrams.

Block diagrams

A **block diagram** provides an overview of an electronic system. It shows the subsystems that make up the overall system and how information or energy flows through them.

Figure 1.6 shows the block diagram of a loudhailer, which is essentially an audio amplifier. From the block diagram, we can see that the loudhailer system consists of two inputs (provided by the microphone and volume control knob), a process (performed by the amplifier) and an output (provided by the loudspeaker).

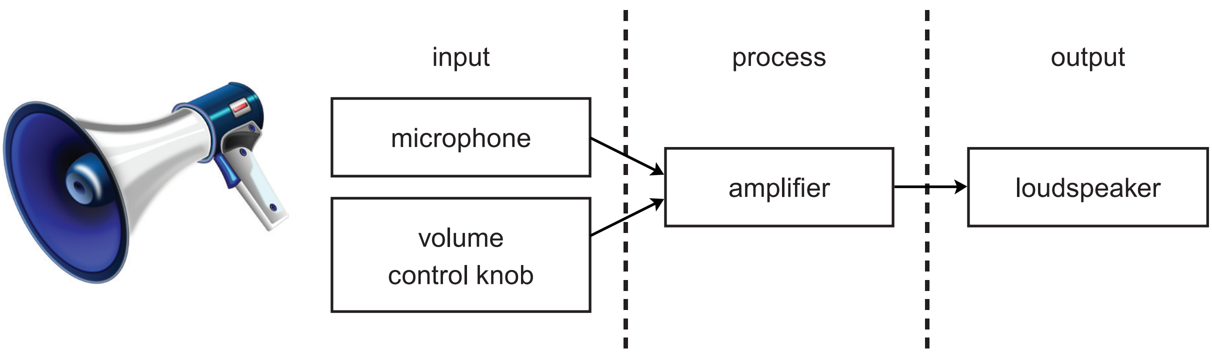


Figure 1.6 Block diagram of a loudhailer (audio amplifier)

Although a block diagram is useful in providing an overview of an electronic system, it does not contain enough information to build the system. To provide the necessary information, a circuit diagram is needed.

Circuit diagrams

All electronic systems come in the form of circuits (see Section 4.1). In an electronic circuit, different electronic components are connected together. The connections need to be made correctly for the system to work properly. Electronic circuits can be connected in different ways, for example, using only wires or on specially made boards such as breadboards or printed circuit boards (PCBs).

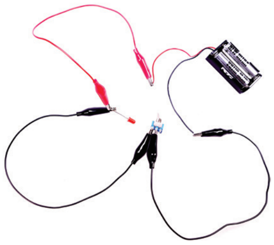


Figure 1.7a A circuit connected using wires only

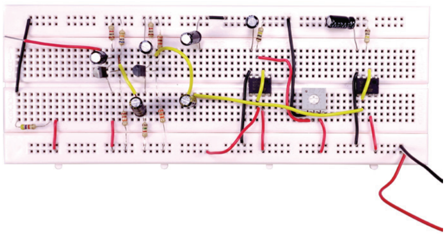


Figure 1.7b A circuit built on a breadboard

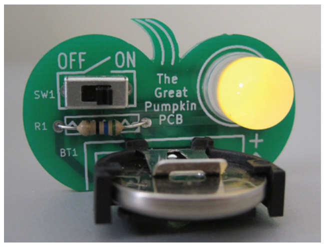
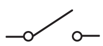
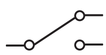
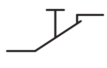
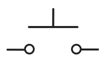
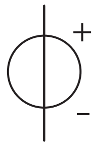
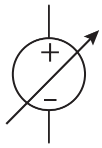
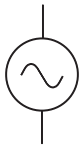
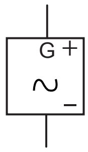
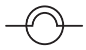
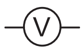
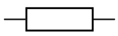
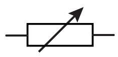
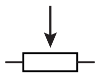
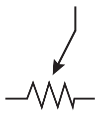
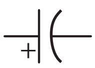


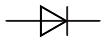
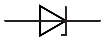
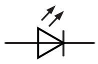
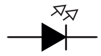
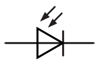
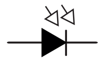
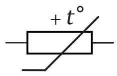
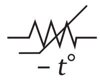
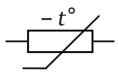
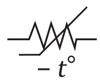
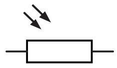
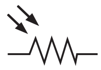
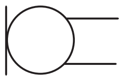
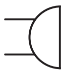
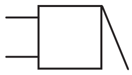
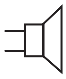
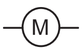
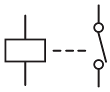
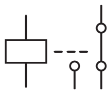
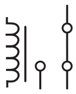
Figure 1.7c A circuit built using a PCB

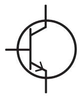
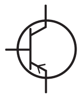
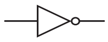
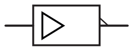
Circuit diagrams (also called **schematic diagrams**) are used to describe how the components in electronic circuits are electrically connected together. These diagrams should be drawn using internationally recognised symbols. Table 1.2 lists some commonly used components and their symbols.

Table 1.2 Electrical/electronic components and their symbols

Component	Sub-category (if any)	Symbol adopted for textbook	Other symbols (if any)
Switch	Single pole single throw (SPST) – open		
	SPST – closed		
	Single pole double throw (SPDT)		
	Pushbutton: Push-to-make (PTM)		
	Pushbutton: Push-to-break (PTB)		

Component	Sub-category (if any)	Symbol adopted for textbook	Other symbols (if any)
Direct current (DC) source	Single-cell battery		
	Multi-cell battery		
	Fixed DC voltage source		
	Variable DC voltage source		
Alternating current (AC) source			
Reference voltage	Positive voltage		
	Ground		
Bulb			
Ammeter			
Voltmeter			
Resistor	Fixed resistor		
	Variable resistor		
	Potentiometer		
Capacitor	Non-polarised capacitor		
	Polarised capacitor		

Component	Sub-category (if any)	Symbol adopted for textbook	Other symbols (if any)
Diode	General-purpose diode		
	Zener diode		
	Light-emitting diode (LED) Infrared (IR) diode		
	Photodiode		
Transducer	Thermistor (positive coefficient)		
	Thermistor (negative coefficient)		
	Light-dependent resistor (LDR)		
	Microphone		
	Buzzer		
	Loudspeaker		
	Motor		
Relay	SPST		
	SPDT		

Component	Sub-category (if any)	Symbol adopted for textbook	Other symbols (if any)
Bipolar junction transistor (BJT)	NPN		
	PNP		
Logic gate	NOT gate		
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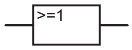
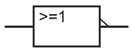
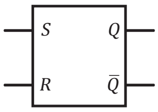
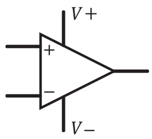
	OR gate		
	NAND gate		
	NOR gate		
Set-Reset (S-R) latch			
Voltage comparator			

A circuit diagram should enable a trained engineer to build an exact copy of the circuit. Besides the connections, a circuit diagram should contain essential details such as component values and model numbers.

Figure 1.8 shows an example of a circuit diagram. The value of the battery (9.0 V), types of resistors, values of the resistors (470 Ω, 47 kΩ and 100 kΩ) and model number of the comparator (LM311) are all clearly indicated.

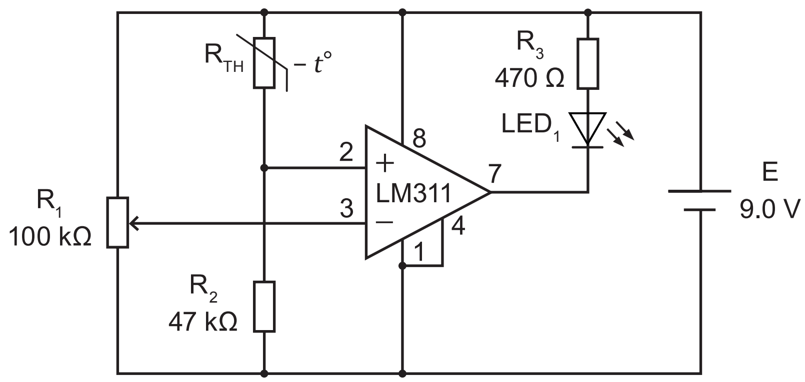


Figure 1.8 Example of a circuit diagram

Review Question 1.2

1. Describe two common ways of representing electronic systems.

1.3 How does information flow in electronic systems?

Learning Outcomes

- State that an electrical signal is an electrical voltage or current that carries information.
- Recognise that electrical signals may be analogue or digital in nature, and differentiate between them.

Key Ideas

- An electrical signal is an electrical voltage or current that carries information.
- An electrical signal can be in analogue or digital form.

Electrical and non-electrical information

Humans can process information obtained through our five senses. This information, such as sound and light, is in non-electrical form. However, electronic systems can only process information in the form of **electrical signals**. Electrical signals are voltages or currents that carry information.

For this reason, non-electrical information needs to be first converted into electrical signals so that it can be processed by an electronic system. After processing, the electrical signals are converted back into a non-electrical form to be understood by humans.

The conversion between electrical and non-electrical forms of information is performed by components or devices called transducers. Keyboards and monitors are two examples of transducers that we often use in our daily lives. Figure 1.9 gives an overview of how they work. We will learn more about transducers in Chapter 8.

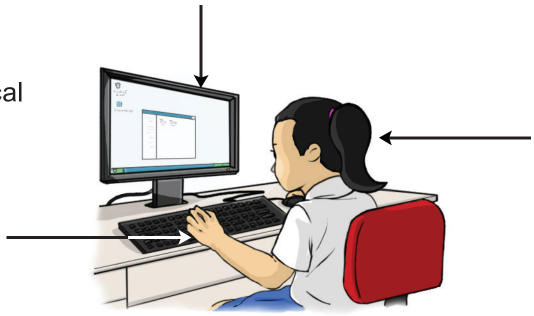


Figure 1.9 The keyboard and monitor are examples of transducers

Electrical signals can be classified into two main types: **analogue signals** that vary continuously over time and **digital signals** that vary in steps. The analogue signal in Figure 1.10 can take on any value between 0 V and 5 V. Conversely, the digital signal can only take on a value of either 0 V or 5 V and not anything in between. We will learn more about digital signals in Section 10.1.

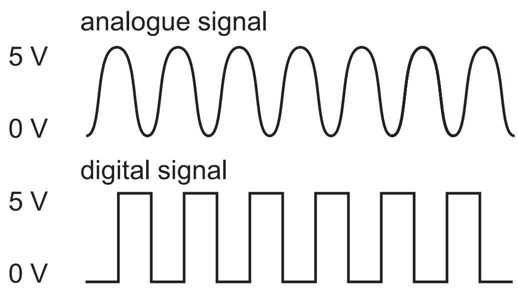


Figure 1.10 Analogue and digital signals

Review Questions 1.3

1. Describe the flow of information in an electronic system.
2. Describe the difference between analogue and digital signals.

2 CURRENT ELECTRICITY

What are the quantities related to current electricity?

Electronic systems require electricity to work. Think about a few electronic systems that you use in daily life – they all need a source of electricity, such as batteries or electrical mains.

Figure 2.1 Electronic systems need a source of electricity to work, e.g., electronic calculators (top) use batteries and desktop computers (bottom) use electrical mains

The components of an electronic system control how electric current flows to different parts of the system. Thus, to be able to design, build and test electronic systems, knowledge of electricity is needed. In this chapter, we will learn about how electricity works.

2.1 What are base and derived quantities?

Learning Outcomes

- Recall the following base quantities and their SI units: mass (kg), length (m), time (s), electric current (A) and temperature (K).
- Recall derived quantities related to electricity (e.g., electric charge, resistivity and frequency) and their SI units.

Key Ideas

- There are seven base quantities and base units.
- We can obtain derived quantities by multiplying or dividing two or more base quantities.

We use different instruments to take different types of measurements. Figure 2.2a shows a digital stopwatch, which is used to measure time, while Figure 2.2b shows a digital multimeter, which is used to measure different types of electrical quantities such as current, voltage and resistance.

Figure 2.2a A digital stopwatch is used to measure time

Figure 2.2b A digital multimeter is used to measure different types of electrical quantities such as current, voltage and resistance

Physical quantities

A **physical quantity** is a quantity that can be measured. It consists of a numerical magnitude and a unit, as shown in Figure 2.3.

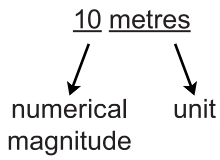


Figure 2.3 A physical quantity consists of a numerical magnitude and a unit

SI units

SI stands for 'Système International d'Unités' in French, which means 'International System of Units' in English. This system recommends the use of a set of common units, which allows for common understanding and clear communication among scientists and engineers.

Base quantities and base units

Base quantities are the physical quantities that make up all other physical quantities. The SI units of the base quantities are called **base units**. Table 2.1 shows the seven base quantities and their respective SI units.

Table 2.1 Base quantities and their respective SI units

Base quantity	Base unit (symbol)
length	metre (m)
mass	kilogram (kg)
time	second (s)
electric current	ampere (A)
temperature	kelvin (K)
amount of substance	mole (mol)
luminous intensity	candela (cd)

The base quantities that will be used in this course are length, time and electric current.

Derived quantities

Derived quantities are obtained by multiplying or dividing two or more base quantities. Figure 2.4 shows how area, a derived quantity, is obtained by multiplying two lengths.

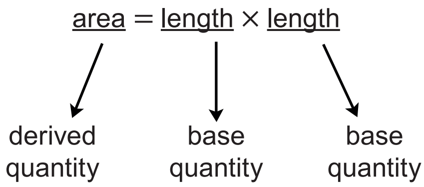


Figure 2.4 Area is an example of a derived quantity

The units of derived quantities are called **derived units**. They are obtained by multiplying or dividing the corresponding base units. Figure 2.5 shows how the SI unit of area is obtained by multiplying the SI unit of length by another SI unit of length.

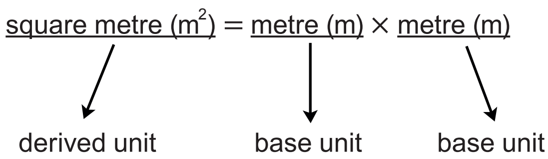


Figure 2.5 Obtaining the derived unit for area

Table 2.2 shows the derived quantities that will be used in this course.

Table 2.2 Derived quantities and their respective SI units

Derived quantity	Derived unit (symbol)
electric charge	coulomb (C)
work done	joule (J)
voltage	volt (V)
resistance	ohm (Ω)
power	watt (W)
energy	joule (J)
area	square metre (m^2)
resistivity	ohm metre (Ωm)
frequency	hertz (Hz)
capacitance	farad (F)

2.2 How do we express very small and very big physical quantities?

Learning Outcomes

- Express the magnitude of quantities in scientific (exponential) notation.
- Use the following prefixes and their symbols to indicate decimal submultiples and multiples of the SI units: pico (p), nano (n), micro (μ), milli (m), centi (c), kilo (k), mega (M), giga (G), tera (T).

Key Idea

- Prefixes and scientific notation can be used to represent quantities that are very small or very large.

We occasionally come across very small or very large quantities in our daily lives. For example, the thickness of a sheet of paper is around 0.00005 metres and the distance between Singapore and Kuala Lumpur is around 350 000 metres. Notice that such quantities have either many decimal places or many zeros.

In electronics, we also have to deal with very small and very large quantities. Figure 2.6 shows two such quantities: a small current and a large resistance.

Figure 2.6 Examples of very small and very large quantities in electronics: a 0.017 A current (left) and a 1 000 000 Ω resistor (right)

To express very small and very big quantities clearly, we usually use **scientific notation** and **prefixes**.

Scientific notation

In scientific notation, numbers are expressed in the form:

$$M \times 10^{N}$$

where $1 \leq M < 10$ and N is an integer.

Worked Example 2.1

Express (a) 12 400 and (b) 0.000 000 78 in scientific notation.

Solution

Step 1: Shift the position of the decimal point to make the number more than or equal to 1 but less than 10.

(a) Shift the decimal point until the number becomes 1.24

12 400

Therefore, $M = 1.24$

(b) Shift the decimal point until the number becomes 7.8

0.000 000 78

Therefore, $M = 7.8$

Step 2: Determine N, where N is the number of decimal places shifted. N is positive if the decimal place is shifted to the left and negative if the decimal place is shifted to the right.

(a) Shifted 4 places to the left

12 400

Therefore, $N = 4$

(b) Shifted 7 places to the right

0.000 000 78

Therefore, $N = -7$

Step 3: Write the number in scientific notation.

(a) $12\,400 = 1.24 \times 10^{4}$

(b) $0.000\,000\,78 = 7.8 \times 10^{-7}$

Prefixes

Prefixes are placed before a unit to make it smaller or larger, e.g., the prefix 'kilo' is placed before the unit 'metre' to form the larger unit 'kilometre'. Some common prefixes are shown in Table 2.3.

Table 2.3 Common prefixes and symbols

	Factor	Prefix	Symbol
Multiples	10^{12}	tera	T
	10^{9}	giga	G
	10^{6}	mega	M
	10^{3}	kilo	k
Submultiples	10^{-1}	deci	d
	10^{-2}	centi	c
	10^{-3}	milli	m
	10^{-6}	micro	µ
	10^{-9}	nano	n
	10^{-12}	pico	p

You may often come across the following prefixes in this course:

- kilo (k) – mainly used for resistance, e.g., 2.2 kΩ
- milli (m) – mainly used for current, e.g., 1.2 mA
- micro (µ) and nano (n) – mainly used for capacitance, e.g., 3.3 µF and 10 nF

Note that 'deci' and 'centi' are not commonly used in electronics and thus will not be used in this course.

Worked Example 2.2

Express (a) 50 000 Ω and (b) 0.0028 A using the appropriate prefixes.

Solution

Step 1: Choose the most appropriate prefix. The factor of the prefix should be just smaller than the number.

(a) For 50 000, 'kilo' is the most appropriate prefix as the factor 1000 is just smaller than 50 000.

(b) For 0.0028, 'milli' is the most appropriate prefix as the factor 0.001 is just smaller than 0.0028.

Step 2: Shift the position of the decimal point based on the selected prefix, e.g., shift the decimal point 3 places to the left to use 'kilo' and 3 places to the right to use 'milli'.

(a) Shift 3 places to the left for 'kilo'

50 000

(b) Shift 3 places to the right for 'milli'

0.0028

Step 3: Write the number using the selected prefixes.

(a) $50\,000\ \Omega = 50 \times 10^{3}\ \Omega$
$= 50\ \text{k}\Omega$ (50 kiloohms)

(b) $0.0028\ \text{A} = 2.8 \times 10^{-3}\ \text{A}$
$= 2.8\ \text{mA}$ (2.8 milliamperes)

Review Questions 2.2

1. Express the following quantities in scientific notation:
   (a) 6 800 000 Ω
   (b) 0.001 22 A

2. Express the following quantities using the appropriate prefixes:
   (a) 47 000 Ω
   (b) 0.026 A

2.3 What is electric current?

Learning Outcomes

- Distinguish between conventional current and electron flow.
- State that current is the rate of flow of charge and is measured in amperes (A).
- Recall and apply the relationship Charge = Current × Time.

Key Ideas

- Conventional current flows from the positive terminal to the negative terminal of a battery.
- Electrons flow from the negative terminal to the positive terminal of a battery.
- Current is the flow of charge per unit time, i.e., Current = $\frac{\text{Charge}}{\text{Time}}$.

In Section 2.1, we learnt that current is one of the base quantities. From this section onwards, we will discuss current and other quantities related to electricity.

Conventional current vs electron flow

When scientists first studied electricity, they assumed that positive electric charges flow from the positive terminal of a battery through a circuit to the negative terminal. This is called **conventional current**, which is widely used and will be adopted in this textbook. Figure 2.7 shows the flow of conventional current in a circuit.

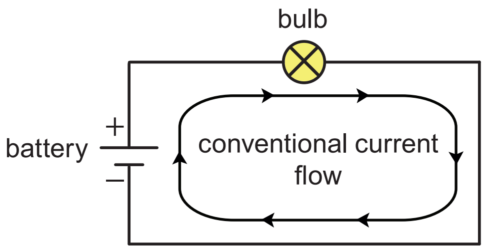


Figure 2.7 Conventional current flows from the positive terminal of a battery to the negative terminal

Scientists then discovered that it is actually the flow of negative electric charges (electrons) that gives rise to a current. The direction of this electron flow is opposite to the direction of conventional current flow, i.e., from the negative terminal of a battery through a circuit to the positive terminal. Figure 2.8 shows the flow of electrons in a circuit.

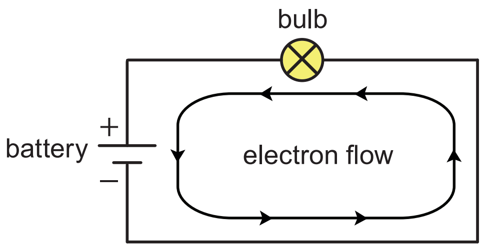


Figure 2.8 Electrons flow from the negative terminal of a battery to the positive terminal

Current as rate of flow of electric charge

Current is defined as the rate of flow of electric charge, which can be expressed by the equation:

$$I = \frac{Q}{t}$$

where I = current (in A),
Q = amount of electric charge (in C),
t = time taken (in s).

The SI unit of electric current is the **ampere (A)**. 1 A is equal to 1 C/s.

Worked Example 2.3

8.0 C of electric charge flows through a point in a circuit in 2.0 s. Calculate the current.

Solution

$$I = \frac{Q}{t} = \frac{8.0\text{ C}}{2.0\text{ s}} = 4.0\text{ A}$$

Worked Example 2.4

A conductor carries a current of 10 A. Calculate the amount of charge that flows through the conductor in 0.50 s.

Solution

$$I = \frac{Q}{t}$$

$$10\text{ A} = \frac{Q}{0.50\text{ s}}$$

$$Q = 10\text{ A} \times 0.50\text{ s}$$
$$= 5.0\text{ C}$$

Measuring current

To measure the current through a component, we connect an ammeter in series with the component. Figure 2.9 shows a circuit with an ammeter connected in series with a light bulb to measure the current through the bulb. In this course, we will be using a digital multimeter as an ammeter.

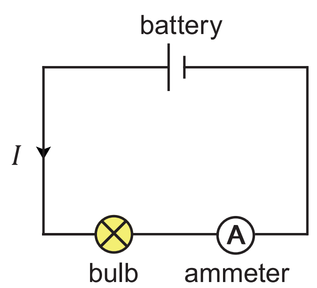


Figure 2.9 An ammeter is always connected in series with the component to be measured

Review Questions 2.3

1. Draw and label the directions of conventional current and electron flow in the circuit shown in Figure 2.10.

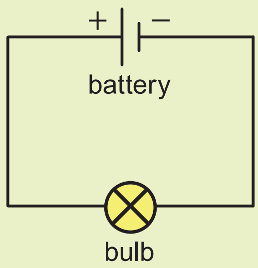


Figure 2.10

2. A current of 20 mA flows through a wire. Calculate the amount of charge that flows through this wire in 50 s.

3. 500 C of charge flows through a circuit in two minutes. Calculate the current through this circuit.

2.4 How is voltage related to current?

Learning Outcomes

- Distinguish between electromotive force (e.m.f.) and potential difference (p.d.).
- State that both e.m.f. and p.d. are measured in volts (V).
- Calculate the effective e.m.f. when several sources are connected in series and in parallel.

Key Ideas

- E.m.f. is the work done by a source in driving a unit charge around a circuit while p.d. is the work done in driving a unit charge through a component.
- Both e.m.f. and p.d. are measured in volts (V).
- For sources connected in series, the effective e.m.f. is the sum of the e.m.f. of each source.
- For sources connected in parallel, the effective e.m.f. is equivalent to the e.m.f. of one source (assuming that all sources have the same e.m.f.).

Electromotive force

Figure 2.11a shows a loop of pipe containing water. The water does not flow around the pipe as there is no force acting on the water. When a pump is added, as shown in Figure 2.11b, water flows around the pipe and the water wheel turns.

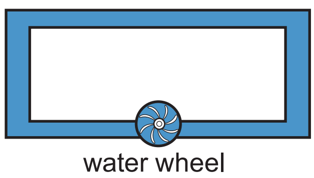


Figure 2.11a Water does not flow around the pipe

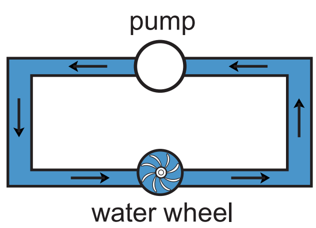


Figure 2.11b Water flows around the pipe when a pump is added

Similarly, there is no current flowing in the electric circuit shown in Figure 2.12a because there is nothing to move the electric charges. When a battery is added, as shown in Figure 2.12b, current flows around the circuit and causes the bulb to light up. The battery causes electric charges to move around the circuit, just as the water pump causes water to flow around the pipe.

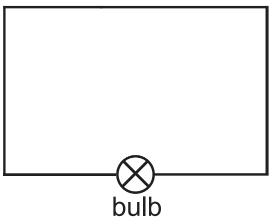


Figure 2.12a Current does not flow around the circuit

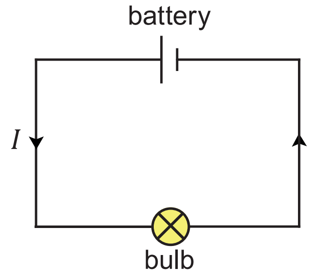


Figure 2.12b Current flows around the circuit when a battery is added

The battery is able to make current flow around the circuit because it provides what is known as an **electromotive force (e.m.f.)**. Without an e.m.f., there is no current. Note that although the term 'e.m.f.' contains the term 'force', e.m.f. is not a physical force.

E.m.f. is defined as the work done by a source in driving a unit charge around a circuit. The SI unit of e.m.f. is the **volt (V)**. In this textbook, we will use E to denote e.m.f. in circuit diagrams.

Figure 2.13 shows a standard AA-sized battery, which has an e.m.f. of 1.5 V.

Figure 2.13 This AA-sized battery has an e.m.f. of 1.5 V

Connecting batteries in series

To obtain a larger e.m.f., we can connect the positive terminal of one battery to the negative terminal of another battery as shown in Figure 2.14. This is called a series arrangement.

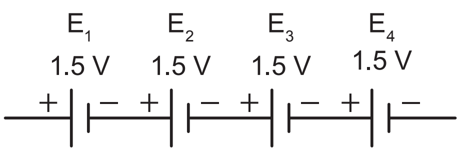


Figure 2.14 Batteries connected in series

The effective e.m.f. of the four 1.5 V batteries in Figure 2.14 is the sum of the e.m.f. of each battery.

$$\begin{aligned}\text{Effective e.m.f.} &= 1.5\text{ V} + 1.5\text{ V} + 1.5\text{ V} + 1.5\text{ V}\\ &= 6.0\text{ V}\end{aligned}$$

When a larger e.m.f. is applied to a component, the current through the component will increase as shown in Figure 2.15. When increasing the e.m.f., we should ensure that the current does not become so large that the component becomes overheated (see Section 2.6).

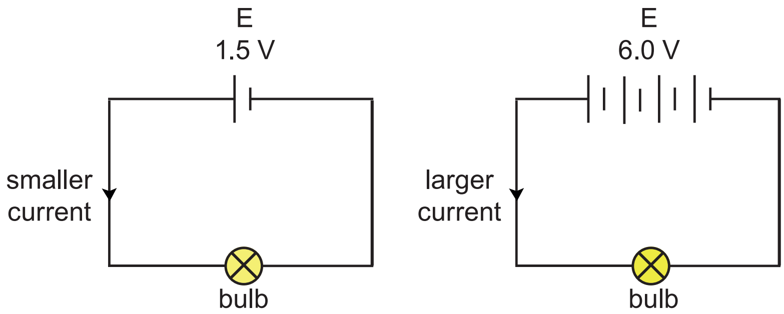


Figure 2.15 The larger the e.m.f. applied to a component, the larger the current through it

Connecting batteries in parallel

Batteries can also be connected in parallel as shown in Figure 2.16. Such an arrangement allows the batteries to provide electricity for a longer period of time than a single battery can. However, the effective e.m.f. remains the same as the e.m.f. of a single battery, i.e., 1.5 V.

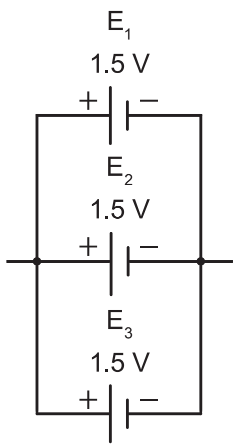


Figure 2.16 Batteries connected in parallel

It is advisable to connect only batteries of the same e.m.f. in parallel. Otherwise, current will flow from the battery of higher e.m.f. to the battery of lower e.m.f., resulting in energy wastage due to the generation of unwanted heat. The effective e.m.f. will also be unpredictable.

Potential difference

The **potential difference (p.d.)** across a component is the work done in driving a unit charge through the component. The SI unit of p.d. is the **volt (V)**.

Figure 2.17 shows a circuit with two identical bulbs connected to a 3.0 V battery. The p.d. across each bulb is 1.5 V. This means that 1.5 J of work is done in driving 1 C of charge through each bulb.

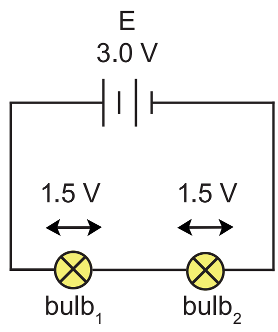


Figure 2.17 Potential difference across bulbs

Table 2.4 compares e.m.f. with p.d.

Table 2.4 Comparison between e.m.f. and p.d.

Electromotive force	Potential difference
Work done by a source to drive a unit charge around a circuit	Work done to drive a unit charge through a component or between two points in a circuit
Measured in volts (V)	Measured in volts (V)

Measuring voltage

We often use the term '**voltage**' in place of 'e.m.f.' or 'p.d.'. For example, the voltage across a resistor would mean the p.d. across the resistor while the voltage of a battery would mean the e.m.f. of the battery.

To measure the voltage across a component, we connect a voltmeter in parallel with the component. Figure 2.18 shows a voltmeter connected in parallel with a light bulb. In this course, we will be using a digital multimeter as a voltmeter.

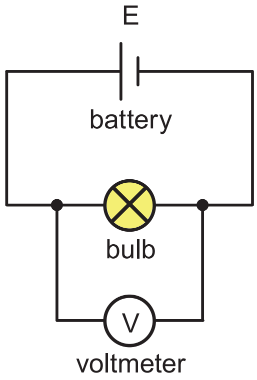


Figure 2.18 A voltmeter is always connected in parallel with the component to be measured

Reference voltage

Figure 2.19 shows a circuit with two identical resistors connected in series with a 6.0 V battery. The voltage across each resistor is 3.0 V.

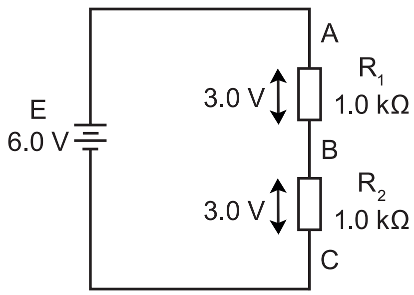


Figure 2.19 A series circuit

The voltage at point A can be described either as:

- 3.0 V higher than the voltage at point B; or
- 6.0 V higher than the voltage at point C.

Either way, we need to make reference to another point (either B or C). To make it easier to describe the voltage at different points in a circuit, we can assign the voltage at a particular point to be the **reference voltage**.

In Figure 2.20, we have assigned the negative terminal of the battery to be the reference voltage. This is indicated by the symbol ⏚. This symbol is called the '**ground**', and it represents a voltage of 0 V. The voltage at other points of the circuit is now taken with reference to this point. If the negative terminal of the battery is the point with the lowest voltage in the circuit, it is usually assigned to be the ground.

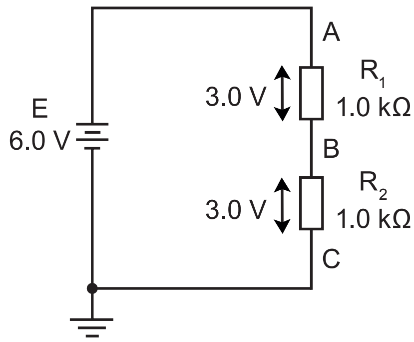


Figure 2.20 A series circuit with a ground reference voltage

The voltages at points A, B and C of the circuit in Figure 2.20 can now be described respectively as:

- $V_A = 6.0$ V;
- $V_B = 3.0$ V; and
- $V_C = 0$ V.

Notice that we no longer need to make reference to another point in these descriptions.

We can replace the positive terminal of the battery with a reference voltage of 6.0 V using the symbol ⊤ and redraw the circuit as shown in Figure 2.21.

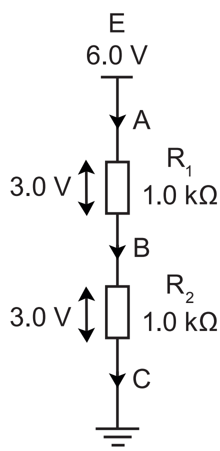


Figure 2.21 A series circuit with ground and positive reference voltages

Although Figure 2.20 and Figure 2.21 look different, they are electrically the same. In other words, the electrical circuit connected will be the same no matter which diagram is used. In Figure 2.21, the current flows from the positive reference voltage (E) through R_1 and R_2 to the ground.

The voltages at points A, B and C of the circuit in Figure 2.21 are also described respectively as:

- $V_A = 6.0$ V;
- $V_B = 3.0$ V; and
- $V_C = 0$ V.

Using reference voltages helps in simplifying circuit diagrams (see Figure 7.47, Figure 8.31, Figure 9.28 and Figure 14.12).

Review Question 2.4

1. Calculate the effective e.m.f. of each of the following arrangements:

(a)

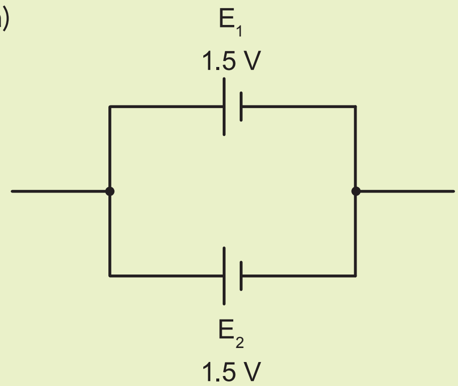


Figure 2.22

(b)

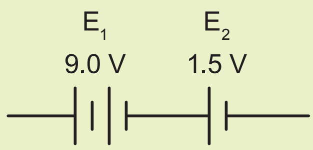


Figure 2.23

2.5 How does resistance affect current?

Learning Outcomes

- State that Resistance $= \dfrac{\text{P.d.}}{\text{Current}}$.
- State and apply Ohm's law to determine current, voltage and resistance.
- Sketch and interpret the graphical linear relationship between current and voltage in a purely resistive circuit.

Key Ideas

- Resistance is a measure of how difficult it is for a current to flow through a component.
- Resistance can be calculated using the equation $R = \dfrac{V}{I}$.
- If the current-voltage (I-V) graph of a conductor is a straight line passing through the origin, then this conductor is said to obey Ohm's law and is called an ohmic conductor.

Resistance

Resistance is a measure of how difficult it is for a current to flow through a component.

Look at the two water pipes in Figure 2.24a and Figure 2.24b. The water pipe in Figure 2.24a has one narrowed section while the pipe in Figure 2.24b has two narrowed sections. The water current in Figure 2.24b is slower due to the higher resistance caused by the additional narrowed section.

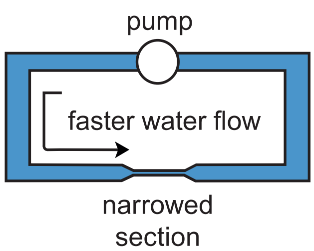


Figure 2.24a Water flows faster in the pipe with only one narrowed section

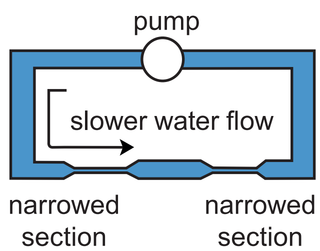


Figure 2.24b Water flows more slowly in the pipe with two narrowed sections

Figure 2.25 shows two circuits – one with a single light bulb and the other with two light bulbs. Like in the water pipe analogy in Figure 2.24b, the current in Figure 2.25b is smaller due to the higher electrical resistance caused by the additional bulb.

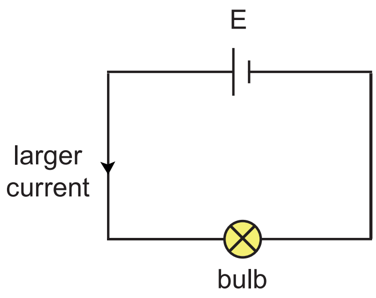


Figure 2.25a The current is larger in the circuit with only one light bulb

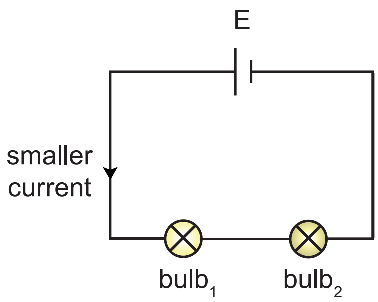


Figure 2.25b The current is smaller in the circuit with two light bulbs

The resistance of a component is defined as the ratio of the p.d. across the component to the current flowing through the component, which can be expressed by the equation:

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

where R = resistance of the component (in Ω),
V = p.d. across the component (in V),
I = current through the component (in A).

The equation can be rearranged into two other forms:

$$V = IR$$

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

The SI unit of resistance is the **ohm (Ω)**.

Worked Example 2.5

A light bulb with a resistance of 100 Ω is connected to a battery with an e.m.f. of 9.0 V. Calculate the current through the light bulb.

Solution

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

$$= \frac{9.0\ \text{V}}{100\ \Omega}$$

$$= 0.090\ \text{A}$$

$$= 90\ \text{mA}$$

Worked Example 2.6

Calculate the resistance of the light bulb in Figure 2.26.

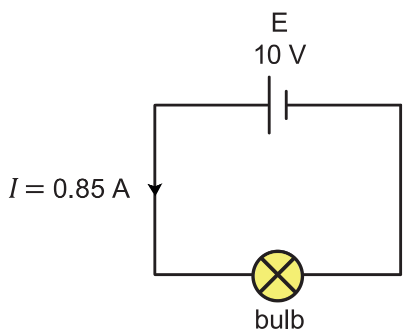


Figure 2.26

Solution

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

$$= \frac{10\ \text{V}}{0.85\ \Omega}$$

$$= 12\ \Omega$$

Resistors

Resistors are components that provide resistance to control the current flowing in a circuit.

There are two types of resistors: **fixed resistors** and **variable resistors**. Fixed resistors have fixed resistances, while the resistance of variable resistors can be adjusted. Their respective symbols are shown in Figure 2.27. We will discuss resistors in greater detail in Chapter 3.

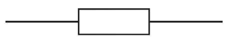


Figure 2.27a Fixed resistor

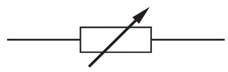


Figure 2.27b Variable resistor

Ohm's law

Ohm's law states that the current flowing through a metallic conductor is directly proportional to the p.d. across the conductor, provided that the physical conditions (e.g., temperature) remain constant.

This can be expressed in symbols as:

$$V \propto I$$

If we plot a graph of the current (I) through this conductor against the p.d. (V) across it, we get the I-V graph shown in Figure 2.28. Notice that the graph is a straight line through the origin. Such a conductor is said to obey Ohm's law and is called an **ohmic conductor**.

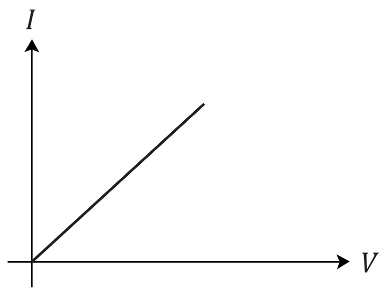


Figure 2.28 I-V graph of an ohmic conductor

Electrical components that do not obey Ohm's law are called **non-ohmic conductors**. Two examples of non-ohmic conductors are filament bulbs and semiconductor diodes. Their I-V graphs are shown in Figure 2.29a and Figure 2.29b respectively.

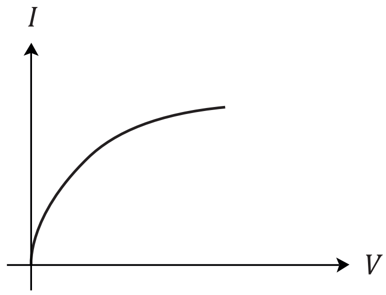


Figure 2.29a I-V graph of a filament bulb

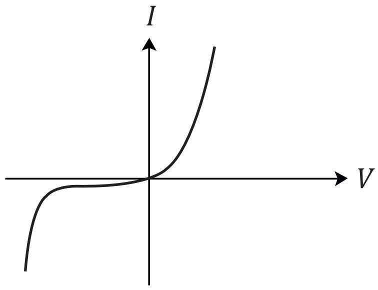


Figure 2.29b I-V graph of a semiconductor diode

Review Questions 2.5

1. Figures 2.30 and 2.31 show the I-V graphs of two conductors. State and explain whether each of the conductors obeys Ohm's law.

(a)

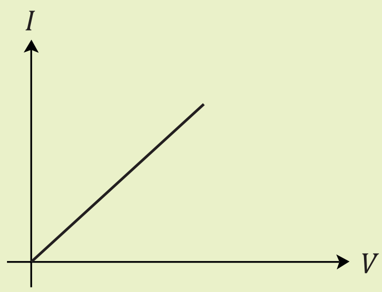


Figure 2.30

(b)

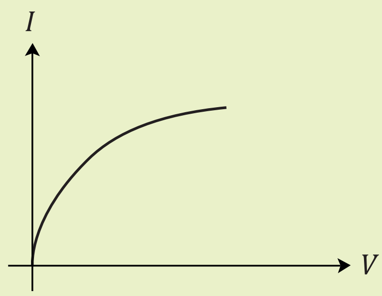


Figure 2.31

2. A 15 Ω resistor is connected as shown in Figure 2.32.

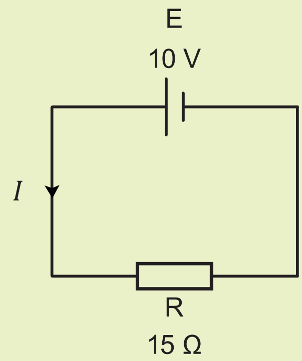


Figure 2.32

(a) Calculate the current through the circuit.

(b) The 15 Ω resistor is now replaced by a 30 Ω resistor. State and explain what happens to the current flowing through the circuit now.

3. Calculate the e.m.f. of the batteries required to provide the currents in the circuits in Figures 2.33 and 2.34.

(a)

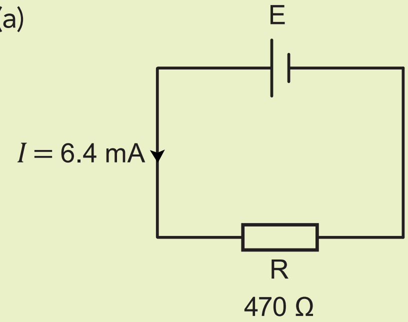


Figure 2.33

(b)

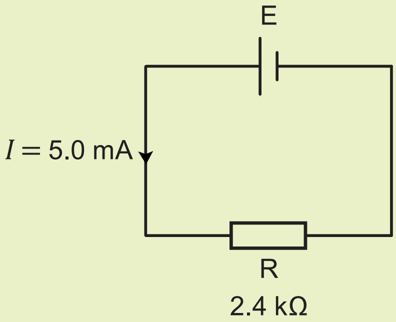


Figure 2.34

2.6 Why is it useful to know the energy and power used by electrical components?

Learning Outcomes

- Describe the use of the heating effect of an electric current flowing through a conductor.
- Define power as the rate of energy conversion.
- Recall the power equations $P = VI$, $P = I^2R$ and $P = \frac{V^2}{R}$ and apply the relationships $P = VI$ and $E = VIt$ to solve problems involving resistive circuits.
- Determine the efficiency of an electrical device.

Key Ideas

- Power is the rate at which energy is converted.
- Power can be calculated using the equations $P = VI$, $P = I^2R$ and $P = \frac{V^2}{R}$.
- Efficiency tells us the percentage of input energy converted to useful energy.

Heating effect of current

Heat is produced when a current passes through a conductor. This is called the **heating effect of current**, and it is caused by the conversion of electrical energy to heat. The effect is put to good use in heating appliances such as the electric kettle shown in Figure 2.35, which uses the converted heat to boil water.

Figure 2.35 Heating appliances such as the electric kettle make use of the heating effect of current

In electronics, however, this heating effect is usually undesirable. Not only does it waste energy, it can also cause electronic components to overheat and become damaged. Figure 2.36 shows a resistor that has been damaged by overheating.

Figure 2.36 Resistor damaged by overheating

Power

Power can be defined as the rate of energy conversion, and is expressed by the equation:

$$P = \frac{E}{t}$$

where P = power (in W),
E = amount of energy converted (in J),
t = time taken (in s).

The SI unit of power is the **watt (W)**. 1 W is equal to 1 J of energy converted in 1 s.

Worked Example 2.7

A small electric motor uses 300 J of energy over 10 s. Calculate the power of the motor.

Solution

$$P = \frac{E}{t}$$
$$= \frac{300\text{ J}}{10\text{ s}}$$
$$= 30\text{ W}$$

Worked Example 2.8

The power used by an electronic component is 2.0 W. Calculate the amount of energy used in one minute.

Solution

$$P = \frac{E}{t}$$

$$2.0\text{ W} = \frac{E}{60\text{ s}}$$

$$E = 120\text{ J}$$

The equation can be expressed in two other forms by substituting $I = \frac{V}{R}$ and $V = IR$:

$$P = VI$$

substitute $I = \frac{V}{R}$ → $P = V\left(\frac{V}{R}\right)$ → rearrange → $P = \frac{V^2}{R}$

substitute $V = IR$ → $P = (IR)I$ → rearrange → $P = I^2R$

where P = power (in W),
I = current (in A),
V = p.d. (in V),
R = resistance (in Ω).

Worked Example 2.9

Using the circuit in Figure 2.37, calculate:

(a) the power supplied to the light bulb; and

(b) the energy used by the bulb in 30 s.

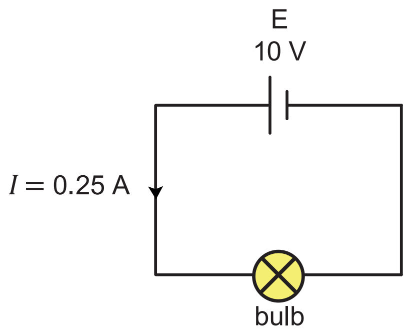


Figure 2.37

Solution

(a) $P = VI$

$= 10\ \text{V} \times 0.25\ \text{A}$

$= 2.5\ \text{W}$

(b) $P = \dfrac{E}{t}$

$2.5\ \text{W} = \dfrac{E}{30\ \text{s}}$

$E = 2.5\ \text{W} \times 30\ \text{s}$

$= 75\ \text{J}$

Worked Example 2.10

A small electric motor draws 0.40 A from a battery. The resistance of the motor is 50 Ω. Calculate the power of the motor.

Solution

$P = I^2R$

$= (0.40)^2 \times 50\ \Omega$

$= 8.0\ \text{W}$

Power rating

An important use of the power equations is to determine whether the power rating of a component or device has been exceeded.

The **power rating** is the maximum power at which a component or device can be used without being damaged. Hence, a component with a power rating of 0.25 W should not be used at a power higher than 0.25 W.

The power rating of a component should not be confused with the actual power used by the component. The power rating can be compared to the speed limit of a road, while the actual power can be compared to the actual speed of a car. If the speed limit of a road is 50 km/h, then the actual speed of a car on that road should not exceed 50 km/h.

Worked Example 2.11

A 100 Ω resistor with a power rating of 0.25 W is connected to a battery with an e.m.f. of 6.0 V. Determine whether the power rating of the resistor has been exceeded.

Solution

$$P = \frac{V^2}{R}$$

$$= \frac{(6.0\text{ V})^2}{100\ \Omega}$$

$$= 0.36\text{ W}$$

The actual power (0.36 W) has exceeded the power rating of the resistor (0.25 W). Overheating is likely to occur, which will damage the resistor. It is recommended to use a resistor with a higher power rating, e.g., a resistor rated 1.0 W.

Calculating energy

We can substitute the equation $P = \dfrac{E}{t}$ into $P = VI$ to obtain an equation relating energy, voltage, current and time.

$$\boxed{P = VI}$$

$$\Big\downarrow \text{ substitute } P = \frac{E}{t}$$

$$\boxed{\frac{E}{t} = VI}$$

$$\Big\downarrow \text{ rearrange}$$

$$\boxed{E = VIt}$$

where E = electrical energy (in J),
I = current (in A),
V = p.d. (in V),
t = time taken (in s).

Worked Example 2.12

A light bulb connected to a 230 V power supply is used for one hour. The current flowing through the bulb is 0.20 A. Calculate the total energy used by the bulb.

Solution

$$\begin{aligned} E &= VIt \\ &= 230\text{ V} \times 0.20\text{ A} \times (1 \times 60\text{ s} \times 60\text{ s}) \\ &= 170\,000\text{ J} \\ &= 170\text{ kJ} \end{aligned}$$

Energy efficiency

In Singapore, it is compulsory for air-conditioners and refrigerators to have an energy label, an example of which is shown in Figure 2.38. This label contains information about the appliance, such as the energy efficiency rating, estimated annual energy cost and estimated annual energy consumption. The number of ticks shown on the label indicates the efficiency rating of the appliance – the greater the number of ticks, the greater its energy efficiency.

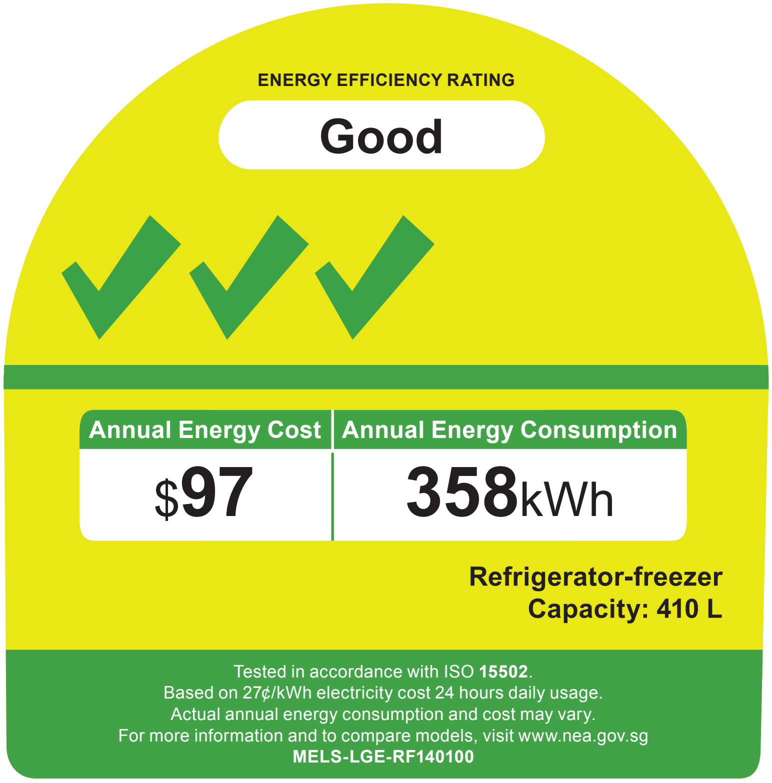


Figure 2.38 Energy label of an appliance

What is **energy efficiency** and why should we be concerned about it? As illustrated by Figure 2.39, when we use an electrical system, the input energy is converted to both useful and wasted energy. We want as much as possible of the input energy to be converted to useful energy. For example, when lighting a room, we want to maximise the conversion of electrical energy (input energy) to light energy (useful energy), with as little heat (wasted energy) as possible.

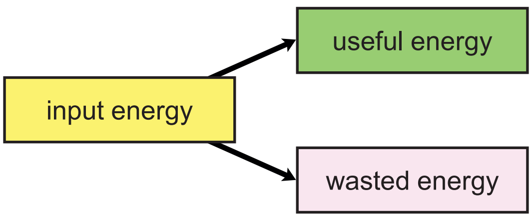


Figure 2.39 Input energy is converted to useful and wasted energy

The efficiency of a system is commonly expressed as a percentage: 100% means that all input energy is converted to useful energy while 0% means that all input energy is converted to wasted energy.

To calculate efficiency, we can use the following equations:

$$\text{Efficiency} = \frac{\text{Useful output energy}}{\text{Input energy}} \times 100\%$$

or

$$\text{Efficiency} = \frac{\text{Useful output power}}{\text{Input power}} \times 100\%$$

Worked Example 2.13

The efficiency of a lighting system is 60%. For 80 kJ of input energy, calculate:

(a) the amount of useful output energy; and

(b) the amount of wasted energy.

Solution

(a) $$\text{Efficiency} = \frac{\text{Useful output energy}}{\text{Input energy}} \times 100\%$$

$$60\% = \frac{\text{Useful output energy}}{80 \times 10^3 \text{ J}} \times 100\%$$

$$\begin{aligned}\text{Useful output energy} &= 48\,000 \text{ J} \\ &= 48 \text{ kJ}\end{aligned}$$

(b) $$\begin{aligned}\text{Amount of wasted energy} &= \text{Input energy} - \text{Useful output energy} \\ &= 80 \text{ kJ} - 48 \text{ kJ} \\ &= 32 \text{ kJ}\end{aligned}$$

Review Questions 2.6

1. Calculate the power supplied to each of the following appliances:

Device	Current	Voltage
Hair dryer	4.0 A	230 V
Computer	0.80 A	230 V
Microwave oven	3.0 A	230 V

2. A current of 0.15 A passes through a light bulb with a resistance of 40 Ω. Calculate:
   (a) the p.d. across the light bulb;
   (b) the power supplied to the light bulb; and
   (c) the electrical energy supplied to the light bulb in 50 s.

3. A small electric motor produces 65 MJ of useful energy. The amount of wasted energy is 5.0 MJ.
   (a) Determine the input energy to the motor.
   (b) Using the result from (a), calculate the efficiency of the motor.

3 RESISTORS

How do we select and use a suitable resistor?

We learnt in Chapter 2 that resistance opposes the flow of current. By adding a resistor with a suitable resistance to a circuit, we can control the current in the circuit to achieve a desired effect. For example, when we turn the volume knob of a music player, we adjust the resistance of a variable resistor inside the music player, which in turn changes the volume of the sound produced.

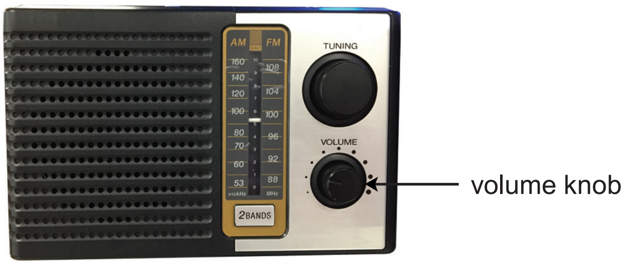


Figure 3.1 A variable resistor is used to adjust the volume of a loudspeaker

In this chapter, we will learn about different types of resistors and how they function in circuits.

3.1 What affects the resistance of a conductor?

Learning Outcome

- Describe resistivity as the characteristic of a material that affects its electrical conductivity and apply the formula $R = \frac{\rho l}{A}$ to perform calculations.

Key Idea

- The resistance of a conductor is affected by its length, cross-sectional area, temperature and the resistivity of the material it is made of.

The resistance of a conductor depends on four factors:

- length
- cross-sectional area
- resistivity of the material it is made of
- temperature

Length

The resistance, R, of a conductor is directly proportional to its length, l.

$$R \propto l$$

A longer conductor has a higher resistance than a shorter one as shown in Figure 3.2, assuming that both have the same cross-sectional area and are made of the same material.

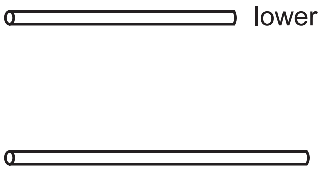


Figure 3.2 A longer conductor has a higher resistance than a shorter one

Cross-sectional area

The resistance of a conductor is inversely proportional to its cross-sectional area, A.

$$R \propto \frac{1}{A}$$

A conductor with a smaller cross-sectional area has a higher resistance than one with a bigger cross-sectional area as shown in Figure 3.3, assuming that both have the same length and are made of the same material.

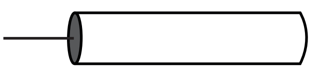


Figure 3.3 A conductor with a smaller cross-sectional area has a higher resistance than one with a bigger cross-sectional area

Table 3.1 shows the American wire gauge (AWG) table, which contains information on the diameter and cross-sectional area of standard wires. The greater the AWG number, the smaller the diameter of the wire. The AWG table is useful in helping us select a suitable wire size to use in an electronic circuit. In this course, we will mainly be using AWG 22 wires to build circuits on breadboards.

Table 3.1 AWG table of some wire gauge numbers

AWG Table		
AWG number	**Diameter / m**	**Cross-sectional area / m²**
1	7.4×10^{-3}	4.3×10^{-5}
2	6.5×10^{-3}	3.3×10^{-5}
3	5.8×10^{-3}	2.6×10^{-5}
4	5.2×10^{-3}	2.1×10^{-5}
5	4.6×10^{-3}	1.7×10^{-5}
6	4.1×10^{-3}	1.3×10^{-5}
7	3.7×10^{-3}	1.1×10^{-5}
8	3.3×10^{-3}	8.6×10^{-6}
9	2.9×10^{-3}	6.6×10^{-6}
10	2.6×10^{-3}	5.3×10^{-6}
11	2.3×10^{-3}	4.2×10^{-6}
12	2.1×10^{-3}	3.5×10^{-6}
13	1.8×10^{-3}	2.5×10^{-6}
14	1.6×10^{-3}	2.0×10^{-6}
15	1.5×10^{-3}	1.8×10^{-6}
16	1.3×10^{-3}	1.3×10^{-6}
17	1.2×10^{-3}	1.1×10^{-6}
18	1.0×10^{-3}	7.9×10^{-7}
19	9.1×10^{-4}	6.5×10^{-7}
20	8.1×10^{-4}	5.2×10^{-7}
21	7.2×10^{-4}	4.1×10^{-7}
22	6.4×10^{-4}	3.2×10^{-7}
23	5.7×10^{-4}	2.6×10^{-7}

Resistivity

Resistivity, ρ, is the property of a material that affects how well it conducts electricity. Table 3.2 shows the resistivity of some common conducting materials.

Table 3.2 Resistivity of some common conducting materials

Material	Resistivity / Ωm
silver	1.6×10^{-8}
copper	1.7×10^{-8}
aluminium	2.8×10^{-8}
tungsten	5.6×10^{-8}
iron	9.7×10^{-8}
nichrome	1.1×10^{-6}
carbon	3.6×10^{-5}

Resistance is directly proportional to resistivity.

$$R \propto \rho$$

A conductor made of a material with higher resistivity has a higher resistance than a similar one made of a material with lower resistivity. For example, nichrome has a higher resistivity than copper. Thus, a nichrome wire has a higher resistance than a copper wire of the same dimensions. In the next section, we will see how nichrome and carbon are used to make various types of resistors.

Resistivity should not be confused with *resistance*. Resistivity is the property of a material while resistance is the property of a particular conductor. Thus, we say 'the resistivity of copper' but 'the resistance of a copper wire'.

We can represent the combined effects of length, cross-sectional area and resistivity on the resistance of a conductor using the equation shown below:

$$R = \frac{\rho l}{A}$$

where R = resistance (in Ω),
l = length of a wire (in m),
A = cross-sectional area of a wire (in m^2),
ρ = resistivity (in Ωm).

Worked Example 3.1

Using the data in Table 3.2, calculate the resistance of a copper wire with a length of 0.30 m and a cross-sectional area of 5.2×10^{-7} m^2.

Solution

$$R = \frac{\rho l}{A}$$

$$= \frac{(1.7 \times 10^{-8})\ \Omega\text{m} \times 0.30\ \text{m}}{5.2 \times 10^{-7}\ \text{m}^2}$$

$$= 0.0098\ \Omega$$

$$= 9.8\ \text{m}\Omega$$

Worked Example 3.2

Table 3.3 shows the length, cross-sectional area and material of four wires.

Table 3.3 Properties of wires A, B, C and D

Wire	Length	Cross-sectional area	Material
A	2.0 m	4.1×10^{-7}m^2	nichrome
B	1.0 m	4.1×10^{-7}m^2	nichrome
C	1.0 m	3.3×10^{-7}m^2	nichrome
D	1.0 m	3.3×10^{-7}m^2	copper

Compare the resistances of the following wires. You can refer to Table 3.2 for the resistivity of the materials.

(a) Wires A and B

(b) Wires B and C

(c) Wires C and D

Solution

(a) The resistance of wire A is higher than that of wire B. Both wires have the same cross-sectional area and are made of the same material but wire A is longer than wire B.

(b) The resistance of wire B is lower than that of wire C. Both wires have the same length and are made of the same material but the cross-sectional area of wire B is bigger than that of wire C.

(c) The resistance of wire C is higher than that of wire D. Both wires have the same length and cross-sectional area but the resistivity of nichrome is higher than that of copper.

Review Questions 3.1

1. A wire with a length of 5.0 m has a resistance of 0.26 Ω. It is made of a material with a resistivity of 1.7×10^{-8} Ωm. Calculate the cross-sectional area of the wire.

2. The copper wire in a laboratory has run out. A student uses nichrome wire as a replacement. Explain whether this is a good practice.

3. Figure 3.4 shows a circuit built using unnecessarily long wires. Explain why this is not a good practice.

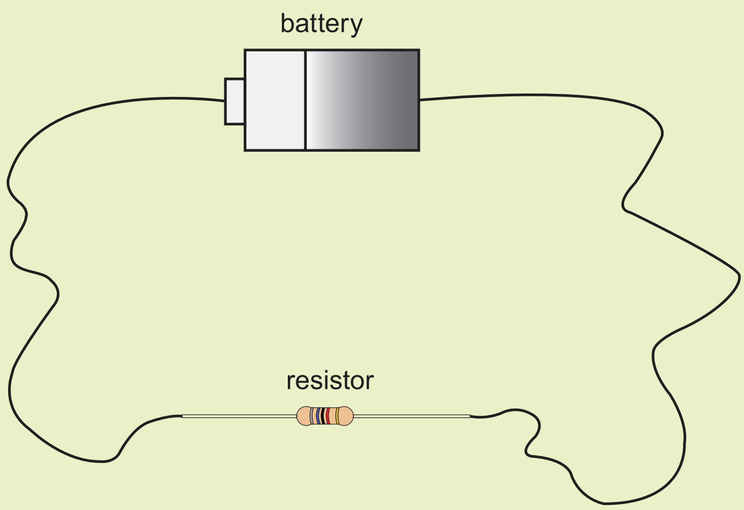


Figure 3.4

3.2 What are the common types of resistors?

Learning Outcome

- Describe the structures of various types of resistors (carbon and wire-wound) and select the appropriate resistor for a particular circuit design.

Key Ideas

- Different types of resistors are suited for different applications.
- Carbon and wire-wound resistors are two common types of fixed resistors.

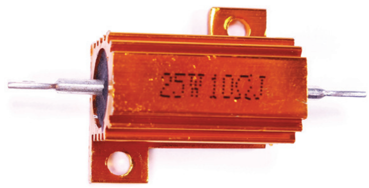
Resistors can be broadly classified into two categories: fixed resistors and variable resistors.

Fixed resistors

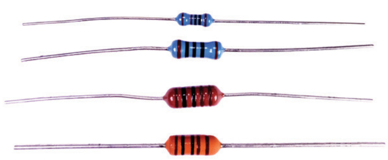
Figure 3.5 shows some common types of **fixed resistors**.

carbon film resistors
(carbon resistor in short)

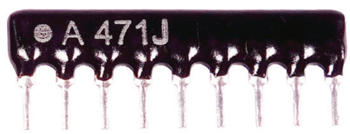
wire-wound resistor
(without cooling fin)



wire-wound resistor
(with cooling fin)



metal film resistors



resistor network

Figure 3.5 Common types of fixed resistors

Carbon resistors

Figure 3.6 shows the structure of a **carbon resistor**, which is commonly used in electronic circuits involving small currents. It consists of a ceramic rod coated with a thin layer of carbon film. The carbon film is cut to produce a spiral conducting path of a certain resistance.

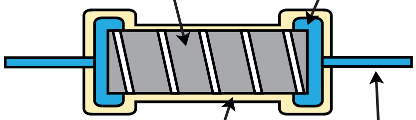


Figure 3.6 Carbon resistor

Wire-wound resistors

Figure 3.7 shows the structure of a **wire-wound resistor**, which is made by winding a thin metal (e.g., nichrome) wire around a cylinder made of an insulating material. As the power ratings of wire-wound resistors can be as high as a few hundred watts, they can produce a lot of heat. Hence, some of them come with cooling fins to help dissipate heat at a faster rate.

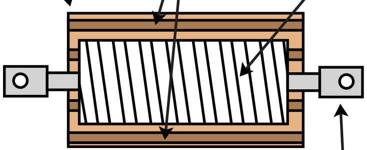


Figure 3.7 Structure of a wire-wound resistor

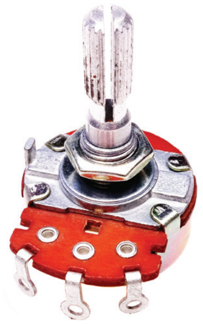
The differences between carbon and wire-wound resistors are shown in Table 3.4.

Table 3.4 Differences between carbon and wire-wound resistors

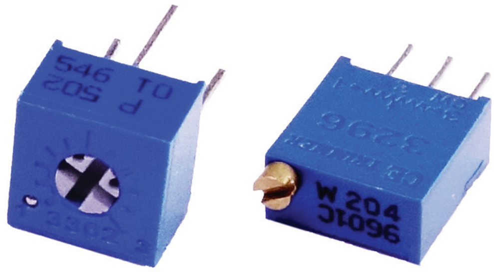
Carbon resistor	Wire-wound resistor
used in low-power applications	used in high-power applications
low temperature stability	high temperature stability
typical power rating range: 0.1–2 W	typical power rating range: 2–500 W
low cost	high cost

Variable resistors

Figure 3.8 shows some common types of **variable resistors**.

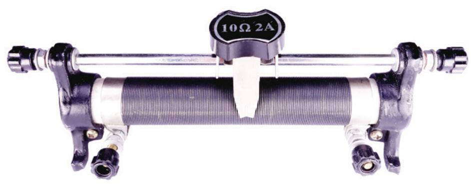


(a) rotary potentiometer

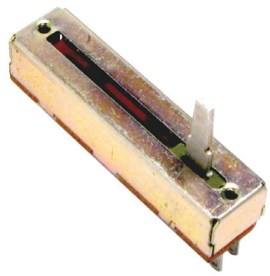


(b) trimmer potentiometer

(c) preset



(d) rheostat



(e) slider potentiometer

Figure 3.8 Common types of variable resistors

Notice that most of the variable resistors shown in Figure 3.8 are also potentiometers. This is because they have three terminals and can be used as potentiometers. We will learn how to connect them as variable resistors in Section 3.6 and as potentiometers in Section 4.5.

Different types of variable resistors are suitable for different applications. For example, the rotary potentiometer shown in Figure 3.8a is suitable for applications that need frequent adjustments, while the trimmer potentiometer (Figure 3.8b) and preset (Figure 3.8c) are usually used in applications where adjustments are less frequent. The rheostat (Figure 3.8d) is usually much bigger in size compared to the other variable resistors and can handle a much higher current, making it suitable for high-power applications.

Review Questions 3.2

1. A certain application requires a resistor that can carry up to 3 A of current without overheating. Explain why a wire-wound resistor is more suitable than a carbon resistor for this application.

2. Name three common types of variable resistors.

3.3 How do we determine the value of a resistor?

Learning Outcomes

- Use the resistor colour code to determine the ohmic value and tolerance of a resistor, and verify the value by measurement.
- Select a suitable resistor from the E24 resistor series for a particular application.

Key Ideas

- The coloured bands printed on a carbon resistor indicate its resistance and percentage tolerance.
- Carbon resistors come in a range of standard values.
- A multimeter can be used to measure the resistance of a resistor.

The resistance of a wire-wound resistor is usually printed on its casing. For example, the one shown in Figure 3.9 is a 10 Ω resistor.

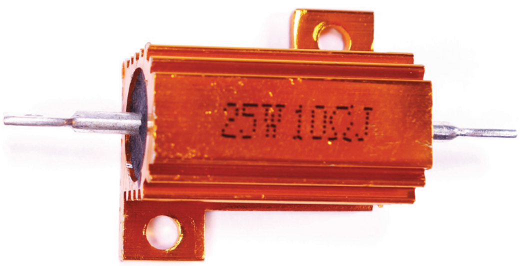


Figure 3.9 The resistance of a wire-wound resistor is usually printed on its casing

However, this is not the case for carbon resistors. Due to their small size, there is insufficient space to display their numerical resistances. Instead, these values are indicated by the coloured bands printed on their coating.

Resistor colour code

The resistance of a carbon resistor is indicated by a series of four coloured bands, as shown in Figure 3.10.

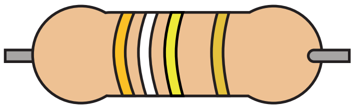
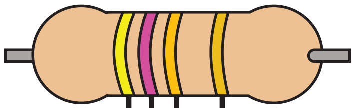


Figure 3.10 A carbon resistor with four coloured bands

Figure 3.11 shows what each band represents and the value represented by each colour.



1st digit	2nd digit	Multiplier	Percentage tolerance
0 black	0 black	1 black	± 1% brown
1 brown	1 brown	10 brown	± 2% red
2 red	2 red	100 red	± 5% gold
3 orange	3 orange	1k orange	± 10% silver
4 yellow	4 yellow	10k yellow	
5 green	5 green	100k green	
6 blue	6 blue	1M blue	
7 purple	7 purple	10M purple	
8 grey	8 grey	0.01 silver	
9 white	9 white	0.1 gold	

Figure 3.11 Resistor colour codes

For a four-band resistor, starting from the left:

- The first and second bands represent the first and second digits of the resistance value, respectively.
- The third band represents the power-of-10 multiplier. Multiply it with the number formed by the first and second digits to obtain the resistance.
- The last band represents the percentage tolerance.

The **percentage tolerance** tells us the percentage value by which the actual resistance may be higher or lower than the indicated resistance. For example, a 100 Ω resistor with 5% tolerance would have an actual resistance falling somewhere between 95 Ω and 105 Ω as shown in Figure 3.12.

$$95\ \Omega \xleftarrow{-5\%} 100\ \Omega \xrightarrow{+5\%} 105\ \Omega$$

Figure 3.12 Range of resistances for a 100 Ω resistor with 5% tolerance

Worked Example 3.3

A carbon resistor has four coloured bands as shown in Figure 3.13.
Using the resistor colour code in Figure 3.11, determine its resistance.

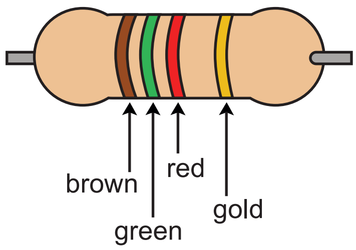


Figure 3.13

Solution

First band: 1
Second band: 5
Third band: 100
Fourth band: ± 5%

Resistance = 15 × 100 Ω ± 5% = 1.5 kΩ ± 5%

Worked Example 3.4

A carbon resistor has four coloured bands as shown in Figure 3.14. Using the resistor colour code in Figure 3.11, determine its range of resistances.

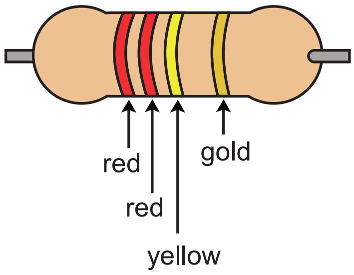


Figure 3.14

Solution

First band: 2
Second band: 2
Third band: 10 000
Fourth band: ± 5%

Resistance = 22 × 10 000 Ω ± 5% = 220 kΩ ± 5%
Range of resistances = (95% × 220) kΩ to (105% × 220) kΩ
= 209 kΩ to 231 kΩ

E24 series

The Electronics Industries Association (EIA) specifies different series of standard values for resistors based on their percentage tolerance. Table 3.5 shows the resistances for the E6, E12 and E24 series. For this course, we will mainly be using carbon resistors from the E24 series, which has a percentage tolerance of 5%.

The values in Table 3.5 form the base resistances of each series. We can multiply these base resistances by powers of 10. The actual resistances in all three series normally range between 1.0 Ω and 10 MΩ. For example, the value '2.2' indicates that 2.2 Ω, 22 Ω, 220 Ω, 2.2 kΩ, 22 kΩ, 220 kΩ and 2.2 MΩ are standard resistances. Resistors with these values are manufactured and sold as standard components.

Although E24 series resistors are easily available, it is common to find circuits that are designed using only values that are common across the E6, E12 and E24 series. For example, 470 Ω resistors (common to all three series) are widely found in circuits but 510 Ω resistors (only available in E24 series) are rarely used. Doing so allows us to build these circuits even if only resistors from the E6 series are available. Another benefit of this practice is to avoid having to stock a wide range of resistors with different resistances.

Table 3.5 Base resistances for the E6, E12 and E24 series

<table>
<tr><th>E6 series
(20% tolerance)</th><th>E12 series
(10% tolerance)</th><th>E24 series
(5% tolerance)</th></tr>
<tr><td rowspan="4">1.0</td><td rowspan="2">1.0</td><td>1.0</td></tr>
<tr><td>1.1</td></tr>
<tr><td rowspan="2">1.2</td><td>1.2</td></tr>
<tr><td>1.3</td></tr>
<tr><td rowspan="4">1.5</td><td rowspan="2">1.5</td><td>1.5</td></tr>
<tr><td>1.6</td></tr>
<tr><td rowspan="2">1.8</td><td>1.8</td></tr>
<tr><td>2.0</td></tr>
<tr><td rowspan="4">2.2</td><td rowspan="2">2.2</td><td>2.2</td></tr>
<tr><td>2.4</td></tr>
<tr><td rowspan="2">2.7</td><td>2.7</td></tr>
<tr><td>3.0</td></tr>
<tr><td rowspan="4">3.3</td><td rowspan="2">3.3</td><td>3.3</td></tr>
<tr><td>3.6</td></tr>
<tr><td rowspan="2">3.9</td><td>3.9</td></tr>
<tr><td>4.3</td></tr>
<tr><td rowspan="4">4.7</td><td rowspan="2">4.7</td><td>4.7</td></tr>
<tr><td>5.1</td></tr>
<tr><td rowspan="2">5.6</td><td>5.6</td></tr>
<tr><td>6.2</td></tr>
<tr><td rowspan="4">6.8</td><td rowspan="2">6.8</td><td>6.8</td></tr>
<tr><td>7.5</td></tr>
<tr><td rowspan="2">8.2</td><td>8.2</td></tr>
<tr><td>9.1</td></tr>
</table>

Choosing a suitable resistor from the E24 series

To choose a suitable resistor, we need to first calculate the resistance required by the circuit. We then choose a resistance from the series that is closest to this calculated value.

Take note that in applications where the resistor is used to limit the current, it is important to choose a resistance that is higher than the calculated value. This ensures that the actual current stays within the current limit.

Worked Example 3.5

A 25 Ω bulb has a current rating of 30 mA (i.e., if the current through the bulb exceeds 30 mA, the bulb will blow). If the bulb is to be used with a 9.0 V battery, choose a suitable resistor from the E24 series that can be connected in series with the bulb to prevent the bulb from blowing.

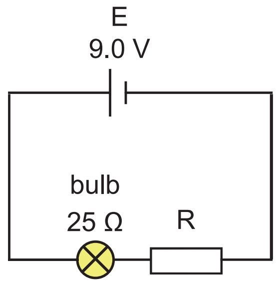


Figure 3.15

Solution

$$R = \frac{V}{I} = \frac{9.0\ \text{V}}{30 \times 10^{-3}\ \text{A}} = 300\ \Omega$$

Additional resistance needed = 300 Ω – 25 Ω = 275 Ω

From Table 3.5, the next standard value below 275 Ω is 270 Ω while the next standard value above 275 Ω is 300 Ω. We should choose a 300 Ω resistor. If we use a 270 Ω resistor, the current through the bulb will exceed 30 mA.

Standard values of variable resistors

In this course, we will mainly use trimmer potentiometers (Figure 3.8b) for low-power applications (up to 0.5 W) and rotary potentiometers (Figure 3.8a) for applications that require more power. Both types are available in standard values (measured in ohms) which are shown below:

100, 200, 500, 1 k, 2 k, 5 k, 10 k, 20 k, 25 k, 50 k, 100 k, 200 k, 250 k, 500 k, 1 M

Measuring resistance with a digital multimeter

The resistance of a resistor can be measured with a digital multimeter (DMM) via the following steps:

Figure 3.16

Step 1: Turn the knob of the DMM to the 'Ω' setting as shown in Figure 3.16.

Figure 3.17

Step 2: Place the probes of the DMM on the two ends of the resistor as shown in Figure 3.17. The resistance of the resistor will be displayed on the DMM. The resistor should not be connected to a circuit during the measurement.

Review Questions 3.3

1. State the colour of the bands for the following resistors:

Resistance	First band	Second band	Third band	Fourth band
(a) 330 Ω ± 5%				
(b) 1.0 kΩ ± 5%				

2. Using the resistor colour code in Figure 3.11, determine the resistances of the resistors in Figures 3.18 and 3.19.

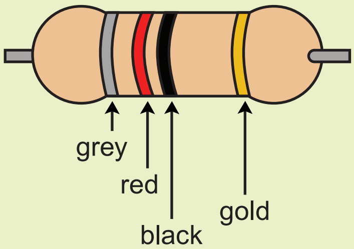


Figure 3.18

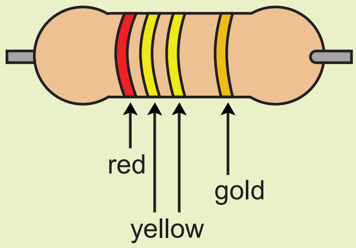


Figure 3.19

3. The calculated resistance needed for an electronic circuit is 450 Ω. Choose a suitable resistor from the E24 series if this resistor is used to limit the current.

3.4 How do we determine the effective resistance of resistors connected in series or in parallel?

Learning Outcome

- Recall and apply the formulae to calculate the effective resistance of resistors connected in series and in parallel.

Key Ideas

- For resistors in series, effective resistance is equal to the sum of the resistance of each resistor.
- For resistors in parallel, the reciprocal of the effective resistance is equal to the sum of the reciprocal of the resistance of each resistor.

Many circuits consist of several components connected together. Each component has its own resistance. The effective resistance of a circuit depends on the resistance of individual components and how the components are arranged in the circuit.

Effective resistance of resistors connected in series

A **series circuit** is a circuit where the current can only follow a single pathway. Figure 3.20 shows three resistors connected in series.

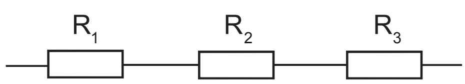


Figure 3.20 Resistors connected in series

The effective resistance of resistors connected in series is equal to the sum of the resistance of each resistor:

$$R_{eff} = R_1 + R_2 + R_3 + \dots$$

where R_{eff} = effective resistance (in Ω).

Worked Example 3.6

Using the circuit in Figure 3.21, calculate
(a) the effective resistance, and
(b) the current through the circuit.

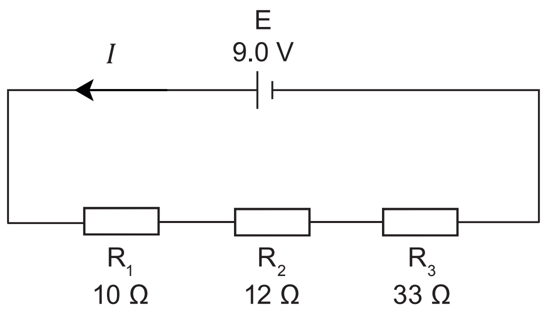


Figure 3.21

Solution

(a) Since the resistors are connected in series, $R_{\text{eff}} = R_1 + R_2 + R_3$

$$= 10\ \Omega + 12\ \Omega + 33\ \Omega$$
$$= 55\ \Omega$$

(b) $$I = \frac{V}{R}$$
$$= \frac{9.0\ \text{V}}{55\ \Omega}$$
$$= 0.16\ \text{A}$$

Effective resistance of resistors connected in parallel

A **parallel circuit** is a circuit where the current can flow through multiple pathways. Figure 3.22 shows three resistors connected in parallel to form three branches for current to flow.

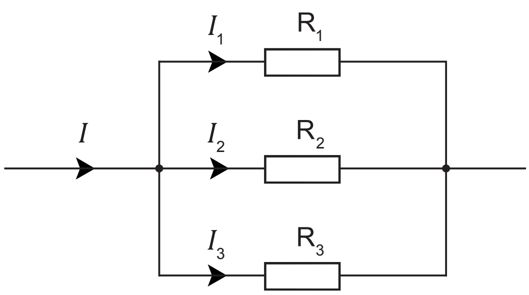


Figure 3.22 A parallel circuit

To calculate the effective resistance of resistors in parallel, we use the following equation where the reciprocal of the effective resistance is equal to the sum of the reciprocal of the resistance of each resistor.

$$\frac{1}{R_{\text{eff}}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots$$

where R_{eff} = effective resistance (in Ω)

Worked Example 3.7

Calculate the effective resistance of the circuit in Figure 3.23.

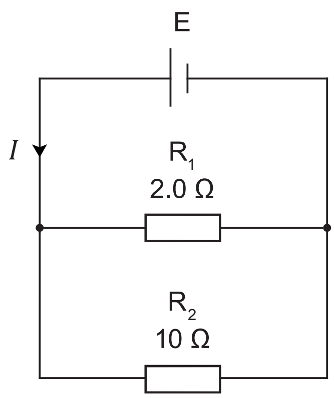


Figure 3.23

Solution

Since the resistors are connected in parallel,

$$\frac{1}{R_{\text{eff}}} = \frac{1}{R_1} + \frac{1}{R_2}$$

$$= \frac{1}{2.0\ \Omega} + \frac{1}{10\ \Omega}$$

$$= \frac{3}{5\ \Omega}$$

$$R_{\text{eff}} = 1.7\ \Omega$$

Determining the effective resistance of resistors connected in series-parallel arrangements

In some circuits, components are connected in both series and parallel arrangements. Figure 3.24 shows two examples of such arrangements.

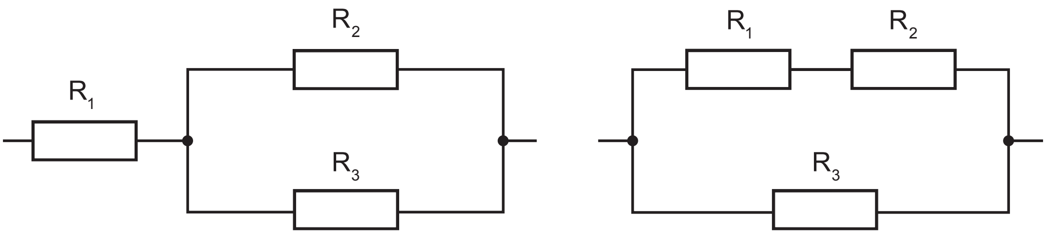


Figure 3.24 Resistors connected in series-parallel arrangements

Figure 3.25 shows how we can determine the effective resistance of the resistors connected in the two different series-parallel arrangements by combining two resistors at a time.

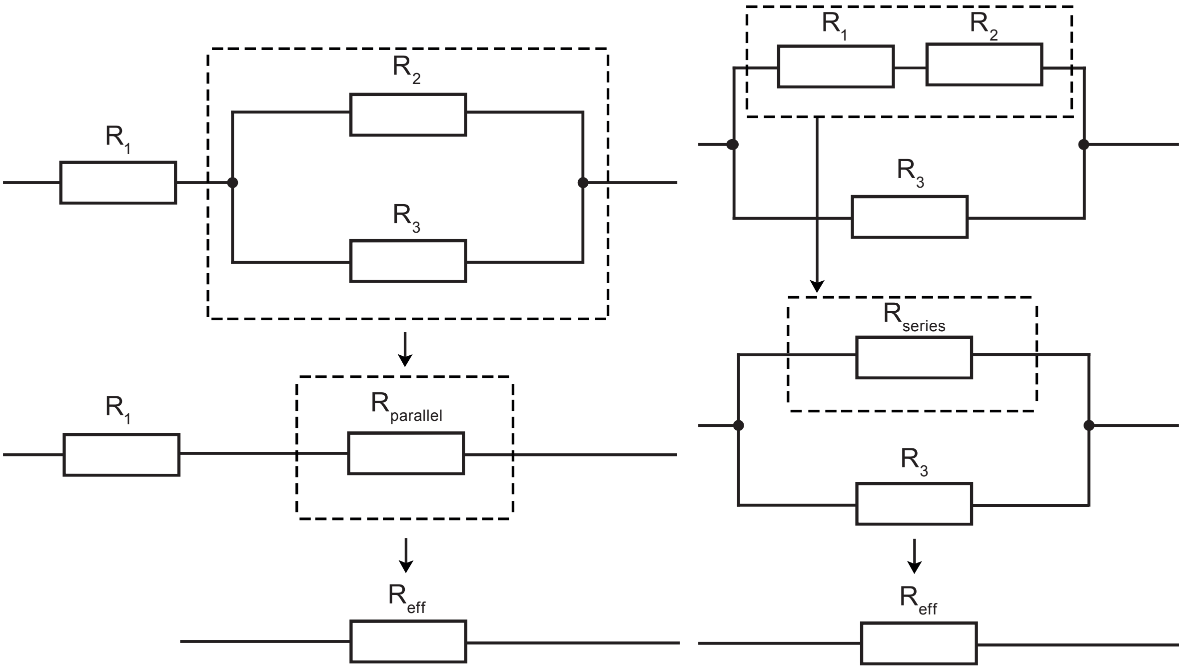


Figure 3.25 Determining the effective resistance of resistors connected in series-parallel arrangements

Worked Example 3.8

Calculate the effective resistance of the circuit in Figure 3.26.

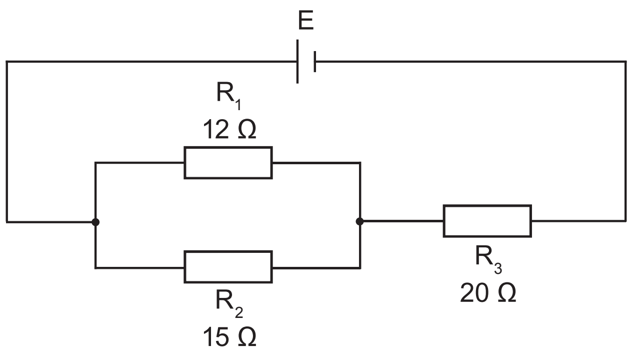


Figure 3.26

Solution

Step 1: Determine the effective resistance of R_1 and R_2 which are connected in parallel.

$$\frac{1}{R_{\text{parallel}}} = \frac{1}{R_1} + \frac{1}{R_2}$$
$$= \frac{1}{12\ \Omega} + \frac{1}{15\ \Omega}$$
$$= \frac{3}{20\ \Omega}$$
$$R_{\text{parallel}} = 6.7\ \Omega$$

Step 2: Redraw the circuit by replacing R_1 and R_2 with R_{parallel}.

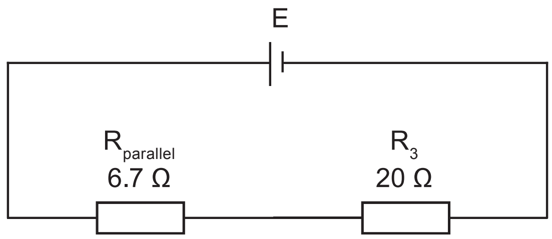


Figure 3.27

Step 3: Determine the effective resistance of R_{parallel} and R_3 which are connected in series.

$$R_{\text{eff}} = R_{\text{parallel}} + R_3$$
$$= 6.7\ \Omega + 20\ \Omega$$
$$= 26.7\ \Omega$$

Review Question 3.4

1. Calculate the effective resistance for the following circuits:

(a)

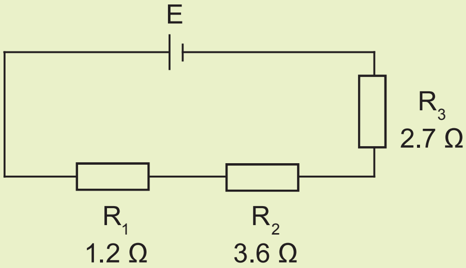


Figure 3.28

(b)

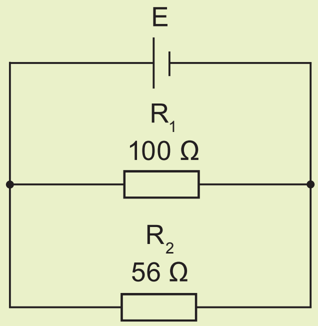


Figure 3.29

(c)

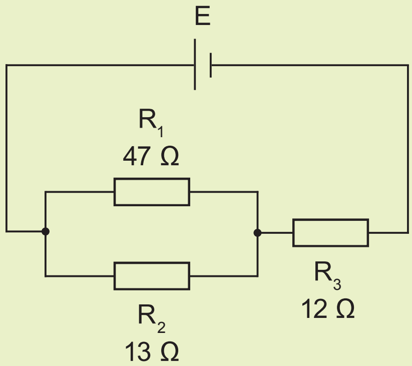


Figure 3.30

(d)

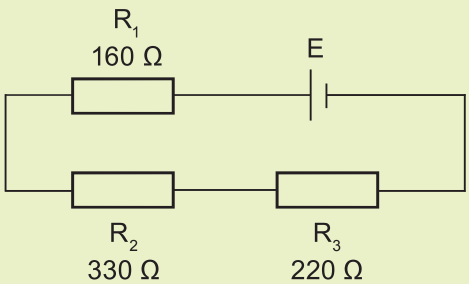


Figure 3.31

(e)

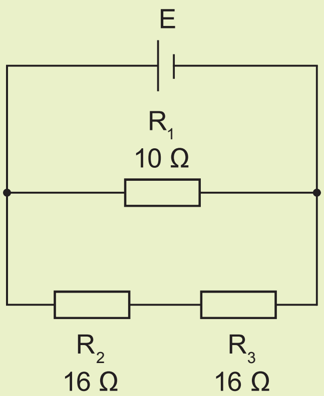


Figure 3.32

(f)

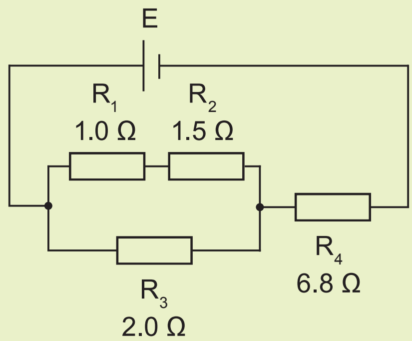


Figure 3.33

3.5 Why is it important to consider the power rating when selecting a resistor?

Learning Outcome

- Determine the power rating of a resistor and explain the factors affecting it.

Key Ideas

- Resistors come in various power ratings.
- Selecting a suitable power rating is important to prevent a resistor from overheating.
- The power rating of a resistor depends on its physical size and whether it has cooling fins.

Power ratings of resistors

When a current flows through a resistor, electrical energy is converted into heat. The larger the current flowing through the resistor, the greater the rate of energy conversion.

We learnt in Chapter 2 that the rate of energy conversion, or power, can be calculated using the following equations:

$$P = IV \quad \text{or} \quad P = \frac{V^2}{R} \quad \text{or} \quad P = I^2R$$

If this rate of conversion is high enough, it can cause the resistor to overheat. Hence, resistors have power ratings, which indicate the maximum power that resistors can safely tolerate. For example, if a resistor has a rating of 0.25 W, then the maximum power that the resistors can withstand is 0.25 W. As a general rule, it is common to choose a resistor with a rating that is twice as large as the actual power used.

Carbon resistors come in power ratings of 0.125 W, 0.25 W, 0.5 W, 1.0 W and 2.0 W. The power rating of a resistor increases with its physical size, as shown in Figure 3.34. For power rating requirements above 2.0 W, wire-wound resistors, which have a power rating of up to a few hundred watts, can be considered. Some wire-wound resistors have cooling fins which help them to dissipate heat at a faster rate and increase their power rating.

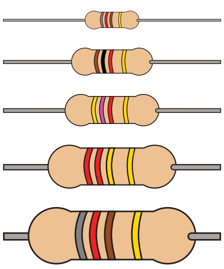


Figure 3.34 The power rating of a carbon resistor increases with its physical size

Worked Example 3.9

The p.d. across a resistor is 6.0 V. The current through it is 0.20 A. Calculate the power output of this resistor and suggest a suitable power rating.

Solution

$$\begin{aligned} P &= IV \\ &= 0.20\ \text{A} \times 6.0\ \text{V} \\ &= 1.2\ \text{W} \end{aligned}$$

We can choose a resistor with power rating of 2.0 W or higher.

Review Questions 3.5

1. 0.10 A of current flows through a 22 Ω resistor.
   (a) Calculate the power output of the resistor.
   (b) Suggest a suitable power rating for this resistor.
2. The p.d. across a 1.0 kΩ resistor is 10 V.
   (a) Calculate the power output of the resistor.
   (b) If the p.d. is increased to 20 V, calculate the new power output and suggest a suitable power rating for the resistor.

3.6 How do we vary the current in a circuit?

Learning Outcomes

- Explain how changing the resistance in a circuit changes the current in the circuit.
- Explain the use of variable resistors in electrical circuits.

Key Idea

- The amount of resistance affects the current in a circuit.

Varying the current in a circuit

We learnt in Section 2.5 that if we increase the resistance of a circuit, the current will decrease, and vice versa. This allows us to vary the current in a circuit by changing the resistor in the circuit to one with a lower or higher resistance.

However, in many situations, we want to be able to vary the current in a circuit without adding or removing any components. Variable resistors are useful for this purpose. Figure 3.35 shows a circuit with a variable resistor connected in series with a bulb. Increasing the resistance of the variable resistor will cause the current to decrease, making the bulb dimmer. Decreasing the resistance of the variable resistor will cause the current to increase, making the bulb brighter.

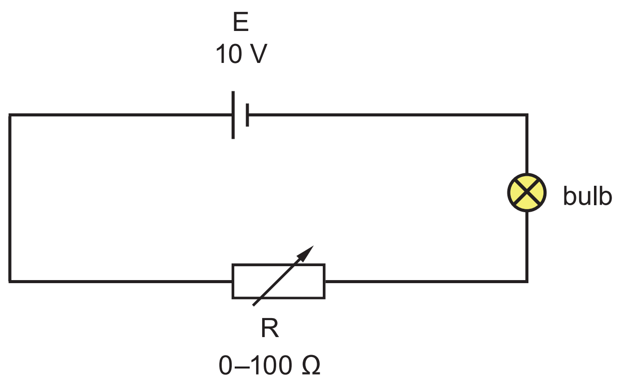


Figure 3.35 Using a variable resistor to control the brightness of a bulb

Connecting a variable resistor

We learnt in Section 3.2 that most variable resistors come in the form of a potentiometer with three terminals – A, B and W. Figure 3.36 shows a trimmer potentiometer ('trimpot' in short) and its internal structure.

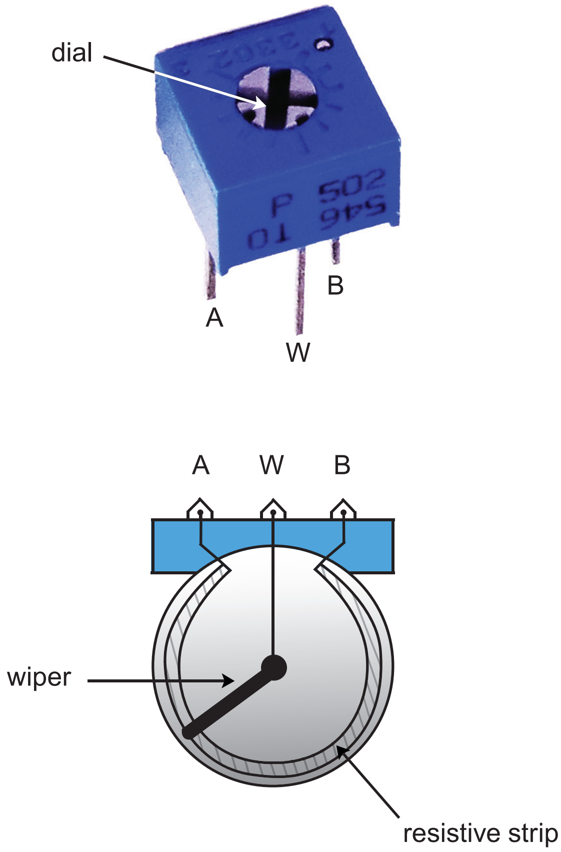


Figure 3.36 A trimmer potentiometer (top) and its internal structure (bottom)

Terminals A and B are connected to two ends of the resistive strip. The centre terminal W is connected to a wiper which can be moved by turning the dial. To use the trimpot as a variable resistor, we can connect terminals A and W to the circuit as shown in Figure 3.37. Note the path taken by the current.

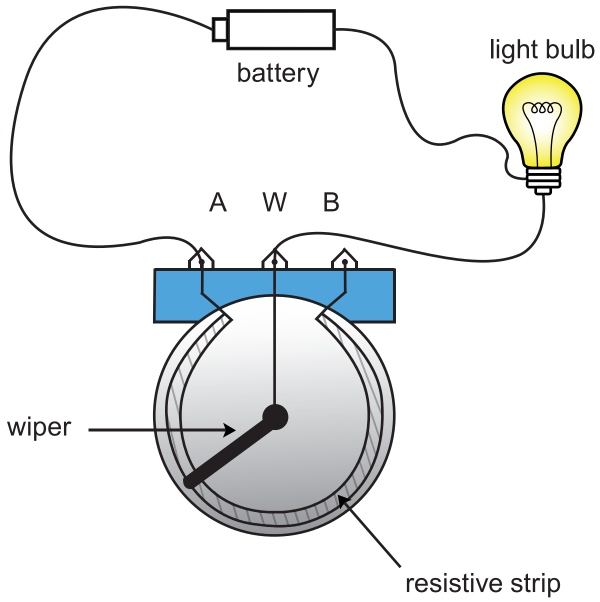


Figure 3.37 Connecting a potentiometer to work as variable resistor

As the wiper is turned towards terminal A, the length of resistive strip travelled by the current becomes shorter, thus lowering the resistance. Conversely, turning the wiper towards terminal B will increase the resistance.

It is a common practice to connect the unused terminal B to terminal W as shown in Figure 3.38. This will prevent an open circuit if the wiper breaks contact with the resistive strip as the current can still flow from terminal A to B via the resistive strip.

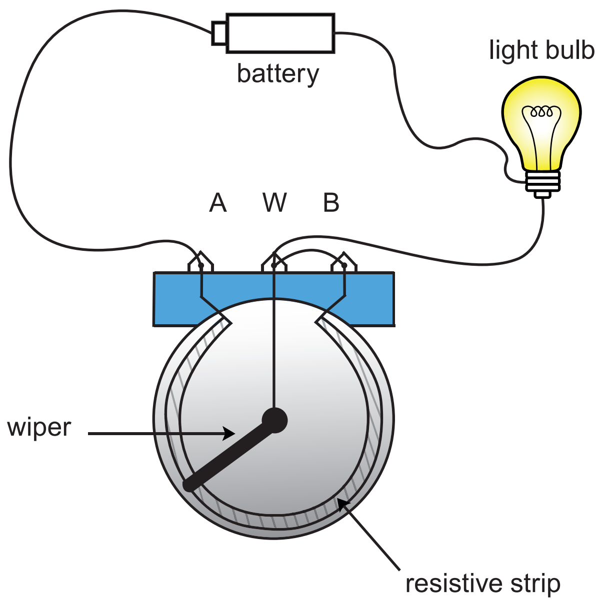


Figure 3.38 It is a common practice to connect the unused terminal to terminal W

A variable resistor can be used together with a fixed resistor in series as shown in Figure 3.39. This setup prevents a current surge in the circuit if the variable resistor is accidentally set to zero resistance.

Figure 3.39 Fixed resistor in series with a variable resistor

This setup is also useful in applications which require a specific value of resistance. This cannot be achieved by using fixed resistors, such as those in the E24 series, as they come in standard values. For such applications, we can connect a variable resistor in series with a fixed resistor. The chosen fixed resistor should have a resistance that is smaller than the required value. We can then adjust the variable resistor until we obtain the required resistance.

Worked Example 3.10

A resistance of 270.2 Ω is required for a circuit. Describe how you would use a fixed resistor from the E24 series and a variable resistor to achieve this required resistance.

Solution

- Choose a fixed resistor of 240 Ω from the E24 series.
- Connect the 240 Ω resistor in series with a 0–100 Ω trimpot.
- Adjust the trimpot to obtain the required resistance of 270.2 Ω. This resistance can be measured with a digital multimeter.

Review Questions 3.6

1. Figure 3.40 shows a battery, a bulb and a trimpot. Draw connecting wires to form a circuit so that the trimpot can be used to adjust the brightness of the bulb.

2. A resistance of 120.5 Ω is required for a circuit. Describe how you would use a fixed resistor from the E24 series and a variable resistor to achieve the required resistance.

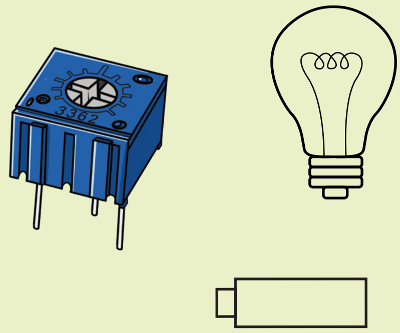


Figure 3.40

Further Reading

Carbon resistors from the E24 series have four coloured bands. Some resistors (mainly metal film resistors) have five coloured bands, as shown in Figure 3.41.

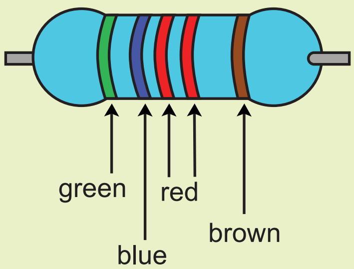


Figure 3.41 A metal film resistor with five coloured bands

For a five-band resistor, starting from the left:

- The first, second and third bands represent the first, second and third digits of the resistance value, respectively.
- The fourth band represents the power-of-10 multiplier for the number formed by the first, second and third digits.
- The last band represents the percentage tolerance.

Thus the resistance of the resistor in Figure 3.41 = 562 × 100 Ω ± 1% or 56.2 kΩ ± 1%.

4 CIRCUIT THEORIES

How do we determine the current and voltage at different points of a circuit?

In Chapter 2, we learnt that current and voltage are two important physical quantities in the study of electricity. When electrical components are connected to a battery, current flows through the components and voltages develop across them. The magnitudes of the currents and voltages depend on the components used and how they are connected.

In this chapter, we will learn a number of theories that will enable us to determine the magnitudes of the voltages and currents in a circuit. Knowledge of these theories and how to apply them will help us to design, build and test electronic systems effectively.

4.1 What are the common terms used to describe a circuit?

Learning Outcomes

- Define the terms – circuit, load, source, open-circuit, short-circuit and overload.
- Show understanding that current flows only in a closed circuit.
- Show understanding of the effect of a short circuit.

Key Ideas

- Current can only flow in a closed circuit with a source.
- Switches are used to open and close a circuit.
- A short circuit is a low-resistance path that is usually undesirable and harmful.
- Overloading occurs when the current through a wire or component exceeds what it can handle.

Circuits

A **circuit** consists of electrical components such as batteries, light bulbs and switches connected together with wires. A circuit provides one or more paths for the current to flow.

We learnt in Chapter 1 that symbols are used to represent electrical components. Diagrams of circuits drawn using these symbols are called **circuit diagrams**. Figure 4.1 shows a circuit diagram with a battery and a resistor.

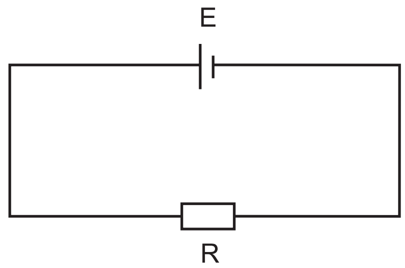


Figure 4.1 Circuit with a battery and a resistor

For a current to flow in a circuit, there must be a **source** to provide the e.m.f. needed to move electric charges around the circuit. The source in Figure 4.1 is a battery. Power supply units such as the one shown in Figure 4.2 are also commonly used as sources. Specifically, the battery and power supply unit are called **direct current (DC) voltage sources** because they provide a constant e.m.f.

Figure 4.2 The battery (left) and power supply unit (right) are two examples of DC voltage sources

The resistor in Figure 4.1 is the **load**. A load is a component which converts the electrical energy supplied by a source into other forms such as light, heat or kinetic energy.

Open and closed circuits

A current can only flow in a circuit with a continuous path linking the positive terminal to the negative terminal of a source. Figure 4.3a shows a **closed circuit** with such a continuous path. The circuit in Figure 4.3b has a break in the path and is called an **open circuit**.

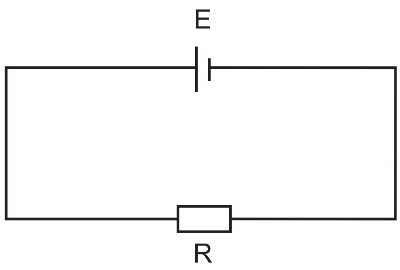


Figure 4.3a Closed circuit

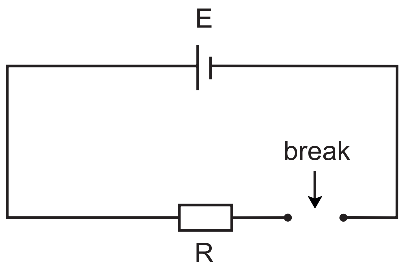


Figure 4.3b Open circuit

Short circuits

A **short circuit** is a low-resistance path that is usually undesirable and harmful.

In Figure 4.4, a wire is accidentally connected across the bulb, creating a short circuit. This causes the current in the circuit to become very large, which can lead to overheating. As the resistance of the wire is much lower than that of the bulb, nearly all the current will flow through the short circuit and bypass the bulb. As a result, the bulb will not light up.

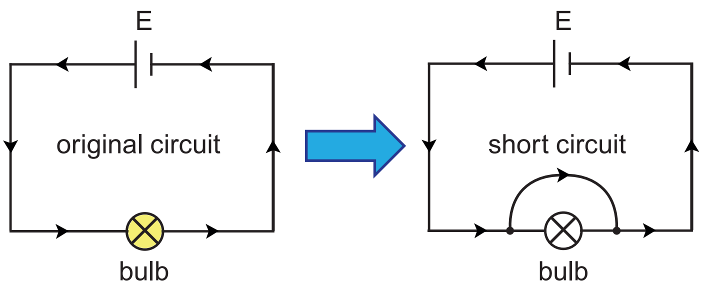


Figure 4.4 An example of a short circuit

Switches

In many applications, we want to be able to open or close a circuit conveniently. This is usually done using switches.

Switches can be classified by their mechanism, e.g., slide, pushbutton, toggle, knife and plug. For this course, the slide switch and the pushbutton switch will be used most frequently.

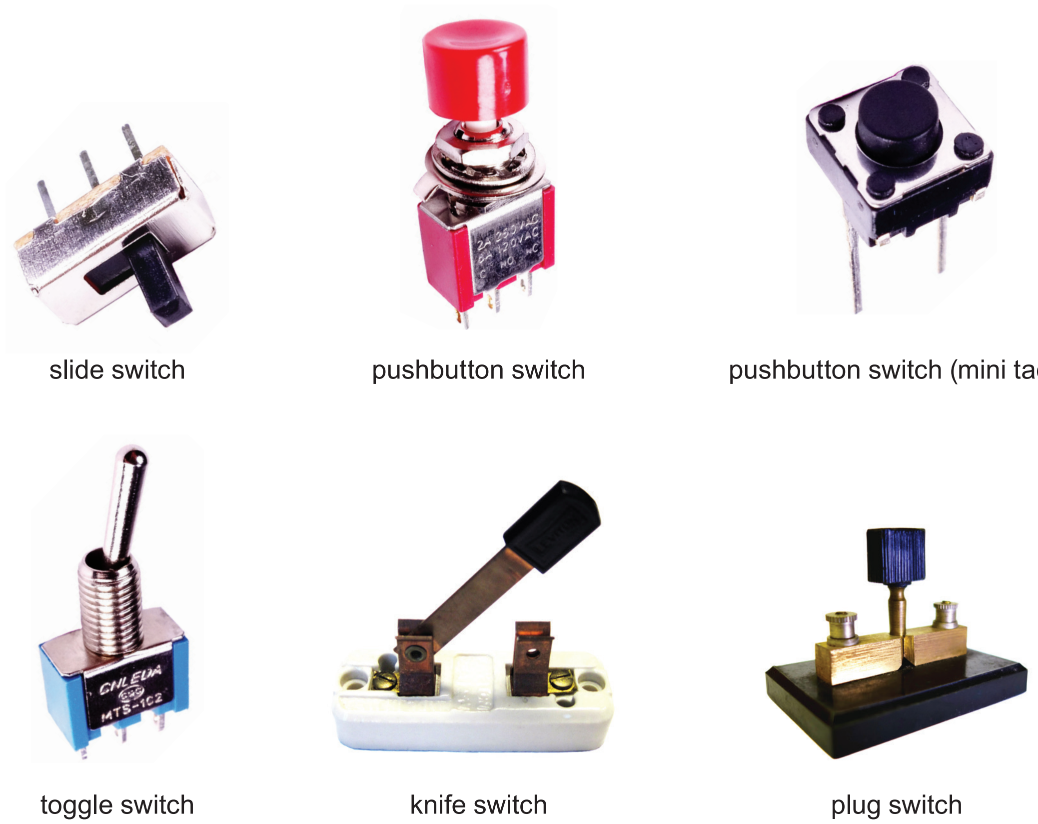


Figure 4.5 Different types of switches

You may have noticed that some of the switches in Figure 4.5 have two terminals while some have three. Those with two terminals are called **single-pole single-throw (SPST)** switches while those with three terminals are called **single-pole double-throw (SPDT)** switches.

An SPST switch has one terminal on each side as shown in Figure 4.6.

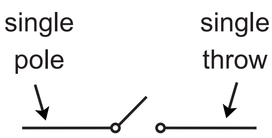


Figure 4.6 An SPST switch

When the switch is closed, current can flow between the two terminals as shown in Figure 4.7.

Figure 4.7 Operation of an SPST switch

An SPDT switch has a common terminal (COM) on one side and two terminals (A and B) on the other side as shown in Figure 4.8.

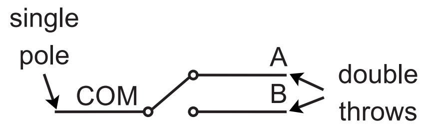


Figure 4.8 An SPDT switch

Depending on the position of the switch, the COM terminal is connected to either terminal A or B. Current can flow between the two connected terminals as shown in Figure 4.9.

Figure 4.9 Operation of an SPDT switch

Connecting an SPST switch

To connect an SPST switch, insert it along the electrical path to be opened or closed as shown in Figure 4.10. Notice that it operates as a simple on/off switch.

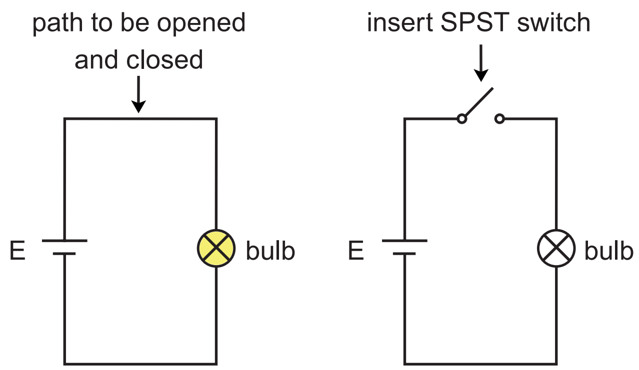


Figure 4.10 Connecting an SPST switch

Connecting an SPDT switch

An SPDT switch can be used as an SPST switch by connecting only terminal A and the COM terminal to the circuit, leaving terminal B unconnected. In Figure 4.11a, the slider is moved to position A. This closes the circuit and the bulb lights up. In Figure 4.11b, the slider is moved to position B. This opens the circuit and the bulb does not light up.

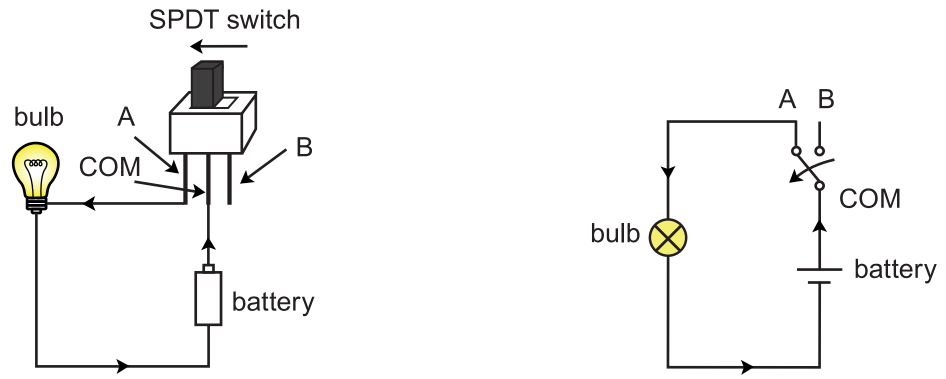


Figure 4.11a The circuit is closed when the slider is moved to position A

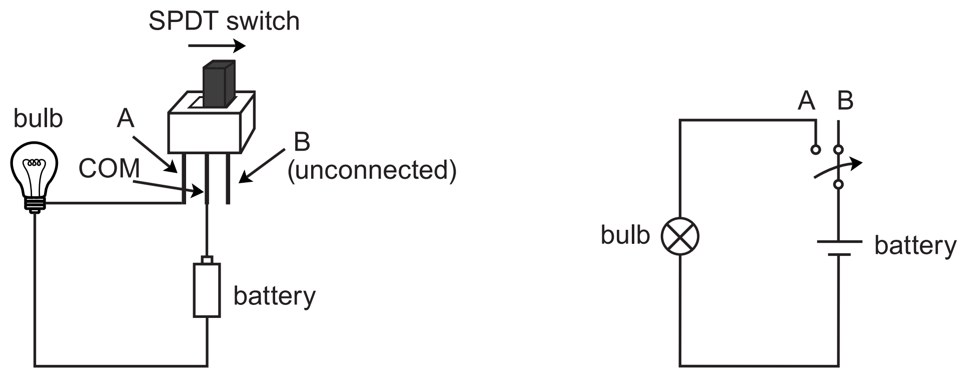


Figure 4.11b The circuit is opened when the slider is moved to position B

The SPDT switch can be used to change the path of the current in a circuit. In Figure 4.12a, the slider is moved to position A, causing a current to flow through bulb 1. In Figure 4.12b, the slider is moved to position B, causing a current to flow through bulb 2.

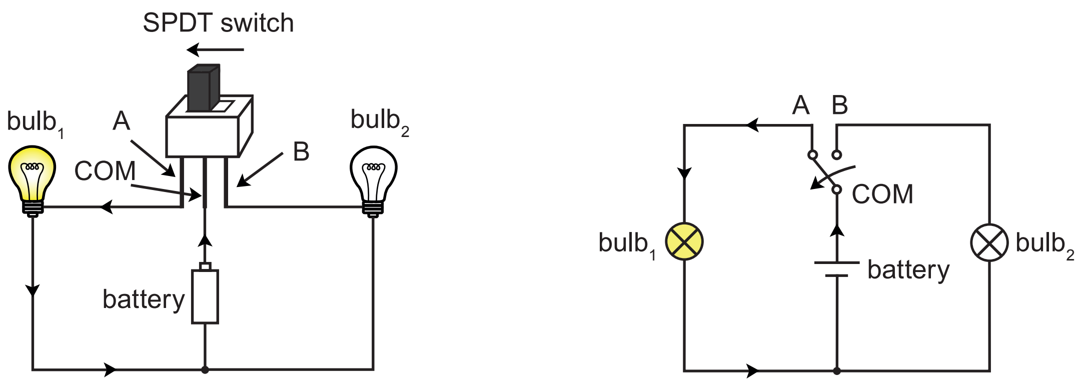


Figure 4.12a Current flows through bulb 1 when the slider is moved to position A

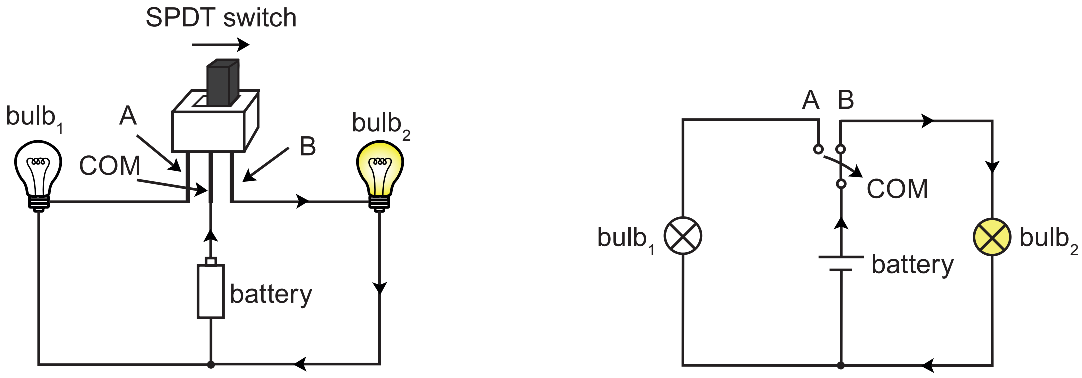
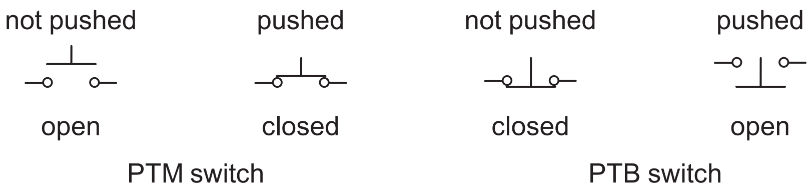


Figure 4.12b Current flows through bulb 2 when the slider is moved to position B

Using push-to-make and push-to-break switches

A **push-to-make (PTM)** switch is normally open. When pushed, it will become closed; when released, it will become open again. A **push-to-break (PTB)** switch is normally closed. When pushed, it will become open; when released, it will become closed again.



Overloading

The **current rating** of a wire or component is the maximum current it can carry without getting overheated or damaged. **Overloading** occurs when the current exceeds the current rating. There are a number of possible causes of overloading:

- Using a wire with a current rating that is too low, e.g., using a wire with a current rating of 0.5 A to carry a current of 1 A.
- When the insulating covering of wires becomes damaged, the bare wires can touch each other, resulting in a short circuit. This causes the current to become very large and exceed the current rating of the wires.
- Connecting multiple appliances to a single mains socket via multi-way adaptors, as shown in Figure 4.13, forces parts of the wiring to carry the sum of the currents used by all the connected appliances. If this sum exceeds the current rating of the wires involved, overloading will occur.

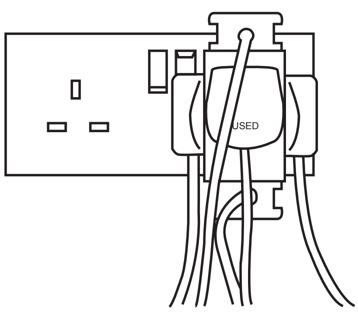


Figure 4.13 Overloaded mains supply socket

Protection against overloading

To prevent overloading, most electrical systems are equipped with safety devices such as fuses and circuit breakers, as shown in Figure 4.14. A fuse consists of a thin wire housed in a casing. This wire will melt and break the circuit when the current exceeds the limit indicated on the casing. A circuit breaker consists of switches which will automatically open and break the circuit when the current exceeds a certain limit.

Figure 4.14 The fuse (left) and the circuit breaker (right) are examples of safety devices that protect against overloading

Review Questions 4.1

1. Give two examples of sources.

2. A student sets up the circuit shown in Figure 4.15. Explain what is wrong with the student's setup.

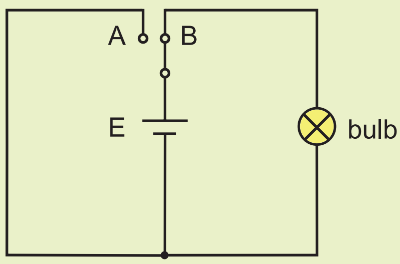


Figure 4.15

3. Classify the switches shown in Figure 4.5 into SPST and SPDT switches.

4. Explain what is meant by overloading and describe a possible cause of it.

4.2 How do we determine the current and voltage in series circuits?

Learning Outcome

- Apply the following principles to a series resistive circuit:
  - The current at every point in a series circuit is the same.
  - The sum of the p.d.s in a series circuit is equal to the p.d. across the whole circuit.

Key Ideas

- The current at every point in a series circuit is the same.
- The p.d. between any two points in a series circuit is equal to the sum of the p.d.s of each component that lies between the two points.

Current in a series circuit

Figure 4.16 shows a series circuit. The resistors are connected such that there is only one path for the current to flow. Since there is only a single path, the current is the same throughout the series circuit, i.e.:

$$I_1 = I_2 = I_3$$

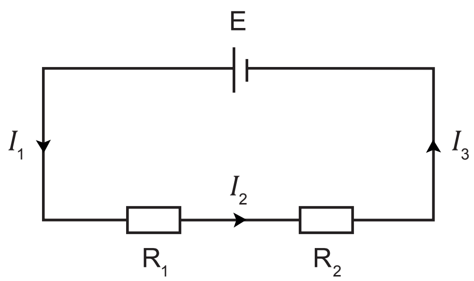


Figure 4.16 Current in a series circuit

P.d. in a series circuit

In a series circuit, the p.d. between any two points is the sum of the p.d.s across each component that lies between the two points. For the circuit shown in Figure 4.17, the p.d. between points A and B is given by:

$$V_{AB} = V_1 + V_2 + V_3$$

In this case, the e.m.f. of the source, E, is also equal to $V_1 + V_2 + V_3$.

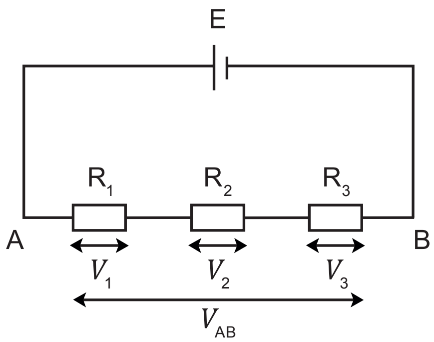


Figure 4.17 P.d. of a series circuit

Worked Example 4.1

Calculate E, the e.m.f. of the source, for the circuit shown in Figure 4.18.

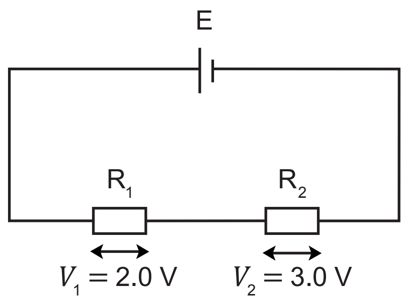


Figure 4.18

Solution

$$\begin{aligned} E &= V_1 + V_2 \\ &= 2.0\text{ V} + 3.0\text{ V} \\ &= 5.0\text{ V} \end{aligned}$$

Worked Example 4.2

For the circuit in Figure 4.19, calculate:

(a) I_1;

(b) I_2;

(c) V_2; and

(d) E.

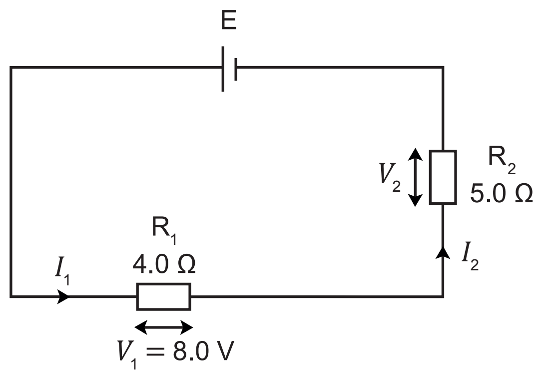


Figure 4.19

Solution

(a) $I_1 = \dfrac{V_1}{R_1}$

$= \dfrac{8.0\ \text{V}}{4.0\ \text{V}}$

$= 2.0$ A

(b) Since R_1 and R_2 are connected in series, $I_2 = I_1 = 2.0$ A.

(c) $V_2 = I_2 \times R_2$

$= 2.0\ \text{A} \times 5.0\ \Omega$

$= 10$ V

(d) $E = V_1 + V_2$

$= 8.0\ \text{V} + 10\ \text{V}$

$= 18$ V

Review Question 4.2

1. Figure 4.20 shows a circuit with two light bulbs connected in series.

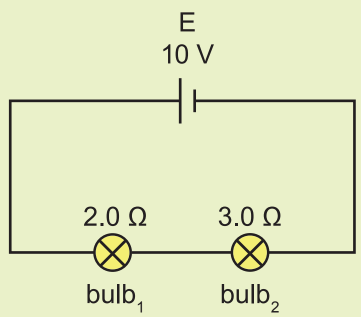


Figure 4.20

Determine:

(a) the effective resistance of the circuit;

(b) the current flowing out from the battery;

(c) the current flowing through each light bulb; and

(d) the p.d. across each light bulb.

4.3 How do we determine the current and voltage in parallel circuits?

Learning Outcome

- Apply the following principles to a parallel resistive circuit:
  - The current from the source is equal to the sum of the currents in the branches of a parallel circuit.
  - The p.d. across each branch of a parallel circuit is the same.

Key Ideas

- The sum of the currents in each branch of a parallel circuit is equal to the total current from the source.
- The p.d. across each branch of a parallel circuit is the same.

Current in a parallel circuit

Figure 4.21 shows a parallel circuit. The components are connected such that there are multiple paths for the current to flow. In this case, there are three paths through R_1, R_2 and R_3, respectively. Each of these paths is called a **branch**.

In a parallel circuit, the sum of the currents in each branch is equal to the total current from the source. For the circuit shown in Figure 4.21,

$$I = I_1 + I_2 + I_3$$

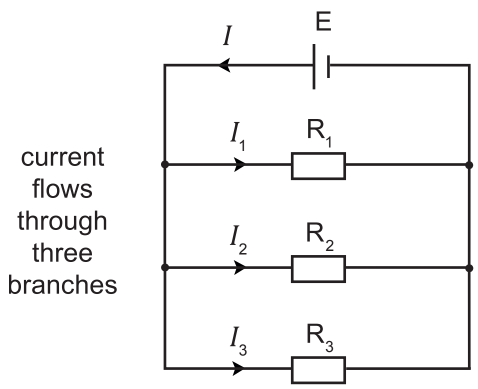


Figure 4.21 Current in a parallel circuit

Worked Example 4.3

For the circuit in Figure 4.22, calculate the current I_2.

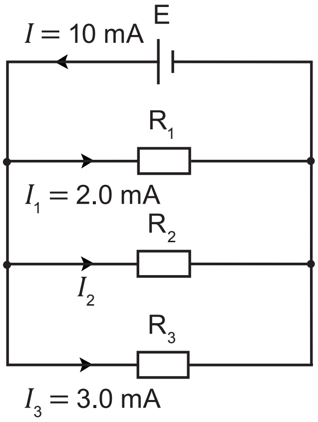


Figure 4.22

Solution

$$I = I_1 + I_2 + I_3$$
$$10 \text{ mA} = 2.0 \text{ mA} + I_2 + 3.0 \text{ mA}$$
$$I_2 = 10 \text{ mA} - 2.0 \text{ mA} - 3.0 \text{ mA}$$
$$= 5.0 \text{ mA}$$

P.d. in a parallel circuit

In a parallel circuit, the p.d. across each branch is the same. For the circuit shown in Figure 4.23,

$$E = V_1 = V_2 = V_3$$

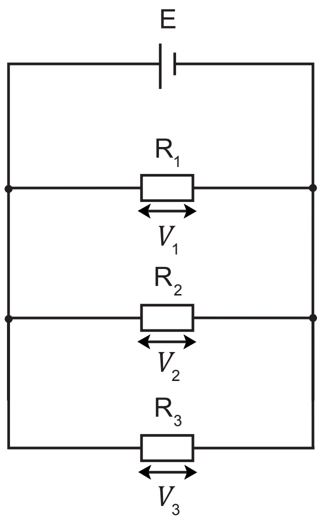


Figure 4.23 P.d. in a parallel circuit

Worked Example 4.4

Two resistors are connected in parallel as shown in Figure 4.24.

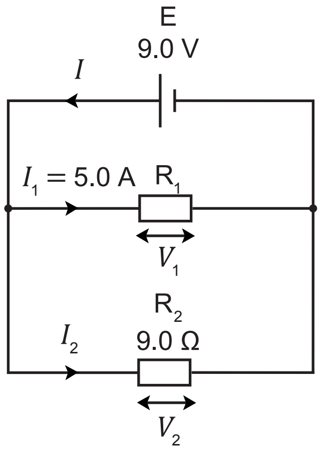


Figure 4.24

Calculate:

(a) V_2;

(b) I_2;

(c) I; and

(d) R_1.

Solution

(a) Since R_2 is connected in parallel with the 9.0 V source, $V_2 = E = 9.0$ V.

(b) $I_2 = \dfrac{V_2}{R_2}$

$= \dfrac{9.0 \text{ V}}{9.0\ \Omega}$

$= 1.0$ A

(c) $I = I_1 + I_2$

$= 1.0 \text{ A} + 5.0 \text{ A}$

$= 6.0$ A

(d) Since R_1 is connected in parallel with the 9.0 V source, $V_1 = E = 9.0$ V.

$R_1 = \dfrac{V_1}{I_1}$

$= \dfrac{9.0 \text{ V}}{5.0 \text{ A}}$

$= 1.8\ \Omega$

Review Question 4.3

1. Figure 4.25 shows a circuit with three resistors connected in parallel.

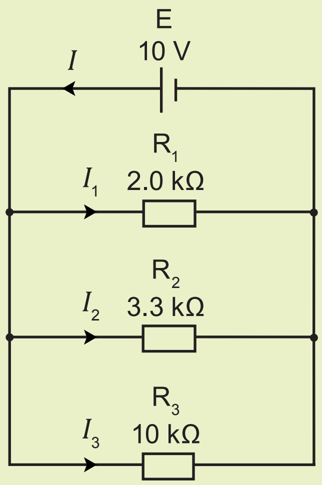


Figure 4.25

(a) State the p.d. across each of the resistors.

(b) Calculate the current through each of the resistors.

(c) Calculate the total current through the circuit.

4.4 How do we determine the current and voltage in series-parallel circuits?

Learning Outcome

- Apply the following principles to a series-parallel resistive circuit:
  - The current at every point in a series circuit is the same.
  - The sum of the p.d.s in a series circuit is equal to the p.d. across the whole circuit.
  - The current from the source is equal to the sum of the currents in the branches of a parallel circuit.
  - The p.d. across each branch of a parallel circuit is the same.

Key Idea

- The principles for series and parallel circuits can be applied to a series-parallel circuit.

Many circuits have a combination of series and parallel connections. For example, in the circuit shown in Figure 4.26, R_1 and R_2 are connected in series and together, they are connected in parallel to R_3. These types of circuits are called **series-parallel circuits**.

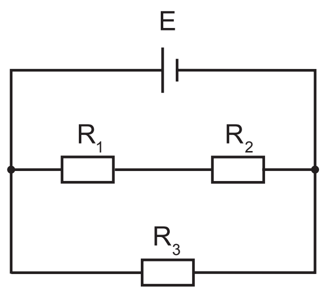


Figure 4.26 A series-parallel circuit

When analysing a series-parallel circuit, we can apply the respective principles for series and parallel circuits.

Worked Example 4.5

For the circuit in Figure 4.27, calculate:

(a) I_1;

(b) I_2; and

(c) I.

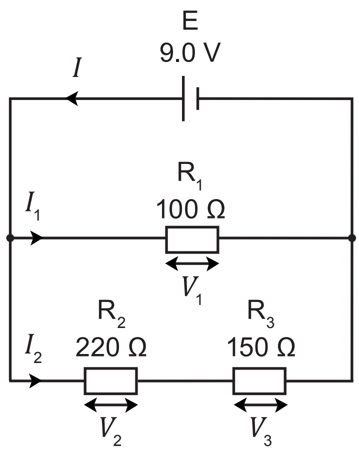


Figure 4.27

Solution

(a) Since R_1 is connected in parallel with the DC source, $V_1 = E = 9.0$ V.

$$I_1 = \frac{V_1}{R_1}$$
$$= \frac{9.0\text{ V}}{100\ \Omega}$$
$$= 90\text{ mA}$$

(b) Since R_2 and R_3 together are connected in parallel with the DC source,

$V_2 + V_3 = E = 9.0$ V

Effective resistance of R_2 and R_3, $R_{series} = 220\ \Omega + 150\ \Omega$
$= 370\ \Omega$

$$I_2 = \frac{V_2 + V_3}{R_{series}}$$
$$= \frac{9.0\text{ V}}{370\ \Omega}$$
$$= 24\text{ mA}$$

(c) Current supplied by source, $I = I_1 + I_2$
$= 90\text{ mA} + 24\text{ mA}$
$= 114\text{ mA}$

Worked Example 4.6

Figure 4.28 shows a series-parallel circuit. Calculate:

(a) the effective resistance of the circuit;

(b) I_1;

(c) V_1; and

(d) V_2.

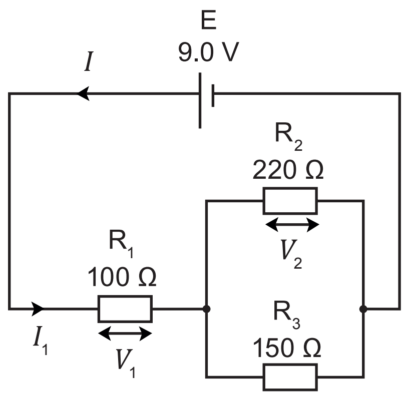


Figure 4.28

Solution

(a) Effective resistance of R_2 and R_3 in parallel,

$$\frac{1}{R_{\text{parallel}}} = \frac{1}{R_2} + \frac{1}{R_3}$$

$$= \frac{1}{220\ \Omega} + \frac{1}{150\ \Omega}$$

$$R_{\text{parallel}} = 89\ \Omega$$

Effective resistance of circuit, $R_{\text{eff}} = R_1 + R_{\text{parallel}}$

$$= 100\ \Omega + 89\ \Omega$$

$$= 189\ \Omega$$

(b) Current supplied by DC source, $I = \frac{E}{R_{\text{eff}}}$

$$= \frac{9.0\ \text{V}}{189\ \Omega}$$

$$= 48\ \text{mA}$$

Since R_1 is connected in series with the DC source, $I_1 = I = 48$ mA

(c) $V_1 = I_1 \times R_1$
$= 48 \text{ mA} \times 100 \ \Omega$
$= 4.8 \text{ V}$

(d) $V_1 + V_2 = E$
$V_2 = E - V_1$
$= 9.0 \text{ V} - 4.8 \text{ V}$
$= 4.2 \text{ V}$

Review Question 4.4

1. Figure 4.29 shows a series-parallel circuit. Calculate the following:
   (a) R_{eff}, the effective resistance of the circuit;
   (b) I_1;
   (c) V_1; and
   (d) V_3.

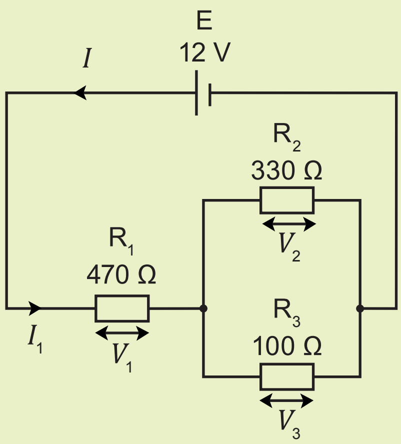


Figure 4.29

4.5 How do we use the voltage-divider and current-divider formulae to determine the voltage and current in a circuit?

Learning Outcomes

- Identify a resistive voltage divider and apply the voltage-divider formula to solve related problems.
- Identify a resistive current divider and apply the current-divider formula to solve related problems.

Key Ideas

- The voltage-divider formula provides a quick way to calculate the voltage across components connected in series.
- The current-divider formula provides a quick way to calculate the current through components connected in parallel.

Resistive voltage divider

Figure 4.30 shows a circuit with two resistors connected in series with a source.

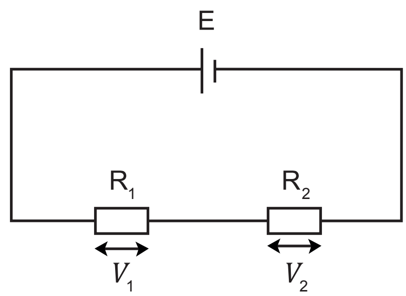


Figure 4.30 Resistors in a series circuit

We can calculate the voltage across each resistor by using the **voltage-divider formula**:

$$V_1 = \frac{R_1}{R_1 + R_2} \times E$$

$$V_2 = \frac{R_2}{R_1 + R_2} \times E$$

From the equations, we can deduce that as the ratio of R_1 to total resistance increases, V_1 also increases. The same applies to R_2 and V_2.

The voltage-divider formula can be applied to any number of resistors connected in series. For example, for the circuit shown in Figure 4.31, the voltage across R_1 is calculated using:

$$V_1 = \frac{R_1}{R_1 + R_2 + R_3 + \ldots + R_n} \times E$$

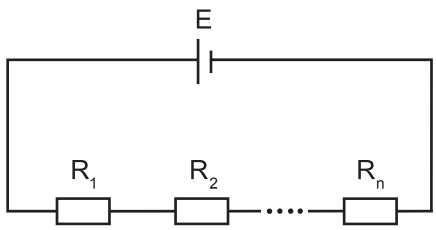


Figure 4.31 Circuit with multiple resistors connected in series

Worked Example 4.7

For the circuit shown in Figure 4.32, calculate V_1 and V_2 using the voltage-divider formula.

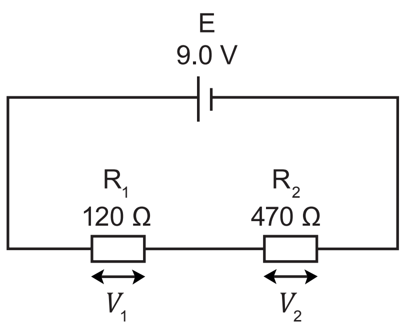


Figure 4.32

Solution

Using the voltage-divider formula,

$$V_1 = \frac{R_1}{R_1 + R_2} \times E$$

$$= \frac{120\ \Omega}{120\ \Omega + 470\ \Omega} \times 9.0\ \text{V}$$

$$= 1.8\ \text{V}$$

$$V_2 = \frac{R_2}{R_1 + R_2} \times E$$

$$= \frac{470\ \Omega}{120\ \Omega + 470\ \Omega} \times 9.0\ \text{V}$$

$$= 7.2\ \text{V}$$

Voltage-divider circuits are used to 'divide' a larger voltage into smaller voltages.

Figure 4.33 shows a voltage-divider circuit with a 1.0 kΩ fixed resistor in series with a 5 kΩ variable resistor. The output voltage is the voltage across R_2. When the variable resistor is set to its minimum value, 0 Ω, the output voltage will be 0 V. When the variable resistor is set to its maximum value, 5 kΩ, the output voltage will be 5.0 V. Hence, by adjusting the variable resistor, an output voltage between 0 V and 5.0 V can be obtained.

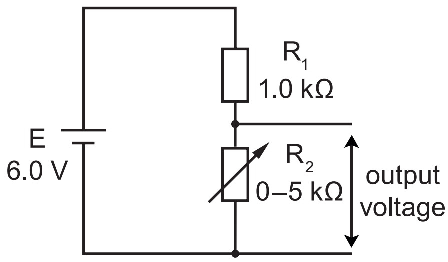


Figure 4.33 Voltage-divider circuit

The voltage-divider circuit in Figure 4.33 is built using two separate resistors. It is also possible to use a potentiometer in place of the two resistors, as shown in Figure 4.34. By adjusting the position of the wiper, an output voltage between 0 V and 6.0 V can be obtained.

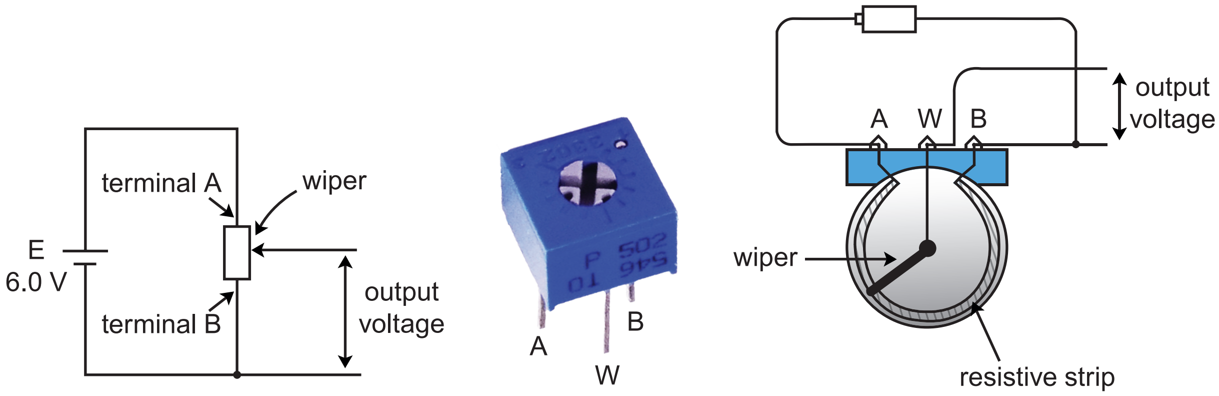


Figure 4.34 Using a potentiometer to build a voltage-divider circuit

Resistive current divider

Figure 4.35 shows part of a circuit with two resistors connected in parallel. The current I is divided into two smaller currents, I_1 and I_2, which flow through the two branches.

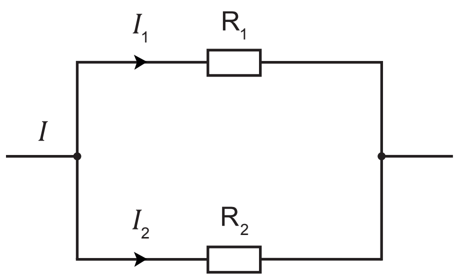


Figure 4.35 Current in a parallel circuit

We can calculate the current through each resistor by using the **current-divider formula**:

$$I_1 = \frac{R_2}{R_1 + R_2} \times I$$

$$I_2 = \frac{R_1}{R_1 + R_2} \times I$$

From the equations, we can deduce that as the ratio of R_1 to total resistance increases, I_1 decreases. The same applies to R_2 and I_2.

Worked Example 4.8

For the circuit shown in Figure 4.36, calculate I_1 and I_2 using the current-divider formula.

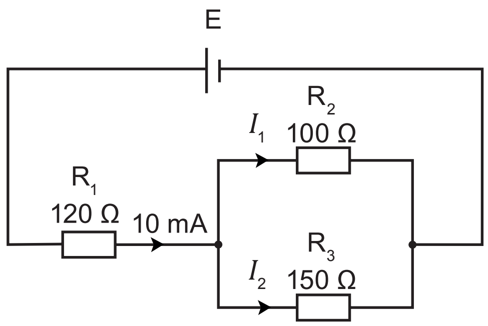


Figure 4.36

Solution

Using the current-divider formula,

$$I_1 = \frac{R_3}{R_2 + R_3} \times I$$
$$= \frac{150\ \Omega}{100\ \Omega + 150\ \Omega} \times 10\ \text{mA}$$
$$= 6.0\ \text{mA}$$

$$I_2 = \frac{R_2}{R_2 + R_3} \times I$$
$$= \frac{100\ \Omega}{100\ \Omega + 150\ \Omega} \times 10\ \text{mA}$$
$$= 4.0\ \text{mA}$$

Review Questions 4.5

1. Using the voltage-divider formula, calculate the p.d. across each resistor for the circuit in Figure 4.37.

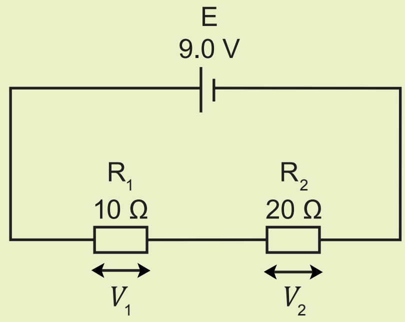


Figure 4.37

2. Using the current-divider formula, calculate the current flowing through each resistor for the circuit in Figure 4.38.

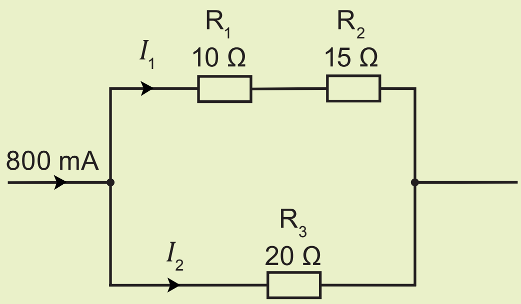


Figure 4.38

4.6 How do we use Kirchhoff's voltage and current laws to determine voltage and current in a circuit?

Learning Outcome

- State and apply Kirchhoff's voltage and current laws.

Key Ideas

- Kirchhoff's current law states that the algebraic sum of all the currents entering and leaving a node is equal to zero.
- Kirchhoff's voltage law states that the algebraic sum of all the voltages within a closed loop is equal to zero.

Kirchhoff's current law

Kirchhoff's current law (KCL) states that the algebraic sum of all the currents entering and leaving a node is equal to zero, i.e.:

$$\Sigma I_{\text{node}} = 0$$

A **node** is a junction where currents meet while the symbol **Σ** means 'sum of'.

Because ΣI_{node} is an algebraic sum, we need to consider the signs of the currents.

- Currents entering a node are considered positive. In Figure 4.39, I_1 and I_4 are considered positive.
- Currents leaving a node are considered negative. In Figure 4.39, I_2 and I_3 are considered negative.

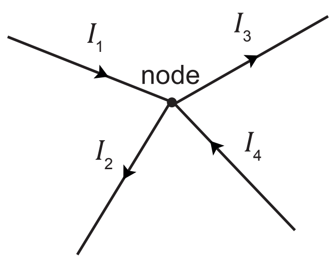


Figure 4.39 Node with four currents

Hence, the equation for the node in Figure 4.39 is written as:

$$I_1 - I_2 - I_3 + I_4 = 0$$

Rearranging the equation gives us:

$$I_1 + I_4 = I_2 + I_3$$

Hence, we can also write the current law as:

$$\Sigma I_{\text{entering}} = \Sigma I_{\text{leaving}}$$

Worked Example 4.9

Using KCL, calculate the currents I_1 and I_2 in the circuit shown in Figure 4.40.

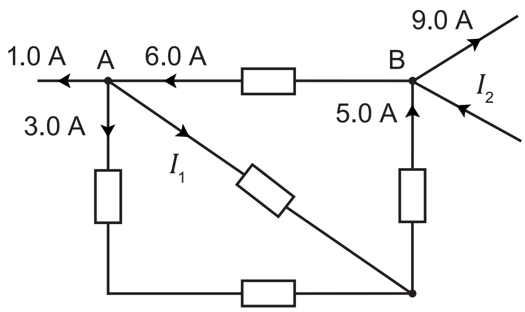


Figure 4.40

Solution

At node A, using KCL,

$$\Sigma I_{\text{entering}} = \Sigma I_{\text{leaving}}$$
$$6.0\text{ A} = 1.0\text{ A} + 3.0\text{ A} + I_1$$
$$I_1 = 2.0\text{ A}$$

At node B, using KCL,

$$\Sigma I_{\text{entering}} = \Sigma I_{\text{leaving}}$$
$$5.0\text{ A} + I_2 = 6.0\text{ A} + 9.0\text{ A}$$
$$I_2 = 10\text{ A}$$

Kirchhoff's voltage law

Kirchhoff's voltage law (KVL) states that the algebraic sum of all the voltages within a closed loop is equal to zero, i.e.:

$$\Sigma V_{\text{loop}} = 0$$

A **closed loop** is an electrical path that starts and ends at the same point. We can move along the loop in a clockwise or anticlockwise direction. In Figure 4.41, the clockwise path that starts from point A and goes to B, C, D and back to A is a closed loop.

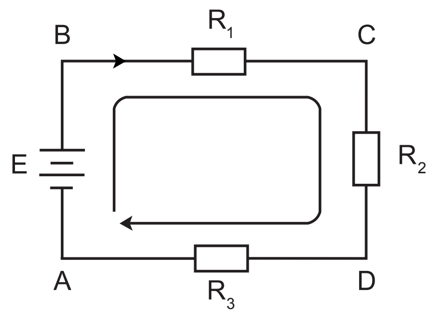


Figure 4.41 The path ABCDA forms a closed loop

Like in KCL, ΣV_{loop} is an algebraic sum and thus the sign of the voltages need to be considered. For this reason, it is useful to label the polarity (positive or negative) of the voltages across the components in the circuit.

- For sources, label their positive and negative terminals as '+' and '–', respectively.
- For other components, label the end which the current enters as '+' and the other end as '–'.

After labelling the polarities of the voltages in Figure 4.41, we would obtain the circuit in Figure 4.42.

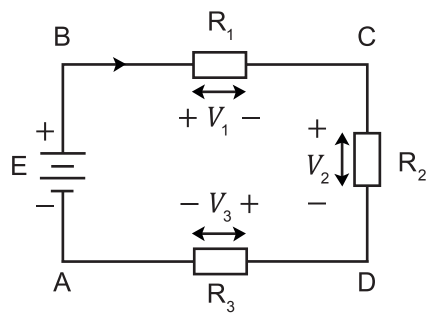


Figure 4.42 Circuit with polarity of voltages labelled

The sign of the voltages can be determined by using the following two rules:

- Voltages that increase in the direction of the loop are considered positive.
- Voltages that decrease in the direction of the loop are considered negative.

For the loop ABCDA in Figure 4.42, E is considered positive while V_1, V_2 and V_3 are considered negative. Hence, the equation for the loop is written as:

$$E - V_1 - V_2 - V_3 = 0$$

Worked Example 4.10

Using KVL, form an equation for the loop ABCDEA for the circuit shown in Figure 4.43.

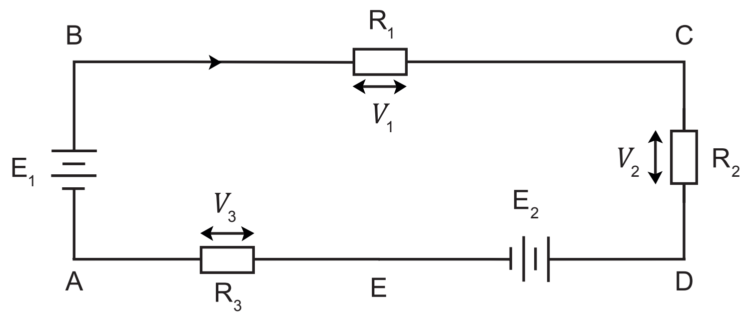


Figure 4.43

Solution

Label the polarities of the voltages of all the components.

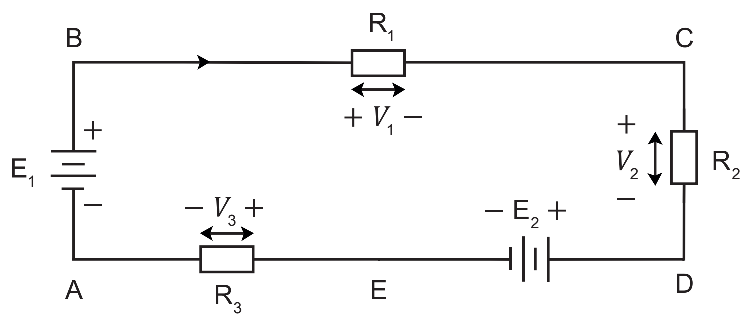


Figure 4.44

For the loop ABCDEA, E_1 is positive while the rest of the voltages are negative.

The equation can be written as: $E_1 - V_1 - V_2 - E_2 - V_3 = 0$

Worked Example 4.11

Figure 4.45 shows a circuit. The directions of the currents are indicated.

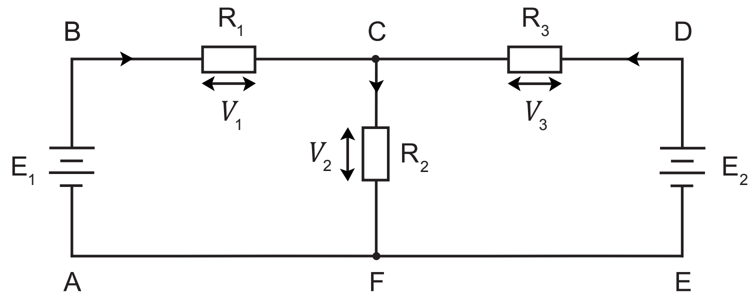


Figure 4.45

(a) Using KVL, form equations for the loops ABCFA and FCDEF.

(b) Given $E_1 = 9.0$ V, $E_2 = 5.0$ V and $V_1 = 4.3$ V, use the equations obtained in (a) to determine V_2 and V_3.

Solution

(a) Label the polarities of the voltages of all the components.

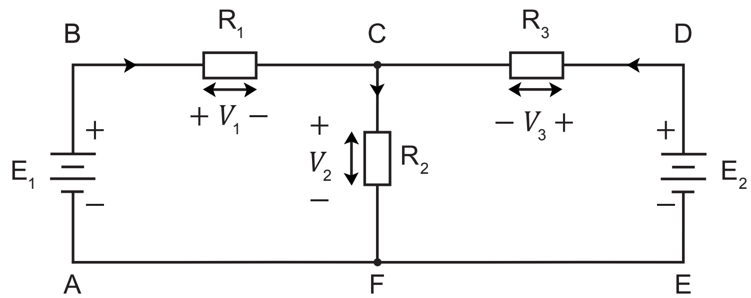


Figure 4.46

For the loop ABCFA, E_1 is positive while V_1 and V_2 are negative. Hence, the equation is written as:

$$E_1 - V_1 - V_2 = 0 \ldots\ldots\ldots\ldots\ldots \text{(1)}$$

For the loop FCDEF, V_2 and V_3 are positive while E_2 is negative. Hence, the equation is written as:

$$V_2 + V_3 - E_2 = 0 \ldots\ldots\ldots\ldots\ldots \text{(2)}$$

(b) Substituting $E_1 = 9.0$ V and $V_1 = 4.3$ V into (1),

$$9.0\text{ V} - 4.3\text{ V} - V_2 = 0$$
$$V_2 = 4.7\text{ V}$$

Substituting $E_2 = 5.0$ V and $V_2 = 4.7$ V into (2),

$$4.7\text{ V} + V_3 - 5.0\text{ V} = 0$$
$$V_3 = 0.3\text{ V}$$

Review Questions 4.6

1. Calculate the unknown currents for the nodes in Figures 4.47 and 4.48.

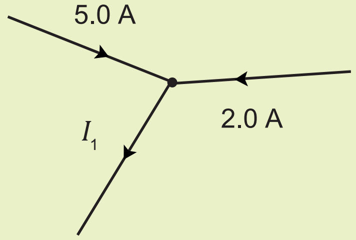


Figure 4.47

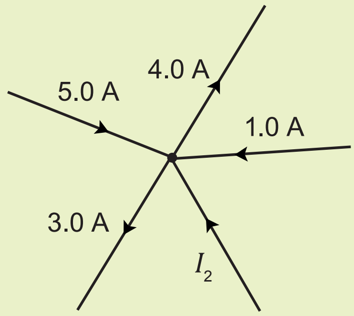


Figure 4.48

2. Figure 4.49 shows a circuit. The directions of the currents are indicated.

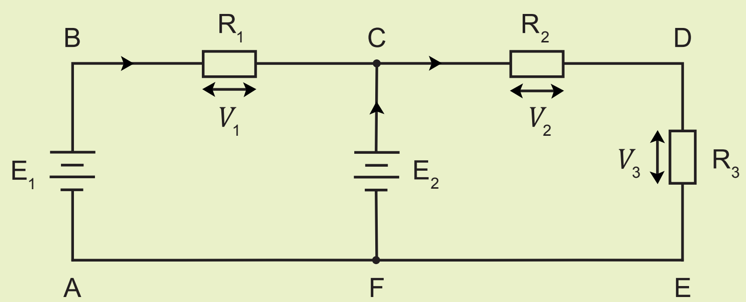


Figure 4.49

(a) Using KVL, form equations for the loops ABCFA and FCDEF.

(b) Given $E_1 = 10$ V, $E_2 = 6.0$ V and $V_2 = 3.6$ V, use the equations obtained in (a) to determine V_1 and V_3.

5 ALTERNATING CURRENTS

How do we describe an alternating current?

When we connect an electrical appliance to the mains supply, a current will flow through the appliance. Do you know that this current actually changes direction periodically at a rate of 50 times every second?

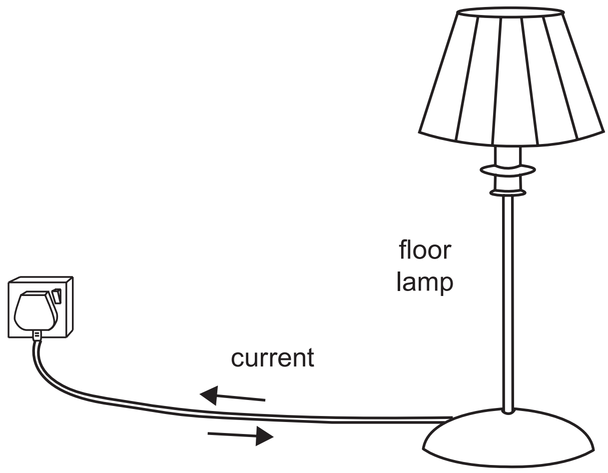


Figure 5.1 The current from the mains supply changes direction periodically

Electrical signals, which are information-carrying currents, may also change direction periodically, although their magnitudes are usually much smaller compared to current from the mains.

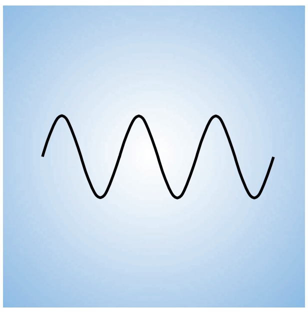


Figure 5.2 An electrical signal that changes direction periodically

Currents that change directions periodically are called alternating currents. In this chapter, we will learn about the characteristics of different types of alternating currents and how to describe them.

5.1 How do we differentiate direct currents from alternating currents?

Learning Outcomes

- Distinguish between direct and alternating currents/voltages (in terms of whether there is a change of direction).
- Give examples of direct currents and alternating currents.
- Show understanding that alternating currents or voltages can be represented by waveforms.

Key Ideas

- Direct currents flow in one direction only but alternating currents change direction periodically.
- Batteries produce direct currents while AC generators produce alternating currents.
- Waveforms are used to represent how voltage and current change with time.

Direct current

A **direct current (DC)** flows only in one direction.

Figure 5.3 shows a circuit with a battery and a resistor. The current in the circuit is a DC as it flows only in the direction indicated by the arrow. Since the terminals of the battery do not change **polarity** (i.e., the positive terminal remains positive while the negative terminal remains negative), the voltage supplied by the battery is a **DC voltage**.

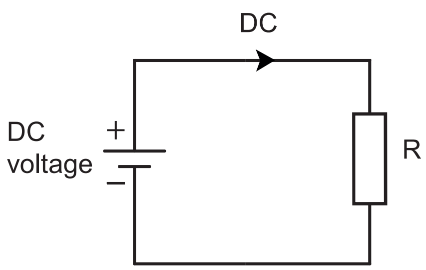


Figure 5.3 Circuit with a battery and a resistor

Figure 5.4 shows the current-time graph of a DC and the voltage-time graph of a DC voltage. Both graphs are horizontal lines, indicating that the voltage and current remain constant throughout. In addition, both graphs are always positive, which indicates that the direction of the current and the polarity of the voltage do not change.

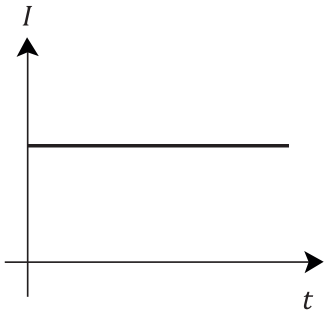


Figure 5.4a Current-time graph of a DC

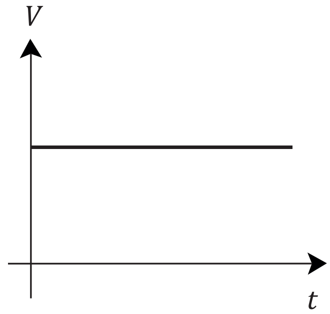


Figure 5.4b Voltage-time graph of a DC voltage

Alternating current

An **alternating current (AC)** changes direction periodically (i.e., at regular time intervals).

Figure 5.5 shows a circuit with a hand-cranked generator and a bulb. Inside the generator, there is a magnet and a coil of wire. The two ends of the coil form terminals A and B. Turning the handle of the crank will turn the coil, which produces a voltage across terminals A and B. Each time the coil passes a point, this voltage switches polarity.

- When terminal A is positive and terminal B is negative, the current flows in the clockwise direction.
- When terminal A is negative and terminal B is positive, the current flows in the anticlockwise direction.

Hence, the current in the circuit is an AC and the voltage supplied by the generator is an **AC voltage**.

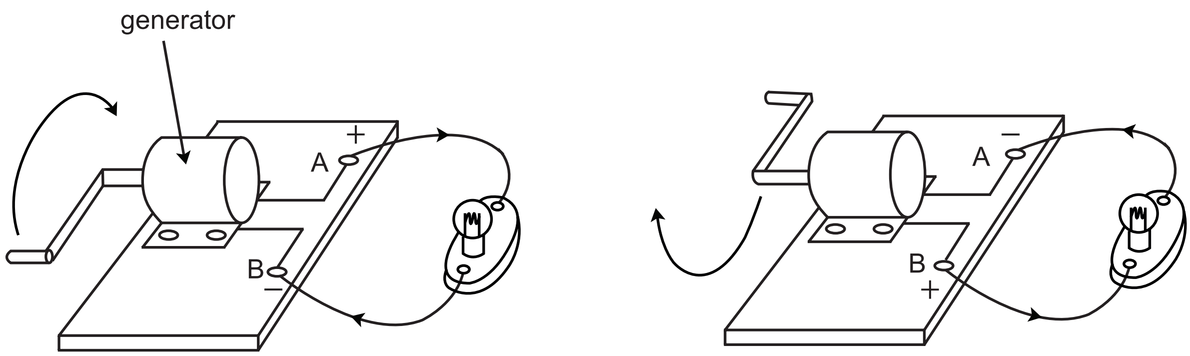


Figure 5.5 Circuit with a hand-cranked generator and a bulb

Figure 5.6 shows the current-time graph of an AC and the voltage-time graph of an AC voltage. Notice that both graphs have positive and negative halves. For the current-time graph, the direction of current is reversed when the graph crosses from one half to the other. For the voltage-time graph, the polarity of the voltage is reversed when the graph crosses from one half to the other.

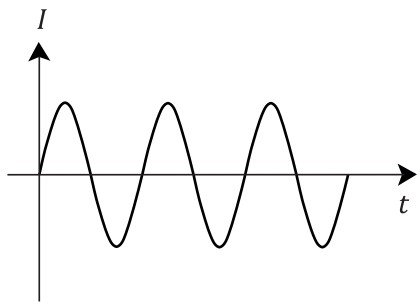


Figure 5.6a Current-time graph of an AC

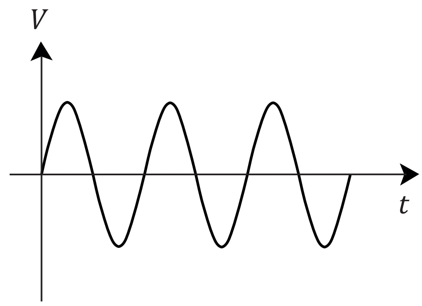


Figure 5.6b Voltage-time graph of an AC voltage

The shape of a current-time or voltage-time graph is called a **waveform**. A waveform is thus a graphical representation of how a current or voltage changes with time.

The symbol of an AC voltage source is shown in Figure 5.7.

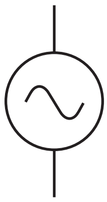


Figure 5.7 Symbol of an AC voltage source

Table 5.1 summarises the differences between DC and AC.

Table 5.1 Differences between DC and AC

	DC	AC
Direction of current	does not change	changes periodically
Polarity of voltage	does not change	changes periodically
Source	batteries	AC generators

5.2 What are the different types of AC waveforms?

Learning Outcome

- Recognise and sketch the common types of AC waveforms (sinusoidal, rectangular, square and triangular).

Key Idea

- The basic types of periodic waveforms are sinusoidal, rectangular, square and triangular.

Periodic waveforms

Figure 5.8 shows four basic types of AC waveforms – sinusoidal, rectangular, square and triangular. They are called **periodic** waveforms as they repeat themselves at regular intervals. One cycle of each waveform has been labelled as shown.

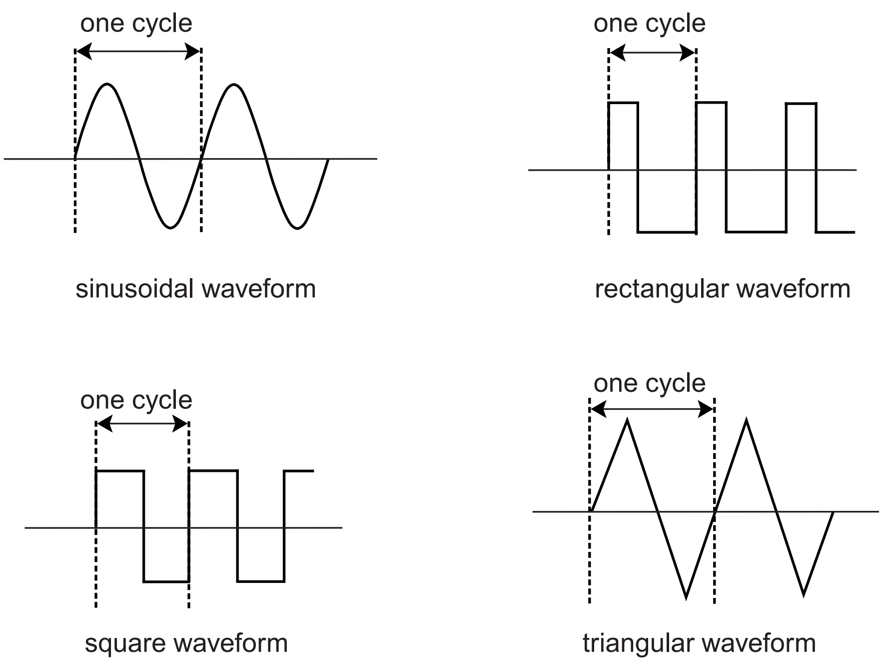


Figure 5.8 Four basic types of AC waveforms

Table 5.2 provides a brief description of the four types of waveforms.

Table 5.2 Description of four basic waveforms

Waveform	Description
Sinusoidal (or sine in short)	A smooth waveform that follows the sine mathematical function. The waveform of the AC produced by the hand-cranked generator in Figure 5.5 is an example.
Rectangular	A waveform which alternates between a maximum and a minimum level. The output produced by an astable multivibrator (see Section 14.2) is an example.
Square	A special type of rectangular waveform which has the same duration at both maximum and minimum levels.
Triangular	A waveform that rises linearly to a maximum point and then falls linearly to a minimum point.

It is important to note that not all periodic waveforms are associated with AC. Figure 5.9 shows the waveform of a periodic square signal. Since the waveform is always positive (i.e., no part of the waveform falls below the horizontal axis), it is a DC signal.

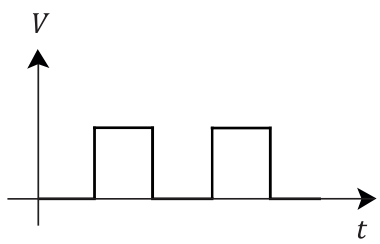


Figure 5.9 Waveform of a periodic square signal

Non-periodic waveforms

Figure 5.10 shows two **non-periodic** waveforms, i.e., waveforms that do not repeat themselves.

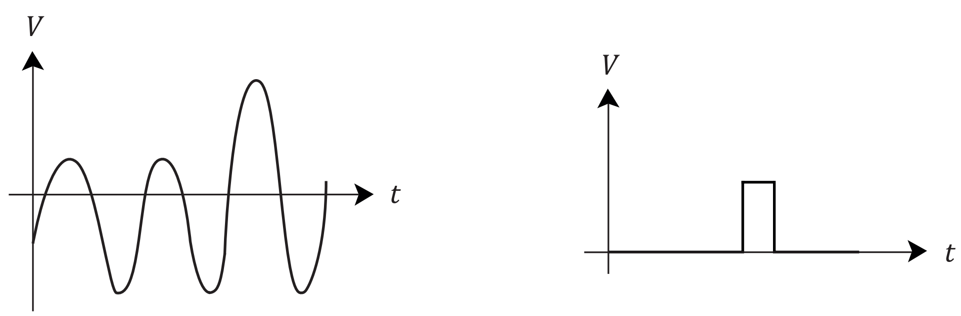


Figure 5.10 Two examples of non-periodic waveforms

Generating periodic signals

Periodic signals are frequently used as input to test if an electronic system is working properly. A convenient way to produce these signals is to use a function generator like the one shown in Figure 5.11.

Figure 5.11 The function generator is used to produce periodic signals

Observing waveforms

It is often necessary to observe the waveforms of input and output signals to find out the workings of an electronic system. An oscilloscope, shown in Figure 5.12, can be used for this purpose. For example, if there is no sound coming out from a loudspeaker, we can use the oscilloscope to check if there is a signal going into the loudspeaker. If so, the loudspeaker may be damaged. If not, the problem could lie with the circuit supplying the signal.

Figure 5.12 The oscilloscope is used to observe waveforms

5.3 How do we describe AC waveforms?

Learning Outcomes

- Determine the DC level, frequency, period, peak and peak-to-peak values of an alternating current/voltage from its waveform.
- Determine the duty cycle of a rectangular waveform.
- Apply the relationship $T = \frac{1}{f}$ to solve related problems.

Key Ideas

- DC level, frequency, period, peak and peak-to-peak values are terms used to describe the characteristics of an AC waveform.
- 'Duty cycle' is a term used to describe a rectangular waveform.

Figure 5.13 shows several terms commonly used to describe a periodic AC waveform.

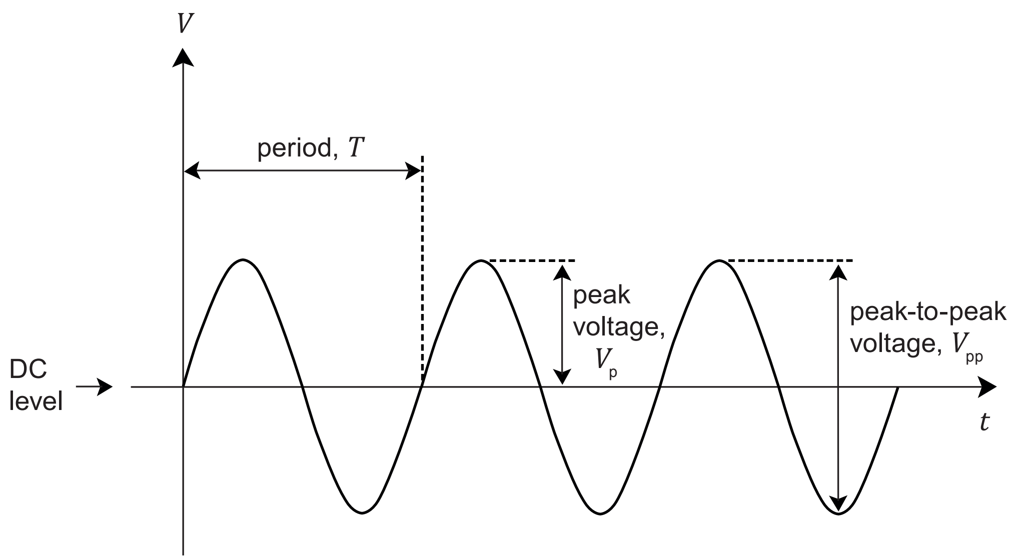


Figure 5.13 Terms used to describe periodic waveforms

- **DC level** is the voltage level which the waveform oscillates about.
- **Peak voltage**, V_p, is the voltage measured from the DC level to the highest point of the waveform.
- **Peak-to-peak voltage**, V_{pp}, is the voltage measured from the lowest to the highest point of the waveform. For waveforms which are symmetrical about the DC level, V_{pp} is twice of V_p.
- **Period**, T, is the time taken to produce one cycle of the waveform.

Another common term (not shown in Figure 5.13) is **frequency**, f, which is the number of complete cycles produced in one second. Frequency can be calculated from the period using the equation below:

$$f = \frac{1}{T}$$

where T = period (in s),
f = frequency (in Hz).

The SI unit for frequency is the **hertz (Hz)**.

A frequency of 50 Hz means that 50 cycles of the waveform are produced in one second.

Conversely, the period, T, can also be calculated from the frequency using the equation:

$$T = \frac{1}{f}$$

Worked Example 5.1

Determine the DC level, peak voltage, peak-to-peak voltage, period and frequency of the periodic AC waveform shown in Figure 5.14.

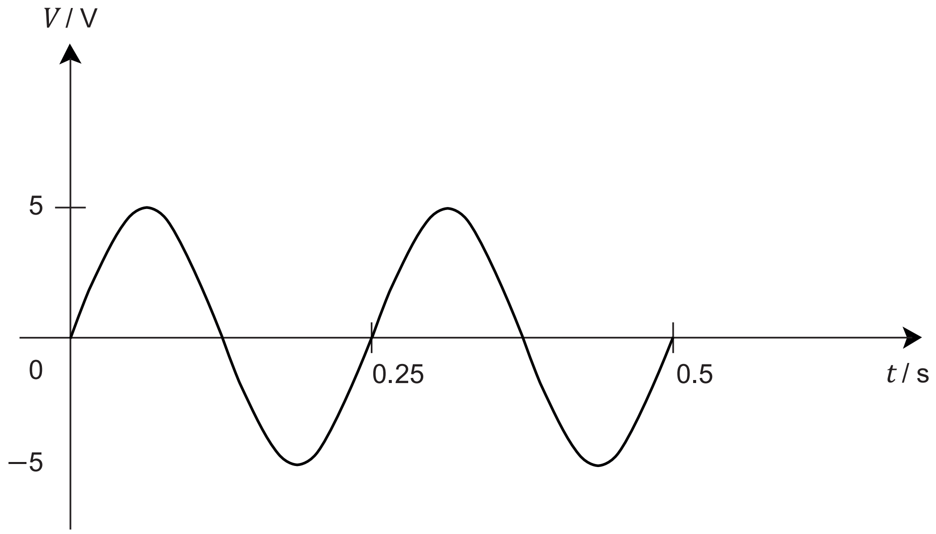


Figure 5.14

Solution

DC level = 0 V
Peak voltage, V_p = 5.0 V
Peak-to-peak voltage, V_{pp} = 10 V
Period, T = 0.25 s

$$\text{Frequency, } f = \frac{1}{T} = \frac{1}{0.25 \text{ s}} = 4.0 \text{ Hz}$$

Worked Example 5.2

Determine the DC level, peak voltage, peak-to-peak voltage, period and frequency of the periodic waveform as shown in Figure 5.15.

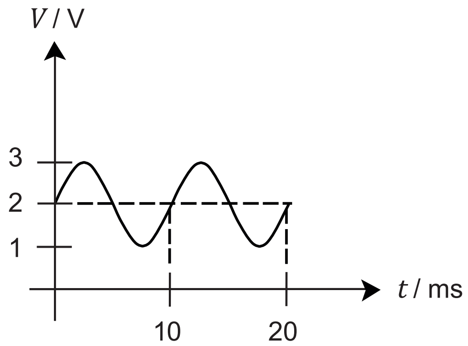


Figure 5.15

Solution

DC level = 2.0 V
Peak voltage, V_p = 1.0 V
Peak-to-peak voltage, V_{pp} = 2.0 V
Period, T = 10 ms

$$\text{Frequency, } f = \frac{1}{T}$$
$$= \frac{1}{(10 \times 10^{-3})\text{ s}}$$
$$= 100 \text{ Hz}$$

Duty cycle of a rectangular waveform

Observe the rectangular waveform shown in Figure 5.16. Within a period, T, the waveform is at the higher voltage level for a duration of t_{high} and at the lower voltage level for a duration of t_{low}. t_{high} is called the 'on time' or 'active time' while t_{low} is called the 'off time' or 'inactive time'.

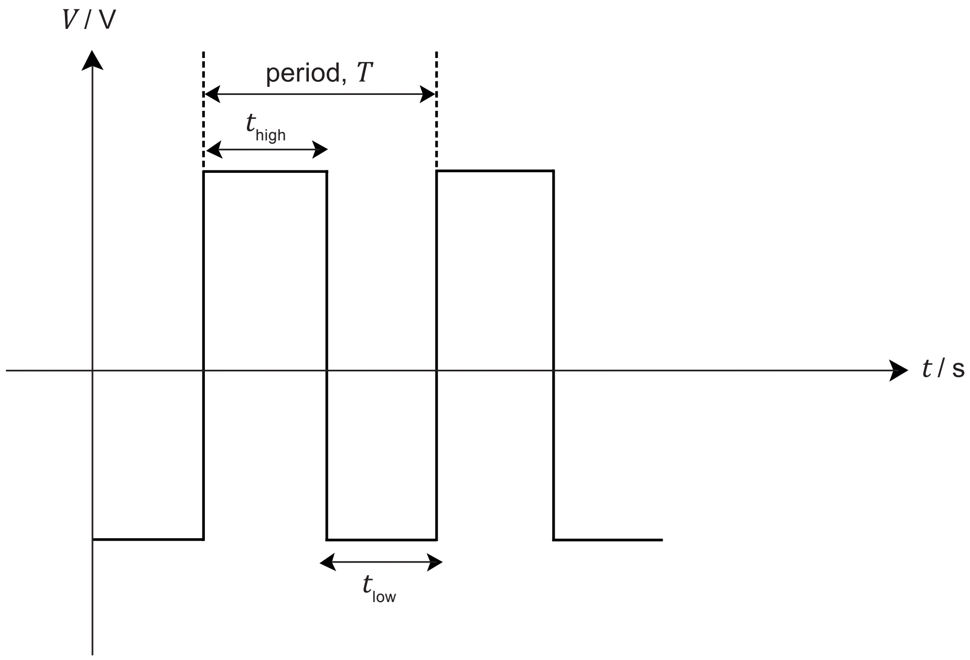


Figure 5.16 Rectangular waveform

A **duty cycle** is the percentage of the period during which the waveform is at the higher voltage level:

$$\text{Duty cycle} = \frac{t_{\text{high}}}{T} \times 100\%$$

If $t_{\text{high}} = t_{\text{low}}$, the duty cycle is 50%, resulting in a square waveform. Figure 5.17 shows three rectangular waveforms with 25%, 50% and 75% duty cycles, respectively.

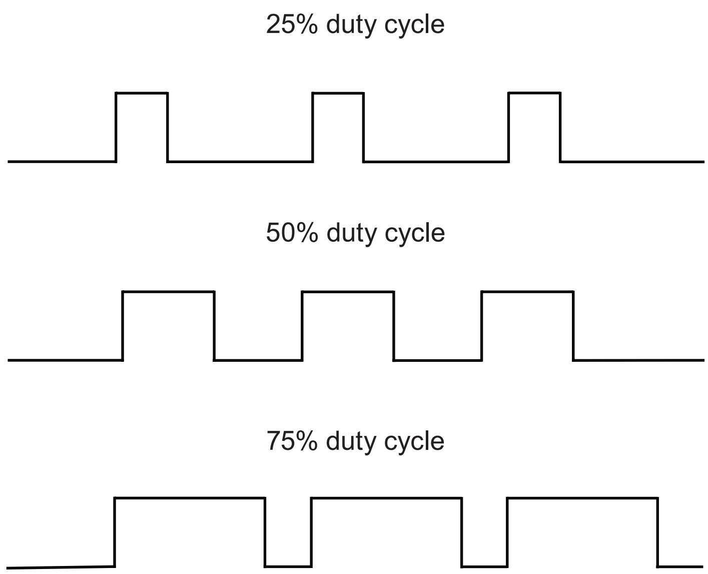


Figure 5.17 From top: rectangular waveforms with 25%, 50% and 75% duty cycles

We can control the power supplied to a device by adjusting the duty cycle of a rectangular voltage supply. Figure 5.18 shows how the power supplied to a motor is varied by changing the duty cycle of the voltage supplied to it.

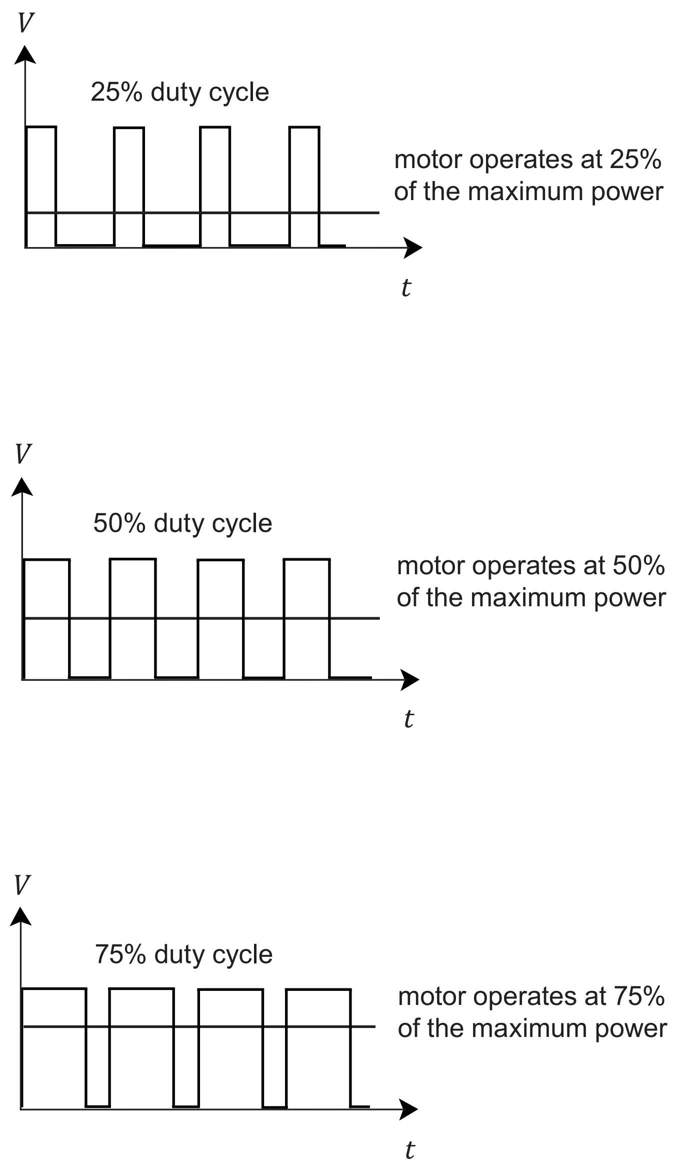


Figure 5.18 Changing the duty cycle of the voltage supplied to a motor changes the power supplied to it

Worked Example 5.3

Calculate the duty cycle of the rectangular waveform shown in Figure 5.19.

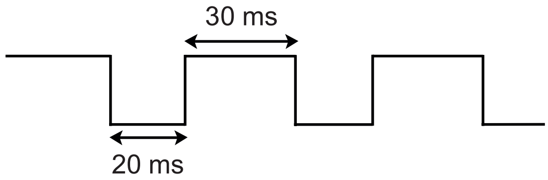


Figure 5.19

Solution

$$\text{Duty cycle} = \frac{t_{\text{high}}}{T} \times 100\%$$
$$= \frac{30 \text{ ms}}{30\text{ms} + 20 \text{ ms}} \times 100\%$$
$$= 60\%$$

Review Questions 5.3

1. Name the types of periodic waveforms shown in Figure 5.20.

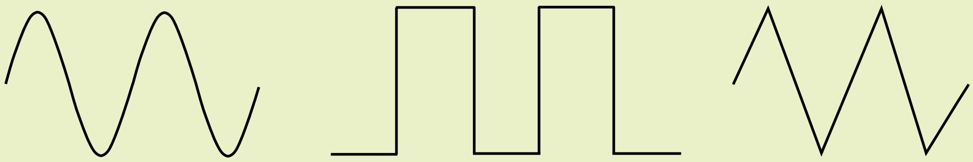


Figure 5.20

2. Figure 5.21 shows a sinusoidal AC waveform.

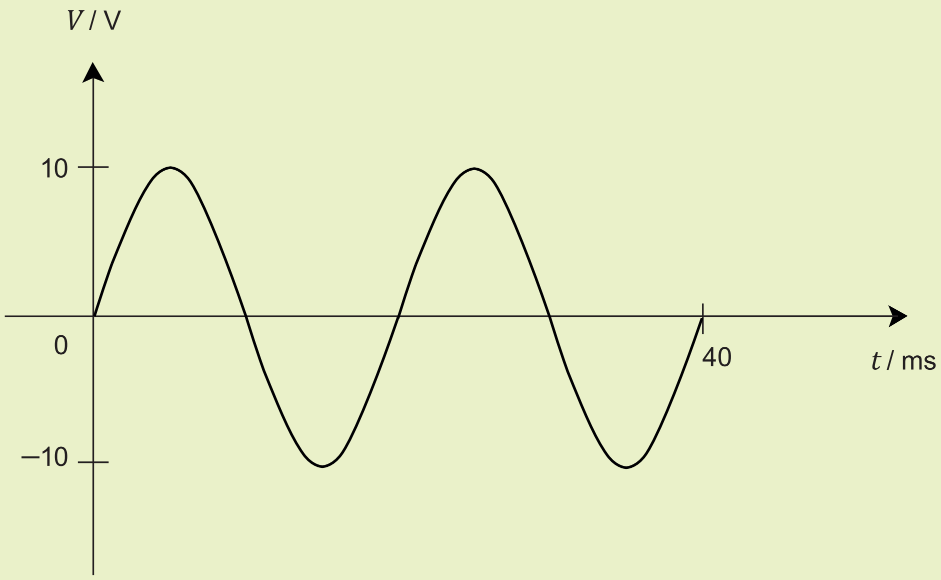


Figure 5.21

Determine

(a) the peak value, V_{peak};

(b) the peak-to-peak value, V_{pp};

(c) the period, T; and

(d) the frequency, f.

3. Calculate the duty cycle of the following rectangular waveforms:

(a)

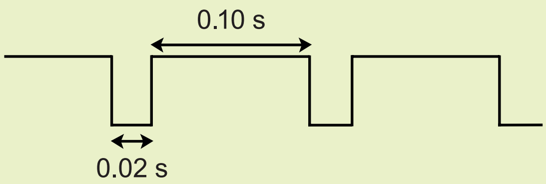


Figure 5.22

(b)

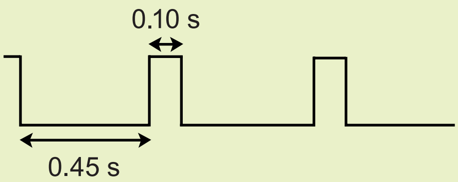


Figure 5.23

6 CAPACITORS

What are the characteristics of capacitors that make them useful?

Like the pail in Figure 6.1a which is used to hold water, capacitors are used to store electric charges. Interestingly, some types of capacitors like those shown in Figure 6.1b look like pails themselves, although they are usually much smaller in size.

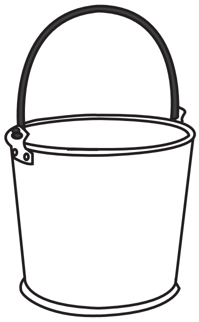


Figure 6.1a A pail holds water

Figure 6.1b Capacitors store electric charges

Capacitors are frequently used in electronic circuits to store electrical charges, create time delays, reduce fluctuation in voltage levels and pass or block signals with certain frequencies. In this chapter, we will learn about the characteristics of capacitors that enable them to perform these functions.

6.1 How does a capacitor work?

Learning Outcome

- Describe the structure and working principles of a basic capacitor.

Key Ideas

- A capacitor is made up of two metal plates separated by a dielectric material.
- When a capacitor is connected to a battery, the capacitor starts charging and a voltage is set up between its two metal plates.

Structure of a capacitor

Figure 6.2 shows the basic structure of a **capacitor**, which consists of two metal plates separated by a thin layer of insulating material called a **dielectric**.

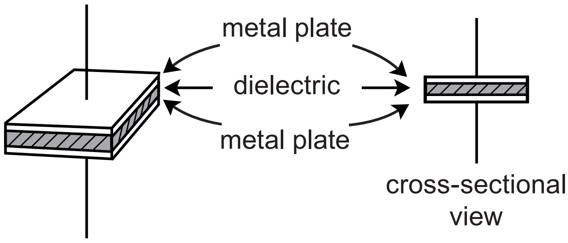


Figure 6.2 Basic structure of a capacitor

Charging a capacitor

When a capacitor is connected to a battery as shown in Figure 6.3, electrons will flow from the upper metal plate of the capacitor to the positive terminal of the battery and from the negative terminal of the battery to the lower metal plate of the capacitor. This redistribution of electrons causes the upper metal plate to become positively charged due to a shortage of electrons and the lower plate to become negatively charged due to an excess of electrons. This process is called **charging**.

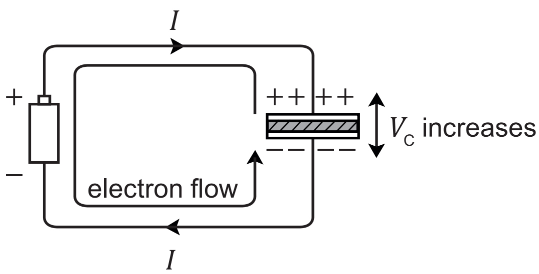


Figure 6.3 Charging a capacitor

As explained in Chapter 2, the direction of electron flow is opposite to that of conventional current. In other words, while the capacitor in Figure 6.3 is charging, there is a current that flows from the lower plate of the capacitor to the battery to the upper plate.

As the capacitor charges, the voltage between its two metal plates, V_C, increases. When V_C reaches the same voltage as the battery, the voltages of the capacitor and the battery cancel each other out and the current becomes zero. At this stage, the capacitor is said to be fully charged and acts like an open circuit.

The work done by the battery to build up the charges at the metal plates is stored as potential energy. This potential energy is released when the capacitor is discharged.

Discharging a capacitor

If the battery in Figure 6.3 is replaced with a load (such as a light bulb) after the capacitor becomes fully charged, the electrons will flow in the reverse direction as shown in Figure 6.4. This causes the amount of charge stored on the plates of the capacitor to decrease and the process is called **discharging**.

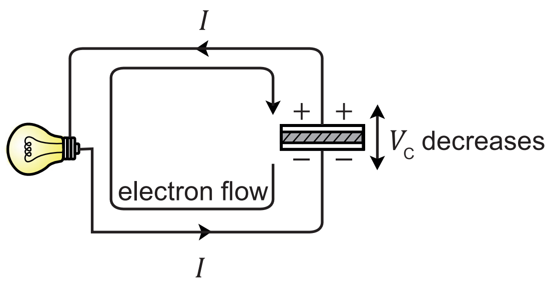


Figure 6.4 Discharging a capacitor

As the capacitor discharges, V_C decreases. When V_C reaches zero, the current becomes zero. At this stage, the capacitor is said to be fully discharged.

Safety precautions when charging and discharging capacitors

It is important to note that without a discharge path, a capacitor can hold on to electric charges (and thus a voltage across its plates) for a long time and may endanger anyone working on the circuit. This is especially so if a capacitor is charged to a high voltage.

To discharge a capacitor, we should not simply short circuit the two metal plates, as this will create a large current spike which can damage the capacitor. Instead, we should connect a resistor between the two metal plates.

Review Questions 6.1

1. Describe the basic structure of a capacitor.
2. Describe the flow of electrons when a capacitor is charging and when it is discharging.

6.2 What determines the amount of charge a capacitor can store?

Learning Outcomes

- Define capacitance and state its SI unit.
- Recall and apply the equation $C = \frac{Q}{V}$ to solve problems.

Key Ideas

- The capacitance of a capacitor determines the amount of charge it can store at a particular voltage level.
- Capacitance can be calculated using the equation $C = \frac{Q}{V}$.

Capacitance

The **capacitance** of a capacitor determines the amount of charge it can store at a particular voltage level – the larger the capacitance of a capacitor, the larger the amount of charge it can store.

The relationship between capacitance, charge and voltage can be expressed as the equation:

$$C = \frac{Q}{V}$$

where C = capacitance (in F),
Q = charge stored (in C),
V = voltage (in V).

The SI unit of capacitance is the **farad (F)**. A 1 F capacitor is able to store 1 C of charge per unit voltage.

The capacitance of a capacitor is affected by:

- the area of the metal plates (the larger the area, the larger the capacitance);
- the distance separating the metal plates (the larger the distance, the smaller the capacitance); and
- the material used for the dielectric (the capacitance depends on a property of the material known as its permittivity).

Worked Example 6.1

The capacitor in Figure 6.5 stores 20 μC of charge when it is fully charged. Calculate the capacitance of the capacitor.

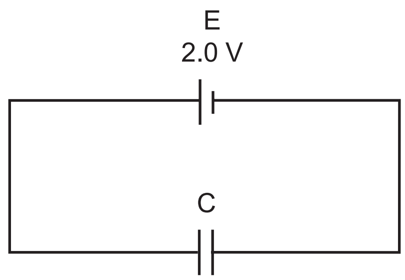


Figure 6.5

Solution

When the capacitor is fully charged, the voltage across the capacitor will be 2.0 V.

$$C = \frac{Q}{V}$$

$$= \frac{20\ \mu\text{C}}{2.0\ \text{V}}$$

$$= 10\ \mu\text{F}$$

Review Questions 6.2

1. A 4.7 μF capacitor is connected to a 6.0 V DC source. Calculate the charge stored in the capacitor when it is fully charged.

2. A 220 μF capacitor stores 2.8×10^{-5} C of electric charge. Calculate the voltage across the plates of the capacitor.

3. A 3300 μF capacitor is connected as shown in Figure 6.6.

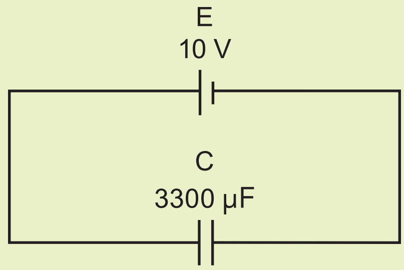


Figure 6.6

When it is fully charged,

(a) state the voltage across the capacitor; and

(b) calculate the amount of electric charge stored in the capacitor.

6.3 What are the different types of capacitors?

Learning Outcomes

- Recognise and give examples of polarised and non-polarised capacitors.
- Explain why capacitors have a maximum working voltage.

Key Ideas

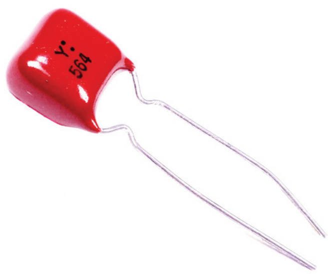
- Capacitors can broadly be classified into polarised and non-polarised capacitors.
- The capacitance of a capacitor can be obtained from its label.
- The voltage applied to a capacitor should not exceed its maximum working voltage.

Types of capacitors

Capacitors can broadly be classified as **non-polarised** and **polarised**. Figures 6.7a and 6.7b show some examples of non-polarised and polarised capacitors, respectively.

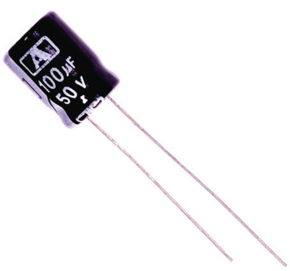
mica

ceramic



polyester film

Figure 6.7a Examples of non-polarised capacitors



aluminium electrolytic

tantalum electrolytic

Figure 6.7b Examples of polarised capacitors

Non-polarised capacitors have two connecting leads of the same length. These capacitors can be connected in any direction without affecting its operation.

Polarised capacitors come with two connecting leads of different lengths. The best method to identify the positive and negative terminals of a polarised capacitor is to look out for the '+' or '–' sign labelled on it, e.g., the negative terminal of the polarised capacitor in Figure 6.8 can be identified by the '–' sign.

Another method is to look out for the longer lead, which is the positive terminal. However, this method only works if the leads have not already been trimmed. The positive terminal of a polarised capacitor should be connected to a higher voltage than its negative terminal.

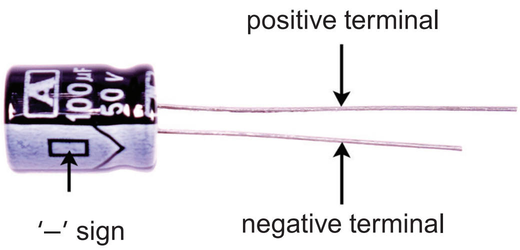


Figure 6.8 Identifying the terminals of a polarised capacitor

The symbols for non-polarised and polarised capacitors are shown in Figure 6.9a and Figure 6.9b, respectively.

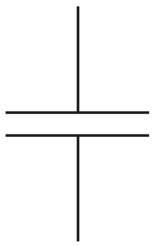


Figure 6.9a Symbol of a non-polarised capacitor

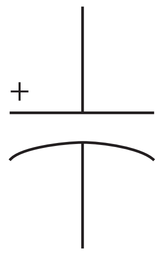


Figure 6.9b Symbol of a polarised capacitor

The differences between the two types of capacitors are summarised in Table 6.1.

Table 6.1 Differences between non-polarised and polarised capacitors

	Non-polarised	**Polarised**
Capacitance	usually have smaller capacitances	usually have larger capacitances
Polarity	no fixed positive or negative terminals	have fixed positive and negative terminals
Physical size	typically smaller in size	typically larger in size

Common capacitor values

Like resistors, capacitors come in a range of standard values as shown in Table 6.2.

Table 6.2 Base capacitances for the E6, E12 and E24 series

<table>
<tr><th>E6 series
(20% tolerance)</th><th>E12 series
(10% tolerance)</th><th>E24 series
(5% tolerance)</th></tr>
<tr><td rowspan="4">1.0</td><td rowspan="2">1.0</td><td>1.0</td></tr>
<tr><td>1.1</td></tr>
<tr><td rowspan="2">1.2</td><td>1.2</td></tr>
<tr><td>1.3</td></tr>
<tr><td rowspan="4">1.5</td><td rowspan="2">1.5</td><td>1.5</td></tr>
<tr><td>1.6</td></tr>
<tr><td rowspan="2">1.8</td><td>1.8</td></tr>
<tr><td>2.0</td></tr>
<tr><td rowspan="4">2.2</td><td rowspan="2">2.2</td><td>2.2</td></tr>
<tr><td>2.4</td></tr>
<tr><td rowspan="2">2.7</td><td>2.7</td></tr>
<tr><td>3.0</td></tr>
<tr><td rowspan="4">3.3</td><td rowspan="2">3.3</td><td>3.3</td></tr>
<tr><td>3.6</td></tr>
<tr><td rowspan="2">3.9</td><td>3.9</td></tr>
<tr><td>4.3</td></tr>
<tr><td rowspan="4">4.7</td><td rowspan="2">4.7</td><td>4.7</td></tr>
<tr><td>5.1</td></tr>
<tr><td rowspan="2">5.6</td><td>5.6</td></tr>
<tr><td>6.2</td></tr>
<tr><td rowspan="4">6.8</td><td rowspan="2">6.8</td><td>6.8</td></tr>
<tr><td>7.5</td></tr>
<tr><td rowspan="2">8.2</td><td>8.2</td></tr>
<tr><td>9.1</td></tr>
</table>

Like in the case of resistors, we can also multiply the base values in Table 6.2 by different powers of 10. For example, the base value of ‘2.2’ indicates that we can obtain capacitors with capacitances of 2.2 pF, 22 pF, 220 pF, 2.2 nF, 22 nF, 220 nF, 2.2 μF, and so on.

Reading capacitor values

The capacitance of larger-bodied capacitors can usually be read directly from their label. For example, the capacitance of the electrolytic capacitor in Figure 6.10 is 100 μF.

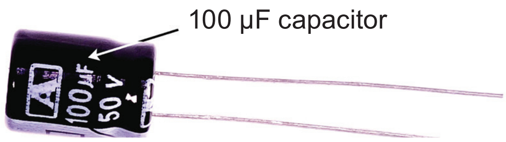


Figure 6.10 The capacitance is usually indicated on the label of a larger-bodied capacitor

For smaller-bodied capacitors, the capacitance may be indicated with two or three digits. Figures 6.11 and 6.12 show how we can interpret the printed values on these capacitors:

- If there are two digits, the number formed by the two digits is the capacitance in pF. For example, if '47' is printed, the capacitance is 47 pF.

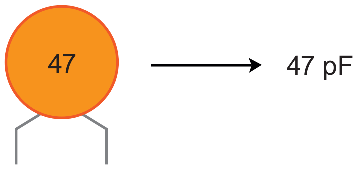


Figure 6.11 Interpreting two-digit capacitances

- If there are three digits, the third digit indicates the number of zeros to be added behind the first two digits. The resulting value is the capacitance in pF. For example, if '472' is printed, the capacitance is 4700 pF.

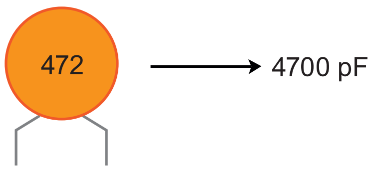


Figure 6.12 Interpreting three-digit capacitances

Table 6.3 shows some more examples.

Table 6.3 Interpreting three-digit capacitances

Marking on capacitor	Capacitance
471	470 pF
472	4700 pF
473	47 000 pF
474	470 000 pF
475	4 700 000 pF

Maximum working voltage of capacitors

Every capacitor has a **maximum working voltage**. The voltage applied across a capacitor should not exceed this value, otherwise the capacitor may be damaged. Figure 6.13 shows an electrolytic capacitor with a maximum working voltage of 50 V indicated on its label.

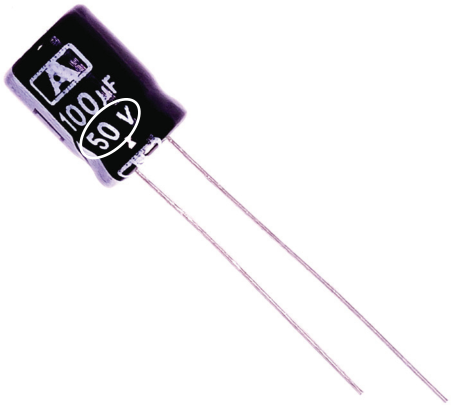


Figure 6.13 A capacitor with a maximum working voltage of 50 V

Review Questions 6.3

1. Explain the difference between polarised and non-polarised capacitors in terms of their physical appearance.
2. Explain how to determine the polarity of a polarised capacitor.
3. Determine the capacitance of each of the three capacitors shown in Figure 6.14.

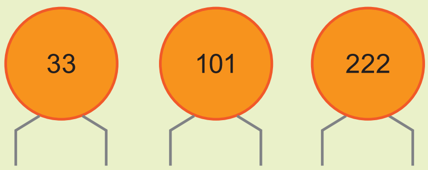


Figure 6.14

6.4 How do we determine the effective capacitance when capacitors are connected in series or in parallel?

Learning Outcome

- Apply the relevant equations for capacitors connected in series and in parallel to solve related problems.

Key Ideas

- For capacitors in series, the effective capacitance can be calculated using $\frac{1}{C_{\text{eff}}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots$
- For capacitors in parallel, the effective capacitance can be calculated using $C_{\text{eff}} = C_1 + C_2 + C_3 + \ldots$

Capacitors in series

Figure 6.15 shows three capacitors connected in series.

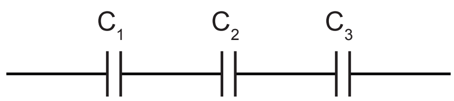


Figure 6.15 Capacitors in series

The effective capacitance of capacitors connected in series can be calculated using the equation:

$$\frac{1}{C_{\text{eff}}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots$$

where C_{eff} = effective capacitance (in F).

Worked Example 6.2

Calculate the effective capacitance for the circuit shown in Figure 6.16.

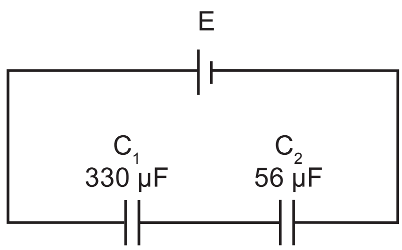


Figure 6.16

Solution

$$\frac{1}{C_{eff}} = \frac{1}{C_1} + \frac{1}{C_2}$$

$$= \frac{1}{(330 \times 10^{-6}\ \text{F})} + \frac{1}{(56 \times 10^{-6}\ \text{F})}$$

$$C_{eff} = 48 \times 10^{-6}\ \text{F}$$
$$= 48\ \mu\text{F}$$

Capacitors in parallel

Figure 6.17 shows three capacitors connected in parallel.

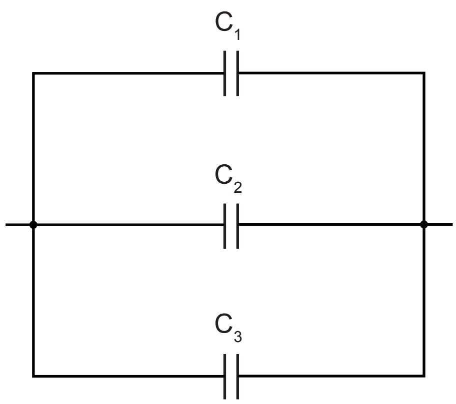


Figure 6.17 Capacitors in parallel

The effective capacitance of capacitors connected in parallel can be calculated using the equation:

$$C_{eff} = C_1 + C_2 + C_3 + \dots$$

where C_{eff} = effective capacitance (in F).

Worked Example 6.3

Calculate the effective capacitance of the circuit shown in Figure 6.18.

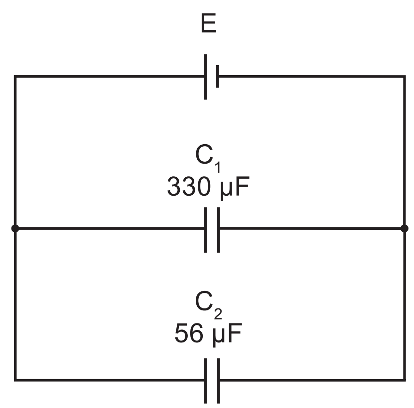


Figure 6.18

Solution

$$\begin{aligned} C_{eff} &= C_1 + C_2 \\ &= 330\ \mu F + 56\ \mu F \\ &= 386\ \mu F \end{aligned}$$

Review Question 6.4

1. Calculate the effective capacitance for each of the arrangements below:

   (a)

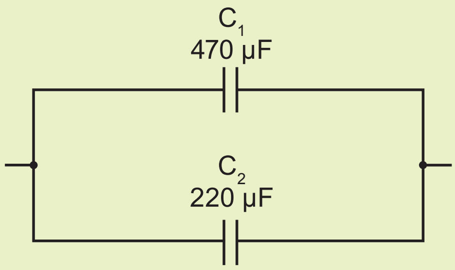


Figure 6.19

   (b)

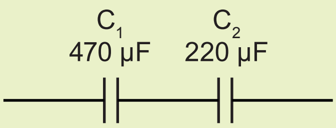


Figure 6.20

   (c)

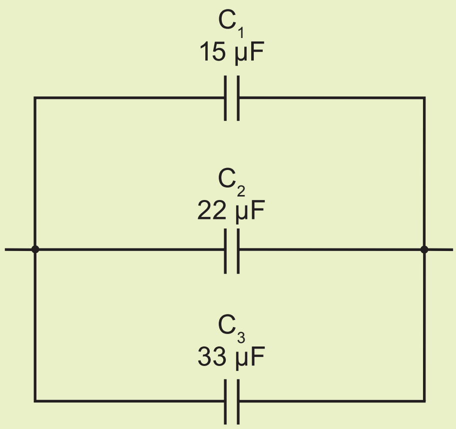


Figure 6.21

6.5 How do we determine the charging and discharging time of a capacitor in a resistor-capacitor circuit?

Learning Outcomes

- Calculate the time constant of a simple resistor-capacitor (RC) circuit using $\tau = RC$.
- Estimate the time for a capacitor to be charged to and discharged by $\frac{2}{3}$ and 100% of the maximum voltage.

Key Ideas

- The charging and discharging times of a capacitor in an RC circuit are affected by the resistance of the resistor and the capacitance of the capacitor.
- The time constant of an RC circuit is expressed by the equation $\tau = RC$.
- During charging, after a period of time equal to τ and 5τ, the voltage across a capacitor will reach approximately $\frac{2}{3}$ and 99.3% of the applied voltage, respectively.
- During discharging, after a period of time equal to τ and 5τ, the voltage across a capacitor will reach approximately $\frac{1}{3}$ and 0.7% of the initial voltage, respectively.

Charging and discharging a capacitor in an RC circuit

In Section 6.1, we learnt about charging a capacitor that is directly connected to a DC source (see Figure 6.3). In most cases, this will cause the capacitor to become fully charged almost instantaneously. By adding a resistor in series with the capacitor, we can prolong the time taken to charge (and discharge) the capacitor, allowing us to create time delays of specific durations.

RC circuits

RC circuits are circuits that consist of at least one resistor and one capacitor. Figure 6.22 shows a simple RC circuit. Let us assume that the capacitor is not charged and $V_C = 0$.

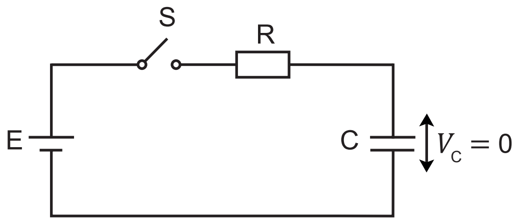


Figure 6.22 An RC circuit

Charging a capacitor in an RC circuit

When the switch is closed, a current will flow in the circuit as shown in Figure 6.23. This causes the capacitor to start charging and V_C to increase.

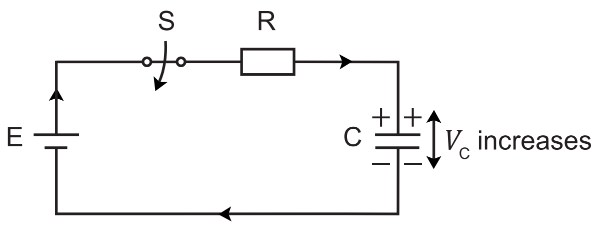


Figure 6.23 Charging a capacitor in an RC circuit

This charging process continues until the capacitor is fully charged and V_C is equal to E. The time needed to complete the process is dependent on both the resistance of the resistor and the capacitance of the capacitor.

- The larger the resistance, the smaller the current in the RC circuit. Since the electric charges are moving at a slower rate, this increases the time needed to charge the capacitor.
- The larger the capacitance, the larger the amount of charge needed to increase V_C by 1 V. This increases the time needed to charge the capacitor.

Figure 6.24 shows a graph of V_C against time (the equation of the graph is beyond the scope of this course). This is called the **charging graph** of a capacitor. Notice that V_C does not increase linearly with time. Instead, V_C increases rapidly at first but slows down as it approaches the value of the applied voltage (E, in the case of Figure 6.23).

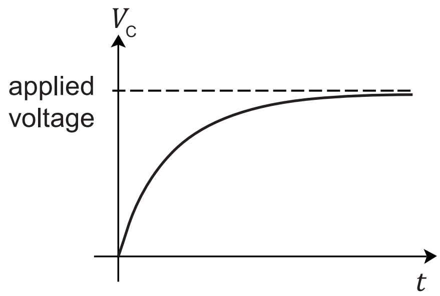


Figure 6.24 Charging graph of a capacitor

Discharging a capacitor in an RC circuit

When the battery in Figure 6.23 is replaced with a short circuit, the capacitor starts to discharge and a current will flow in the opposite direction as shown in Figure 6.25. As the capacitor discharges, V_C decreases.

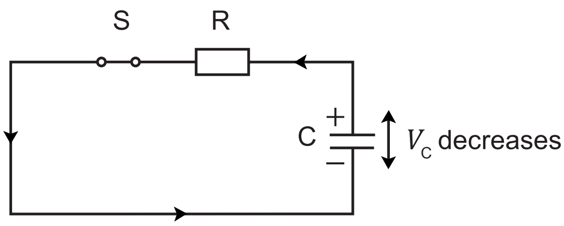


Figure 6.25 Discharging a capacitor in an RC circuit

This discharging process continues until the capacitor is fully discharged and V_C is zero. Similar to the charging process, the time needed to complete the process is dependent on both the resistance of the resistor and the capacitance of the capacitor.

- The larger the resistance, the smaller the current flowing in the RC circuit. Since the electric charges are moving at a slower rate, this increases the time needed to discharge the capacitor.
- The larger the capacitance, the larger the amount of charge needed to be removed to decrease V_C by 1 V. This increases the time needed to discharge the capacitor.

The **discharging graph** of a capacitor is shown in Figure 6.26. Notice that V_C does not decrease linearly with time. Instead, V_C decreases rapidly at first but slows down as it approaches zero.

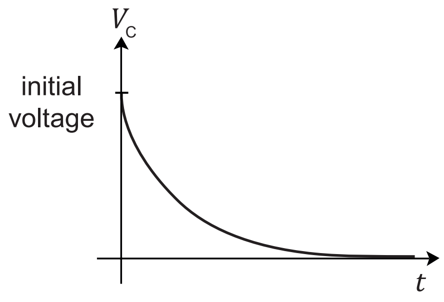


Figure 6.26 Discharging graph of a capacitor

Time constant

The **time constant**, τ (pronounced 'tau'), of an RC circuit helps us determine the charging and discharging time of the capacitor. The time constant can be calculated using the equation:

$$\tau = RC$$

where τ = time constant (in s),
R = resistance of resistor (in Ω),
C = capacitance of capacitor (in F).

Worked Example 6.4

Calculate the time constant of the RC circuit shown in Figure 6.27.

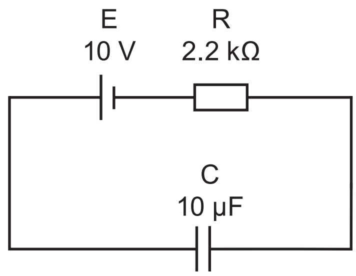


Figure 6.27

Solution

$\tau = RC$
$= (2.2 \times 10^{3}\ \Omega) \times (10 \times 10^{-6}\ \text{F})$
$= 0.022$ s
$= 22$ ms

Figure 6.28 shows a charging graph with τ and 5τ marked on the time axis.

- After τ (one time constant), V_C will reach approximately $\frac{2}{3}$ of the applied voltage.
- After 5τ (five time constants), V_C will reach approximately 99.3% of the applied voltage. We can consider the capacitor to be fully charged at this point.

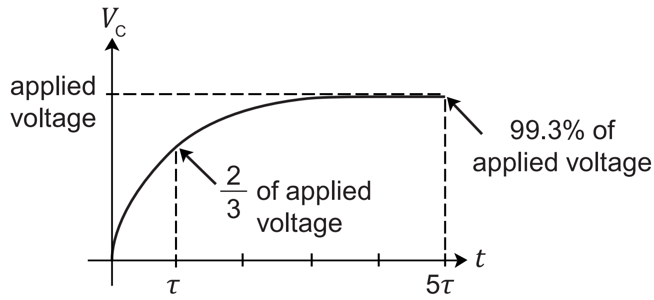


Figure 6.28 Charging graph marked with intervals of τ

Worked Example 6.5

For the RC circuit shown in Figure 6.29,

(a) calculate the time constant;

(b) estimate the voltage across the capacitor one time constant after the switch is closed (assume that the capacitor is fully discharged at the start); and

(c) estimate the time required for the capacitor to be fully charged.

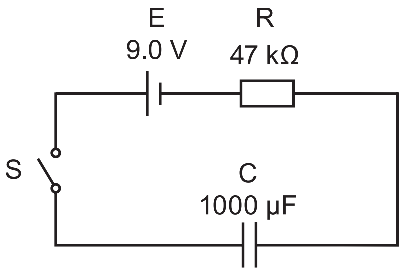


Figure 6.29

Solution

(a) $\tau = RC$
$= (47 \times 10^3\ \Omega) \times (1000 \times 10^{-6}\ \text{F})$
$= 47\ \text{s}$

(b) After τ, the voltage across the capacitor will be approximately $\frac{2}{3}$ of 9.0 V, which is 6.0 V.

(c) After 5τ, the capacitor is considered fully charged.

Time taken $= 5 \times \tau$
$= 5 \times 47\ \text{s}$
$= 235\ \text{s}$

Figure 6.30 shows the discharging graph with τ and 5τ marked on the time axis.

- After τ, V_C will reach approximately $\frac{1}{3}$ of the initial voltage.
- After 5τ, V_C will drop to approximately 0.7% of the initial voltage. We can consider the capacitor fully discharged at this point.

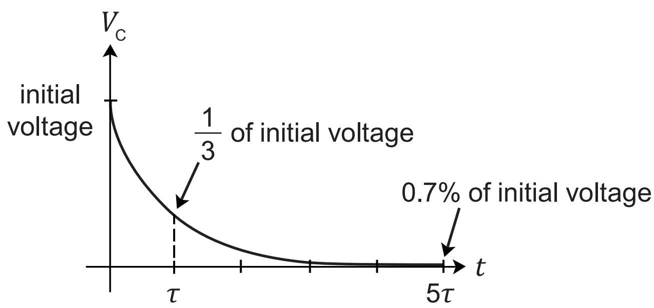


Figure 6.30 Discharging graph marked with intervals of τ

Worked Example 6.6

An RC circuit is connected as shown in Figure 6.31a. When the voltage across the capacitor becomes 10 V, the battery is replaced with a short circuit as shown in Figure 6.31b.

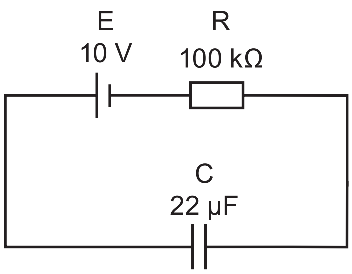


Figure 6.31a

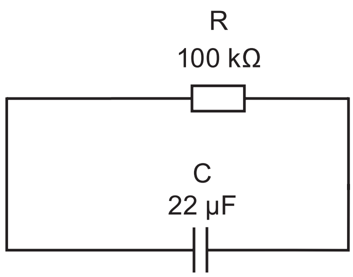


Figure 6.31b

(a) Calculate the time constant of the RC circuit.

(b) Estimate the capacitor voltage one time constant later.

(c) Estimate the time required for the capacitor to be fully discharged.

Solution

(a) $\tau = RC$

$= (100 \times 10^{3}\ \Omega) \times (22 \times 10^{-6}\ \text{F})$

$= 2.2\ \text{s}$

(b) After τ, the voltage across the capacitor will be approximately $\frac{1}{3}$ of 10 V, which is 3.3 V.

(c) After 5τ, the capacitor is considered fully discharged.

Time taken $= 5 \times \tau$

$= 5 \times 2.2\ \text{s}$

$= 11\ \text{s}$

Applications of capacitors

Capacitors are commonly used to keep track of time and create time delays.

Suppose we need to design a circuit that is able to produce a sound 25 s after being activated by a switch. We can set up an RC circuit like the one shown in Figure 6.32 to form a timing circuit. The output of this timing circuit is fed into another subsystem that will produce a sound when the input is more than 4.0 V.

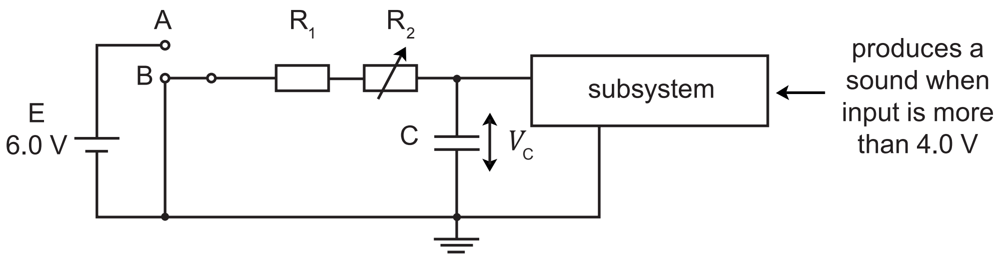


Figure 6.32 RC timing circuit

Since the sound-producing subsystem is connected in parallel with the capacitor, we need V_C to reach 4.0 V after 25 s for a sound to be played. Since 4.0 V is also $\frac{2}{3}$ of the e.m.f. of the battery (6.0 V), the time constant of the RC circuit should be 25 s.

As 25 s is considered a long duration for RC circuits, we can choose a 680 μF capacitor, which has a fairly large capacitance (the larger the capacitance of a capacitor, the longer the time needed to charge it). We then calculate R, the overall resistance of the circuit:

$$\tau = RC$$
$$25\text{ s} = R \times 680 \times 10^{-6}\text{ F}$$
$$R = 36.8\text{ k}\Omega$$

To obtain 36.8 kΩ, we can choose a 33 kΩ resistor from the E24 series for R_1 and connect it in series with a 0–5 kΩ variable resistor for R_2. R_2 is then adjusted until an overall resistance of 36.8 kΩ is obtained.

The charging and discharging of capacitors in RC circuits will be discussed again in Chapter 14, where we will learn about a device called the 555 timer.

Besides keeping track of time, capacitors can also be used as voltage-smoothing capacitors (see Section 7.6) and coupling capacitors (see Section 9.3).

Review Questions 6.5

1. State two factors that affect the charging and discharging time of a capacitor in an RC circuit.

2. Describe how the time constant of an RC circuit can be used to estimate the charging and discharging time of a capacitor in the RC circuit.

3. An RC circuit is connected as shown in Figure 6.33.

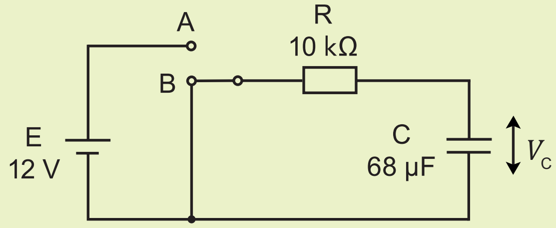


Figure 6.33

(a) Calculate the time constant of the RC circuit.

(b) Estimate the time taken to charge the capacitor to 8.0 V when the switch is moved to position A.

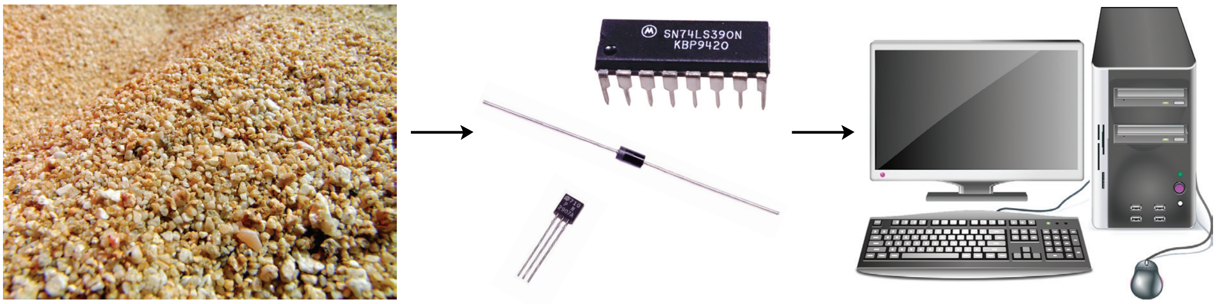
(c) Estimate the time taken to fully charge the capacitor.

7 SEMICONDUCTOR DIODES

How do we select and use a suitable semiconductor diode?

When you use electronic products such as computers, you would hardly think that they are related to sand. Yet the key components of computers are made from silicon, which is one of the main elements of sand. As the second most abundant element on earth after oxygen, silicon constitutes around 25% of the weight of the Earth's crust and is easily available. Silicon is used to make electronic components because of its unique electrical property – its electrical conductivity lies between that of electrical conductors and insulators. Thus, silicon is known as a semiconductor.

Silicion and other types of semiconductors are used to make a wide range of electronic products such as those shown in Figure 7.1.



semiconductors (e.g., silicon which is found in sand) | semiconductor components | electronic products

Figure 7.1 Semiconductors and their products

The simplest semiconductor component is the semiconductor diode. A common type of semiconductor diode is the light-emitting diode (LED), which is used in traffic lights and, increasingly, in lighting for homes.

Figure 7.1a LED traffic lights

Figure 7.2b LED lamp used in homes

In this chapter, we will learn more about semiconductors and several types of diodes.

7.1 What is the structure of a semiconductor diode?

Learning Outcomes

- State that there are two types of semiconductors: n-type and p-type.
- Describe the basic structure of the PN junction diode.

Key Ideas

- We can obtain n-type and p-type semiconductors by adding impurities to a pure semiconductor.
- A PN junction diode is formed by joining a p-type semiconductor with an n-type semiconductor.

Semiconductor diodes are two-terminal electronic components. Figure 7.3 shows several types of semiconductor diodes.

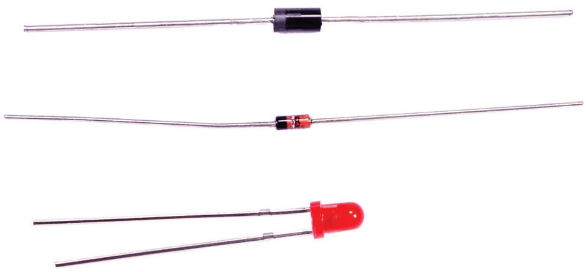


Figure 7.3 Semiconductor diodes

To understand how semiconductor diodes work, we need to first understand the term 'semiconductor'. **Semiconductors** are materials with an electrical conductivity that lies between that of electrical conductors and insulators. In other words, semiconductors can conduct electricity better than insulators but not as well as conductors. Figure 7.4 compares the conductivity of good insulators, semiconductors and good conductors.

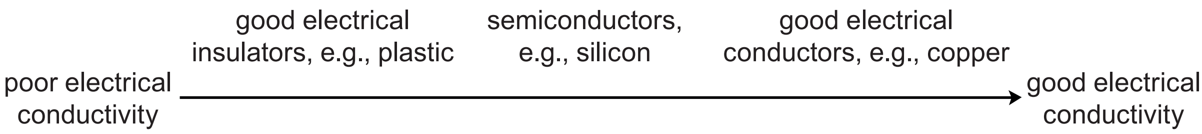


Figure 7.4 Conductivity of insulators, semiconductors and conductors

Three common semiconductors are silicon, germanium and gallium arsenide. Each of these has unique characteristics that make them suitable for different applications. For example, silicon has good temperature characteristics and is widely used to make transistors (see Chapter 9) and integrated circuits (see Section 11.4). Figure 7.5 shows a silicon wafer that is used to make integrated circuits.

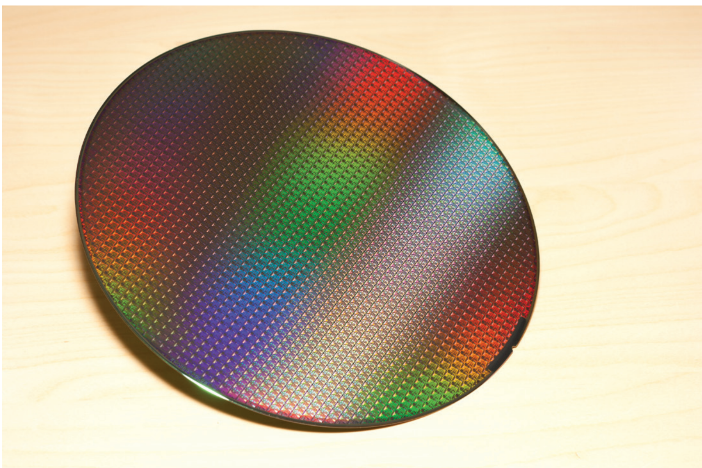


Figure 7.5 A silicon wafer is an example of a semiconductor

In their pure form, semiconductors do not conduct electricity well. However, their conductivity can be increased by adding impurities through a process called **doping**. Depending on the type of impurity added, doping will result in either **n-type** or **p-type semiconductors**, as shown in Figure 7.6. N-type semiconductors rely primarily on negative charges to conduct electricity while p-type semiconductors rely primarily on positive charges.

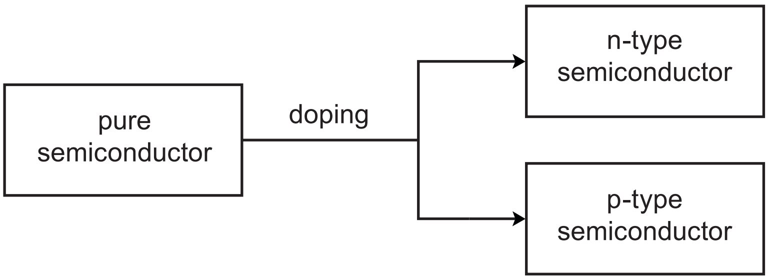


Figure 7.6 Doping a pure semiconductor results in either an n-type or a p-type semiconductor

When an n-type and a p-type semiconductor are joined together, the simplest semiconductor component, the **PN junction diode**, is formed. Figure 7.7 shows the basic structure of a PN junction diode. The end connected to the p-type semiconductor is called the **anode (A)** or positive terminal while the end connected to the n-type semiconductor is called the **cathode (K)** or negative terminal. The junction between the two materials is called the **PN junction**.

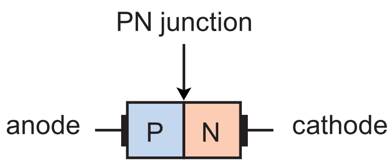


Figure 7.7 Basic structure of a PN junction diode

To identify the anode and cathode of a diode, look out for the band on one of the ends. The end with the band is the cathode and the other end is the anode as shown in Figure 7.8.

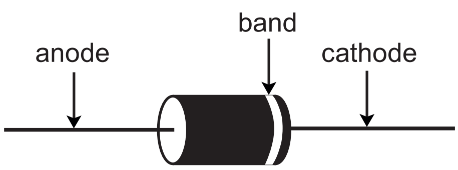


Figure 7.8 Identifying the anode and cathode of a diode

Review Questions 7.1

1. Describe the purpose of doping a pure semiconductor.
2. Name the two types of semiconductors obtained through doping.
3. Describe the basic structure of a PN junction diode.

7.2 How does a diode behave?

Learning Outcomes

- Explain how a PN junction diode is biased in the forward and reverse directions.
- Describe the I-V characteristics of a diode.
- Explain the difference between ideal and practical diodes.
- Interpret typical diode specifications (forward voltage, maximum current, maximum reverse voltage) using datasheets.

Key Ideas

- A diode allows a current to flow easily in only one direction.
- A diode is forward-biased when its anode is connected to the positive terminal of a source and its cathode is connected to the negative terminal. When connected in the other direction, the diode is reverse-biased.
- The I-V characteristic graphs of ideal and practical diodes can be used to describe and explain their respective characteristics.
- Datasheets provide important information on how to use diodes safely and correctly.

How a PN junction diode works

Figure 7.9 shows the symbol of a diode. The voltage across the diode, V_D, is measured with reference to the cathode. The current through the diode, I_D, is measured in the direction shown. When V_D is positive, it is also known as the forward voltage, V_F.

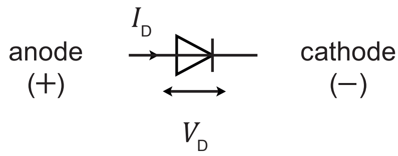


Figure 7.9 Symbol of a diode

The most important characteristic of a diode is that it allows a current to flow easily in one direction but not the other. The triangle in the symbol points towards the direction in which a current is allowed to flow easily.

Forward-bias mode

In Figure 7.10, the anode of a diode is connected to the positive terminal of the battery while its cathode is connected to the negative terminal (through the bulb). This causes the diode to be **forward-biased**, which allows a current to pass through it easily. Thus, the bulb lights up.

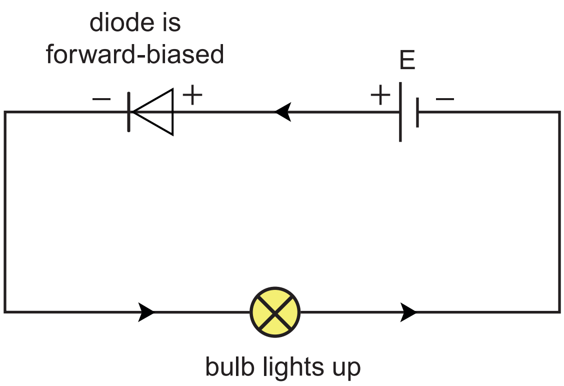


Figure 7.10 Diode in forward-bias mode

Reverse-bias mode

In Figure 7.11, the cathode of a diode is connected to the positive terminal of the battery while its anode is connected to the negative terminal (through the bulb). This causes the diode to be **reverse-biased**, which does not allow a current to pass through it easily. Thus, the bulb does not light up.

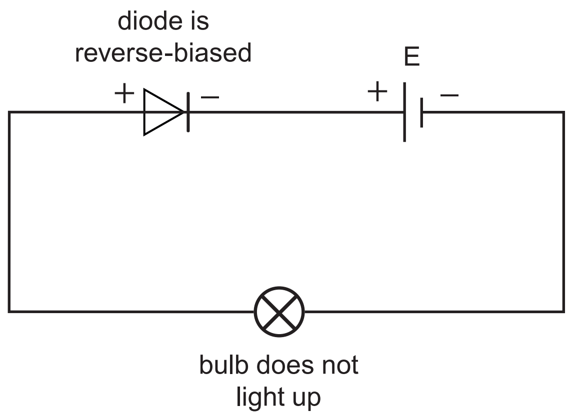


Figure 7.11 Diode in reverse-bias mode

Ideal diode

The **ideal diode** is a model that treats a forward-biased diode as a perfect conductor (zero resistance) and a reverse-biased diode as a perfect insulator (infinite resistance). We will represent the perfect conductor as a closed switch and the perfect insulator as an open circuit as shown in Figure 7.12.

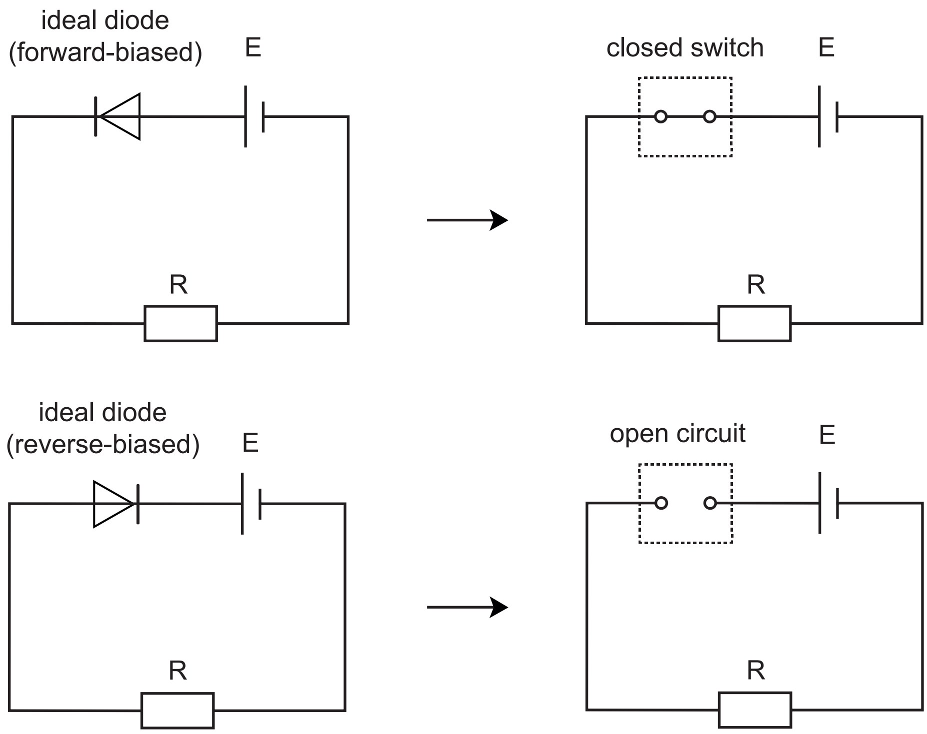


Figure 7.12 The forward-biased and reverse-biased ideal diodes are represented by a closed switch (top) and an open circuit (bottom), respectively

The most important characteristic graph of a diode is its current-voltage (I-V) graph. The I-V graph of an ideal diode is shown in Figure 7.13.

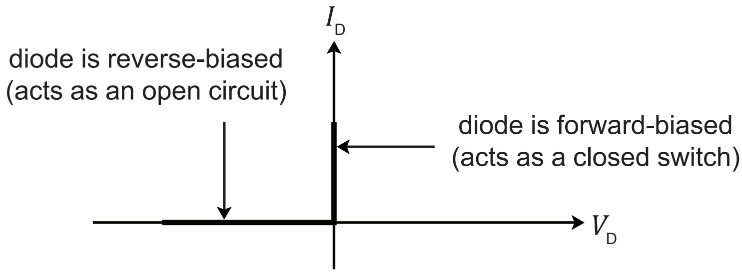


Figure 7.13 Characteristic graph of an ideal diode

We will now relate the graph to the characteristics of an ideal diode:

- The vertical part of the graph represents the behaviour of the diode when it is forward-biased. At this part, $V_D = 0$ and I_D can be as high as the circuit requires. Since V_D is zero, using $R = \frac{V}{I}$, the resistance of the diode is also zero (perfect conductor). The diode is said to be 'on'.
- The horizontal part of the graph represents the behaviour of the diode when it is reverse-biased. At this part, $I_D = 0$ regardless of the value of V_D. Since I_D is zero, using $R = \frac{V}{I}$, the resistance of the diode is infinite (perfect insulator). The diode is said to be 'off'.

The ideal diode is a model that is useful for a quick (but rough) analysis of circuits with diodes. However, due to the limitations of semiconductors, real-life (also known as practical) diodes cannot behave in the same way as ideal diodes.

Practical diode

Since ideal diodes do not exist, we normally use commercially available **practical diodes** such as silicon diodes or germanium diodes. Figure 7.14 shows the characteristic graph of a practical diode.

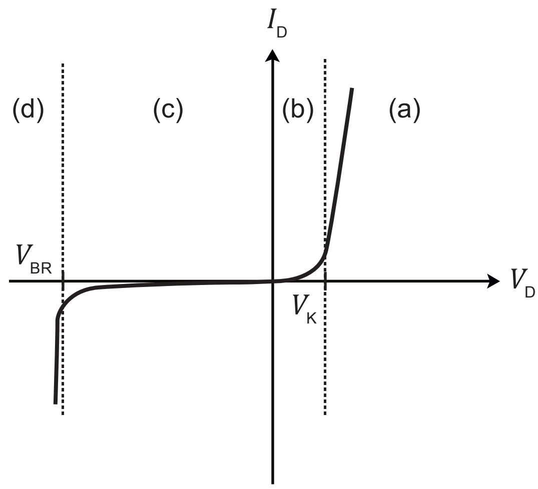


Figure 7.14 Characteristic graph of a practical diode (not drawn to scale)

Table 7.1 relates the four regions of the graph to the characteristics of a practical diode:

Table 7.1 Operating regions of a practical diode

Region	Conditions to enter region	Diode characteristics
(a)	• The diode is forward-biased. • The voltage of the source is higher than a value called the **knee voltage, V_K**, of the diode (around 0.7 V for silicon diodes and 0.3 V for germanium diodes).	• The diode is turned on and allows a current to pass through easily. • V_D is equal to or slightly higher than V_K.
(b)	• The diode is forward-biased. • The voltage of the source is lower than V_K.	• I_D is small as the diode is not fully conductive.
(c)	• The diode is reverse-biased. • The voltage of the source is lower than a value called the **breakdown voltage, V_{BR}**, of the diode.	• The diode is turned off and does not allow a current to pass through easily. • The small reverse current (in the order of μA) through the diode is called a **reverse leakage current**.
(d)	• The diode is reverse-biased. • The voltage of the source is higher than the V_{BR} of the diode. • This region is known as the **breakdown region**.	• A large reverse current (called an **avalanche current**) flows through the diode (this should be avoided as it will damage the diode).

Table 7.2 summarises the differences between ideal and practical diodes.

Table 7.2 Differences between ideal and practical diodes

	Ideal diode	Practical diode
Condition for diode to be turned on	voltage of source > 0	voltage of source > V_K
V_D when diode is turned on	zero	V_K or slightly higher
Current when diode is reverse-biased	zero	small reverse leakage current
Maximum negative voltage to be applied across diode	no limit	V_{BR}

Datasheets for practical diodes

The **datasheet** of a diode contains important information that allows us to use the device in a correct and safe manner. Figure 7.15 shows an extract from the datasheet of an IN4001 general purpose diode.

Semiconductor Technical Data

1N4001

General Purpose Plastic Rectifier Diode

MAXIMUM RATINGS

Parameter	Symbol	Maximum	Unit
Peak repetitive reverse voltage	V_{RRM}	50	V
RMS reverse voltage	V_{RMS}	35	V
DC blocking voltage	V_{DC}	50	V
Average forward rectified current	$I_{F(AV)}$	1.0	A

ELECTRICAL CHARACTERISTICS

Parameter	Symbol	Typical	Maximum	Unit
Maximum instantaneous forward voltage drop (forward current = 1.0 A, T_J = 25 °C)	V_F	0.93	1.1	V

Figure 7.15 Extract of an IN4001 diode datasheet

The full datasheets supplied by various manufacturers are easily available on the Internet and contain much more information than what is shown in Figure 7.15. In this course, we will focus on three basic but important characteristics that are needed to use diodes correctly and safely:

- **Forward voltage, V_F**, which is the voltage drop across the diode when it is forward-biased. In the datasheet, this value is stated as 0.93 V (typical) and 1.1 V (maximum) when $I_D = 1.0$ A. Smaller values of I_D will result in slightly smaller values of V_F.

- **Maximum average forward current, $I_{F(AV)}$**, which is the maximum average current that can flow through the diode without damaging it. In the datasheet, this value is stated as 1.0 A.

  To avoid exceeding this value, a diode should always be connected in series with a resistor to limit the current flowing through the diode as shown in Figure 7.16. The resistor is thus called a **current-limiting resistor**.

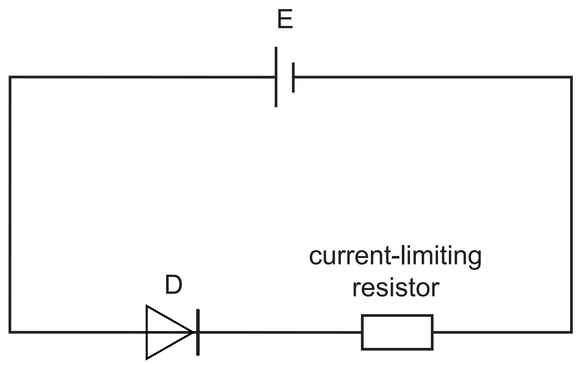


Figure 7.16 Using a current-limiting resistor to avoid damaging the diode

- **Peak repetitive reverse voltage, V_{RRM}**, (also known as breakdown voltage) which is the maximum negative voltage that should be applied across a diode. Beyond that, the diode will enter the breakdown region and a large current will flow through the diode in the reverse direction (from cathode to anode) which may damage the diode permanently. In the datasheet, this value is stated as 50 V.

These three characteristics apply to all types of diodes, including the general purpose diode discussed in this section, the light-emitting diode in Section 7.5 and the Zener diode in Section 7.7.

Review Questions 7.2

1. Describe the differences between ideal diodes and practical diodes.

2. For each of the circuits in Figure 7.17, determine whether the diode is forward-biased or reverse-biased.

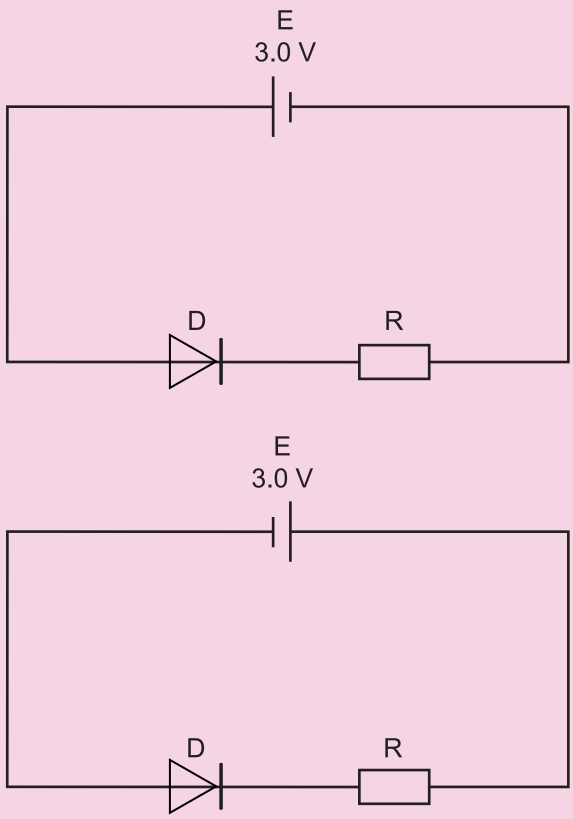


Figure 7.17

3. Discuss why we need to know the forward voltage, maximum forward current and peak reverse voltage when using a diode.

7.3 How do we use the simplified diode model to analyse circuits?

Learning Outcome

- Apply the simplified diode model to solve problems.

Key Idea

- The simplified diode model can be used to perform a quick analysis of circuits with diodes.

The practical diode characteristic graph shown in Figure 7.14 is the most accurate representation of the behaviour of a PN junction diode. However, it is not easy to use in analysing circuits. In addition, many analyses do not need such a high level of accuracy. For quick analyses, we often use the **simplified diode model** (technically called the offset or constant-voltage-drop model) shown in Figure 7.18.

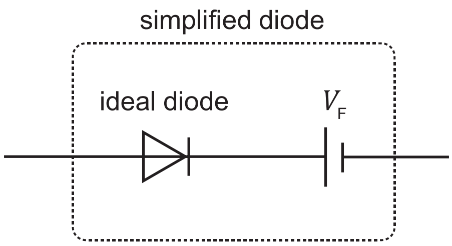


Figure 7.18 Simplified diode model

This simplified diode model consists of an ideal diode connected in series with a battery that represents the V_F of a practical diode. It is important to note that the battery does not act as a DC source. As such, there will not be a voltage measured if a multimeter is connected across the simplified diode model.

Figure 7.19 shows the characteristic graph of the simplified diode model.

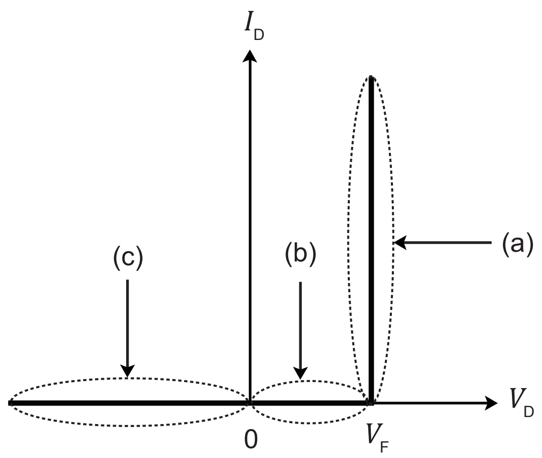


Figure 7.19 Characteristic graph of the simplified diode model

We will now relate the three parts of the graph to the characteristics of the simplified diode model:

(a) The diode enters this region when it is forward-biased and the voltage of the source is higher than V_F. The diode acts as a closed switch with $V_D = V_F$.

(b) The diode enters this region when it is forward-biased but the voltage of the source is lower than V_F. The diode is treated as if it is reverse-biased.

(c) The diode enters this region when it is reverse-biased. The diode acts as an open circuit and $I_D = 0$.

Figure 7.19 is meant to be a simplified version of the characteristic graph of a practical diode (Figure 7.14). In Figure 7.14, the positive upward swing of the graph starts at the knee voltage, V_K. Hence, in Figure 7.19, the value of V_F is taken to be V_K of the diode.

Worked Example 7.1 illustrates how the simplified diode model can be used to analyse circuits.

Worked Example 7.1

Determine the current in each of the three circuits shown in Figure 7.20 using the simplified diode model with $V_F = 0.7$ V.

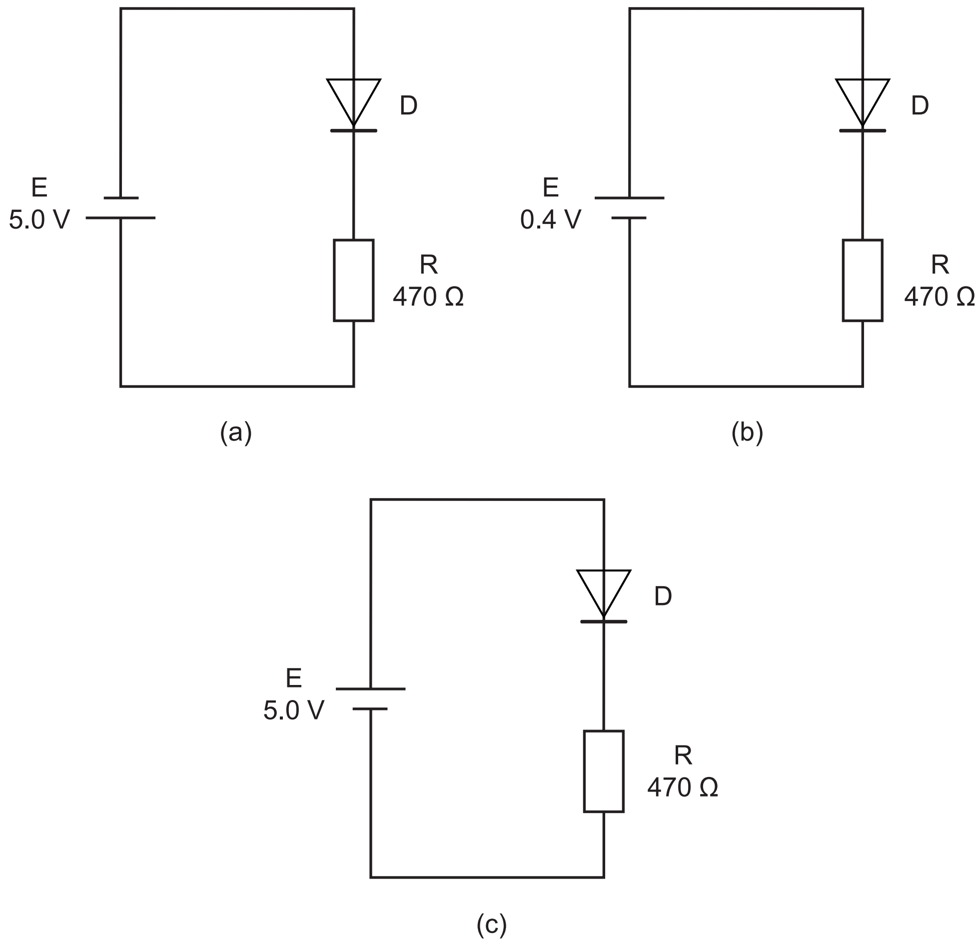


Figure 7.20

Solution

(a) Since the diode is reverse-biased, it acts as an open circuit. There will be no current in the circuit.

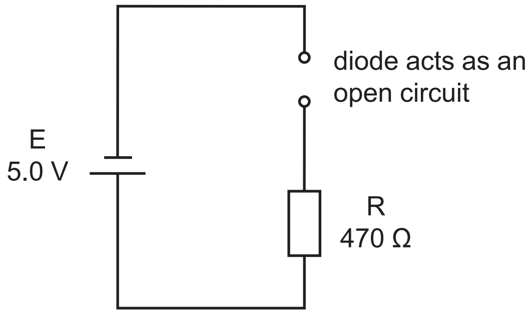


Figure 7.21

(b) Although the diode is forward-biased, the voltage of the source is smaller than V_F, hence the diode acts as an open circuit. There will be no current in the circuit.

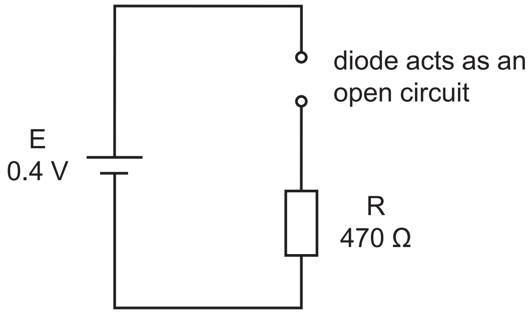


Figure 7.22

(c) Since the diode is forward-biased and the voltage of the source is larger than V_F, the diode acts as a closed switch with $V_D = V_F = 0.7$ V.

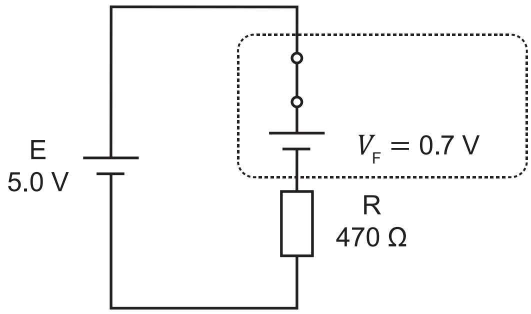


Figure 7.23

Using KVL, voltage across R, $V_R = 5.0\text{ V} - 0.7\text{ V}$
$= 4.3\text{ V}$

Current through R, $I = \dfrac{V}{R}$

$= \dfrac{4.3\text{ V}}{470\ \Omega}$

$= 0.0091\text{ A}$

$= 9.1\text{ mA}$

Therefore, the current in the circuit is 9.1 mA.

When a current flows through the diode, heat is produced. We can calculate the power dissipated in the diode using the equation $P = V \times I$. It is important to ensure that the power dissipated does not exceed the power rating of the diode.

Worked Example 7.2

Using the simplified diode model with $V_F = 0.7$ V, calculate the power dissipated in the diode in Figure 7.23.

Solution

From Worked Example 7.1, current through diode = 9.1 mA.

Power dissipated in diode, $P = V \times I$
$= 0.7 \text{ V} \times 9.1 \text{ mA}$
$= 6.4 \text{ mW}$

Review Questions 7.3

1. State two differences between the characteristics of an ideal diode (Figure 7.13) and the simplified diode model (Figure 7.19).

2. Calculate the current in the circuit shown in Figure 7.24 using the simplified diode model with $V_F = 0.7$ V.

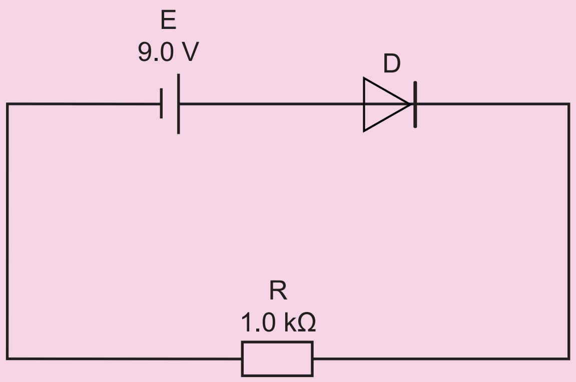


Figure 7.24

7.4 How can diodes be used to convert an alternating current to a direct current?

Learning Outcome

- Describe and explain the use of diodes in half-wave and full-wave rectifiers.

Key Ideas

- Diodes can be used to convert AC to DC through a process called rectification.
- There are two types of rectification: half-wave and full-wave.

One important use of diodes is to convert AC to DC through a process called **rectification**. To perform this process, we use circuits called **rectifiers**. There are two types of rectifiers: half-wave and full-wave.

Half-wave rectifier

The circuit shown in Figure 7.25 is called a **half-wave rectifier**. It consists of a diode and a resistor. The input to the circuit is the voltage applied across both the diode and the resistor. The output is the voltage across the resistor.

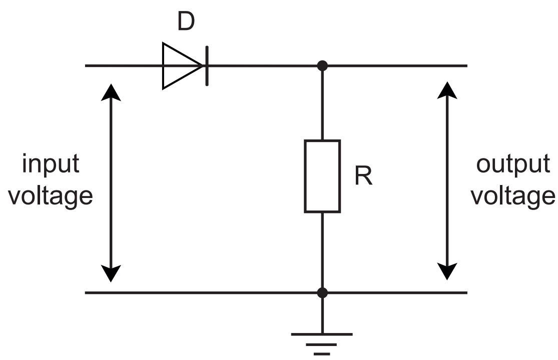


Figure 7.25 A half-wave rectifier

We will now learn how the half-wave rectifier works by using an AC sine wave with a peak voltage of 5 V as the input. The first explanation will be based on an ideal diode and the second explanation will be based on the simplified diode model with $V_F = 0.7$ V.

Ideal diode

During the positive half of the input, the diode is forward-biased and acts like a closed switch. The equivalent circuit is shown in Figure 7.26. Thus, the output is the same as the input.

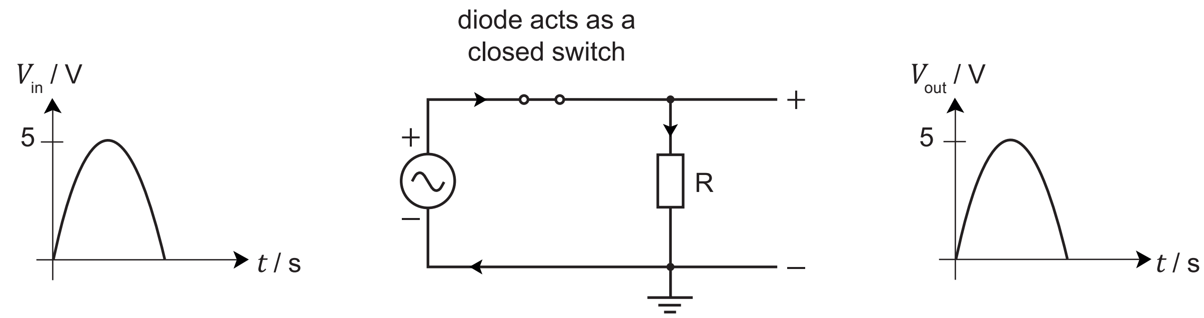


Figure 7.26 Equivalent circuit of a half-wave rectifier (ideal diode) during the positive half of the input

During the negative half of the input, the diode is reverse-biased and acts like an open circuit. The equivalent circuit is shown in Figure 7.27. Thus, the output is zero.

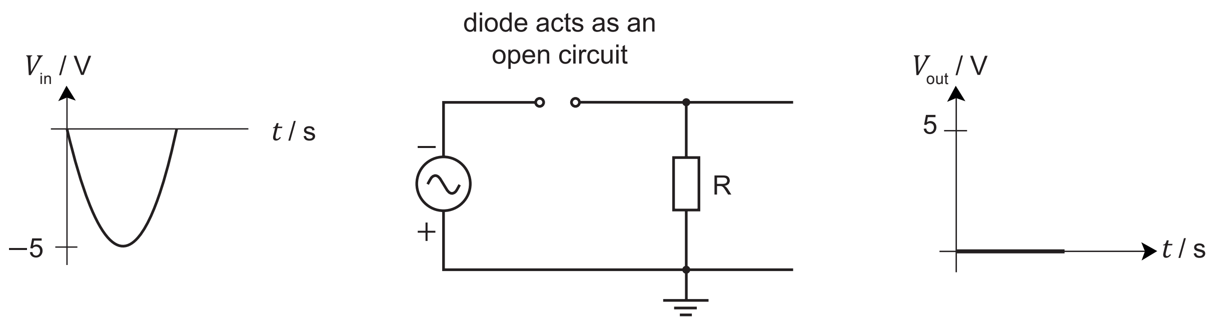


Figure 7.27 Equivalent circuit of a half-wave rectifier (ideal diode) during the negative half of the input

Figure 7.28 shows the input and output waveforms of a half-wave rectifier which uses an ideal diode. Notice that the output contains only the positive halves of the input. Since the output waveform is always positive, the output is a DC voltage. By removing the negative halves of the input, the half-wave rectifier has converted an AC to a DC.

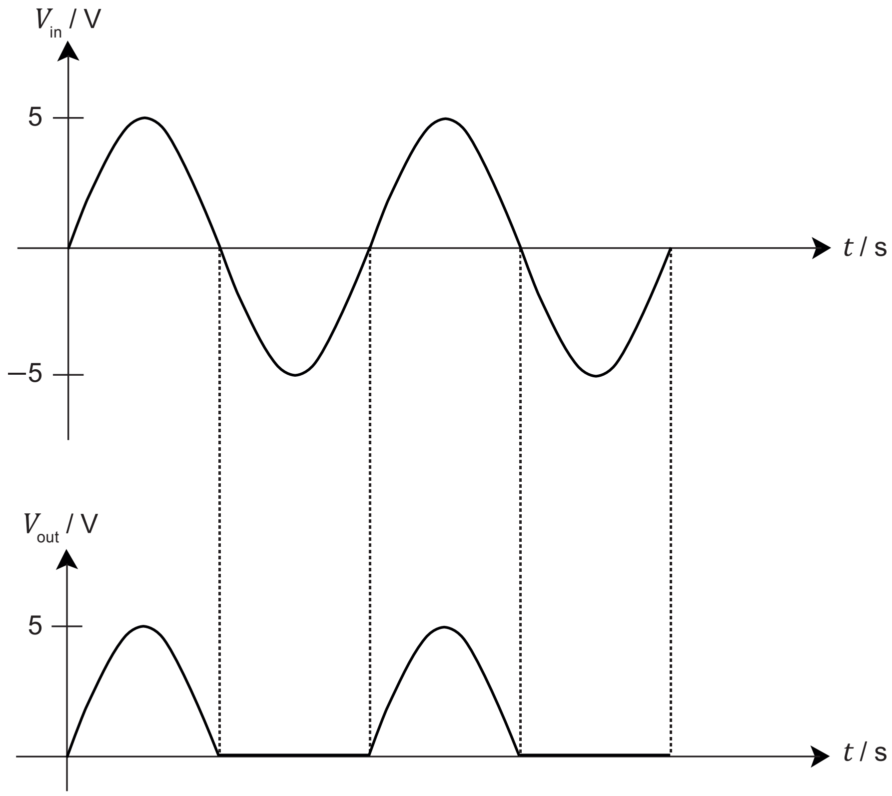


Figure 7.28 Input and output of a half-wave rectifier (ideal diode)

Simplified diode model with V_F = 0.7 V

The equivalent circuit during the positive half of the input is shown in Figure 7.29. There are two differences compared to the ideal diode:

- The input needs to be 0.7 V or higher (to overcome the V_F of the diode) in order to produce an output voltage.
- The output is 0.7 V lower than the input due to the voltage drop of V_F across the diode when it is forward-biased.

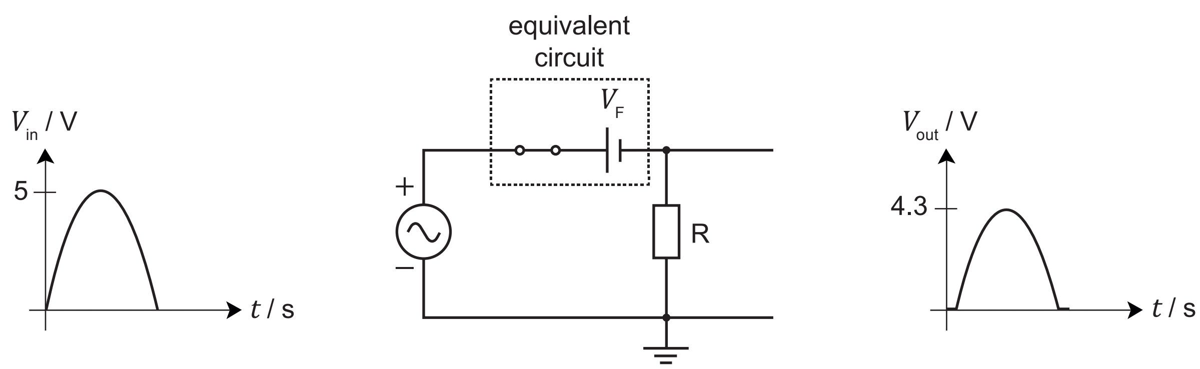


Figure 7.29 Equivalent circuit of a half-wave rectifier (simplified diode model) during the positive half of the input

During the negative half, the simplified diode model behaves in the same way as the ideal diode, i.e., it acts as an open circuit. Figure 7.30 shows the input and output waveforms of a half-wave rectifier which uses the simplified diode model.

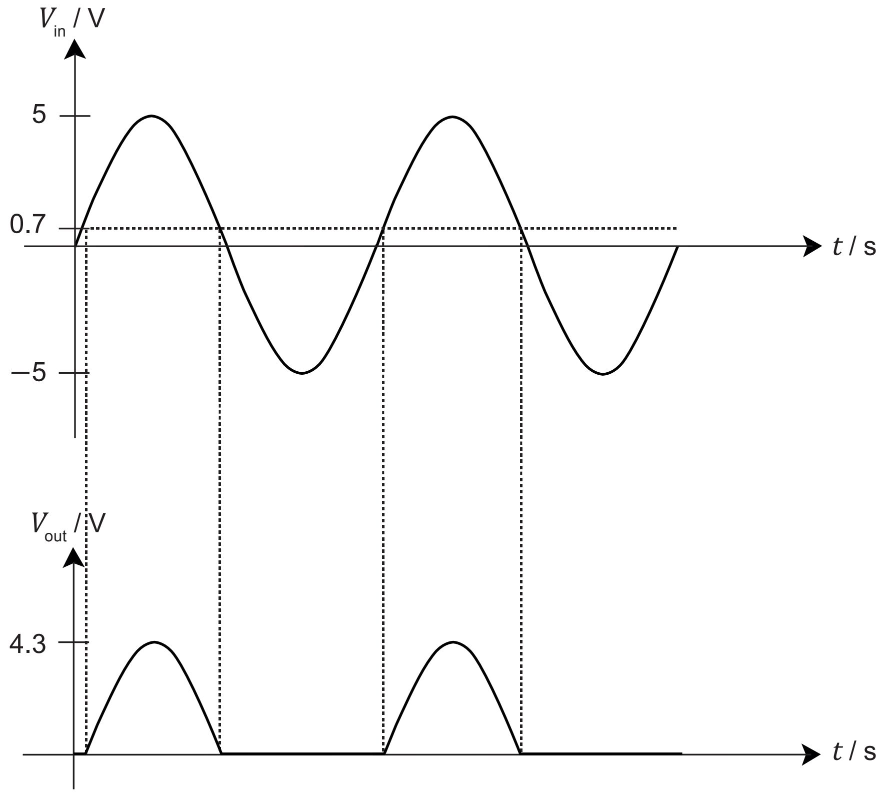


Figure 7.30 Input and output of a half-wave rectifier (simplified diode model)

Full-wave rectifier

Figure 7.31 shows a **full-wave rectifier** consisting of four diodes. The diodes are arranged in a **bridge configuration**. The input is connected to A and C. The output is the voltage between B and D which is applied across the load resistor, R_L.

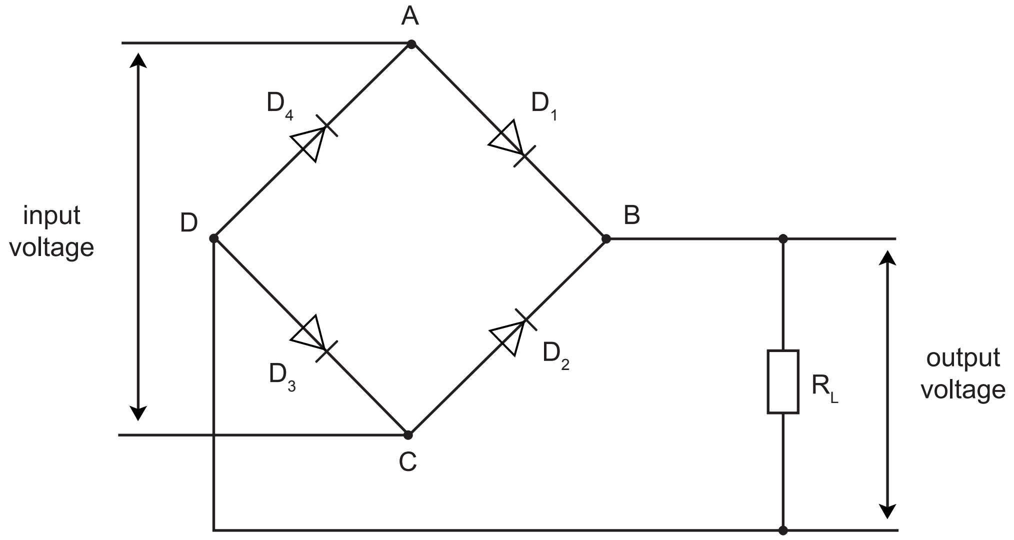


Figure 7.31 Full-wave rectifier circuit

We will now learn how the full-wave rectifier works by using an AC sine wave with a peak voltage of 5 V as the input. The first explanation will be based on an ideal diode and the second explanation will be based on the simplified diode model with $V_F = 0.7$ V.

Ideal diode

During the positive half of the input, D_1 and D_3 are forward-biased and act like closed switches. However, D_2 and D_4 are reverse-biased and act like open circuits. The equivalent circuit is shown in Figure 7.32. The output is the same as the input and the current flows along the path indicated.

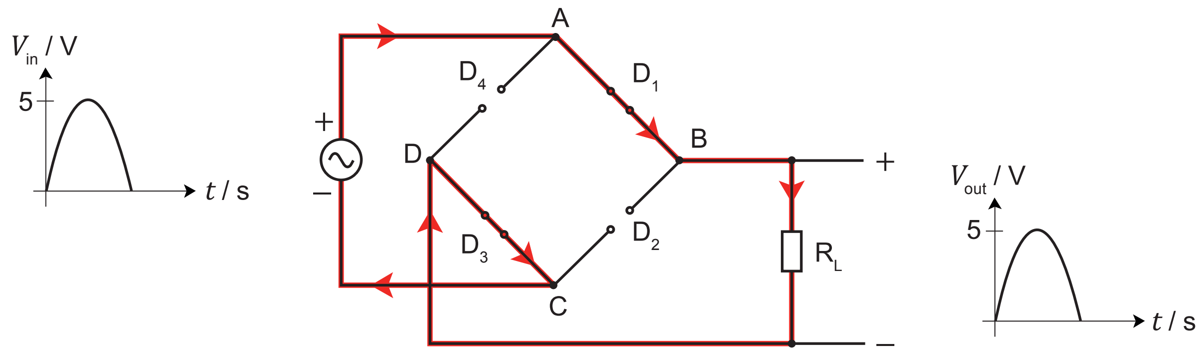


Figure 7.32 Equivalent circuit of a full-wave rectifier (ideal diode) during the positive half of the input

During the negative half of the input, D_2 and D_4 are forward-biased and act like closed switches. However, D_1 and D_3 are reverse-biased and act like open circuits. The equivalent circuit is shown in Figure 7.33. Notice that during the negative half of the input, a current still flows through the load resistor in the same direction as the positive half. Because of this, the output remains positive even though the input is negative.

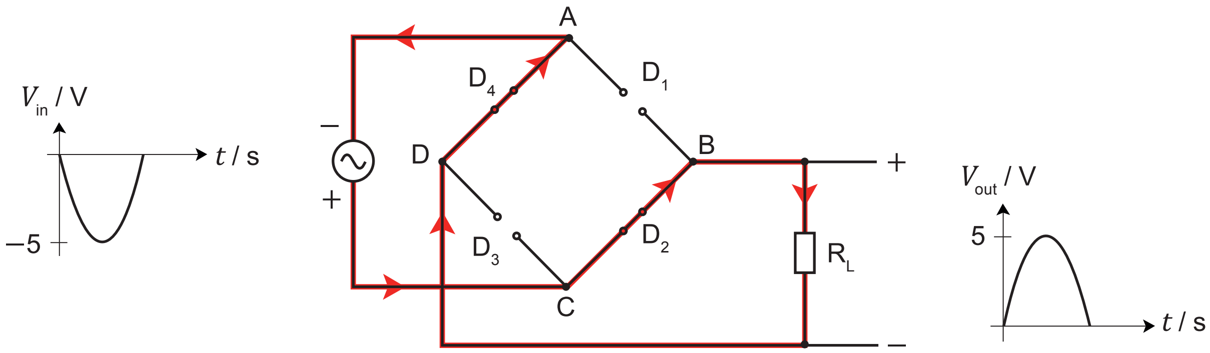


Figure 7.33 Equivalent circuit of a full-wave rectifier (ideal diode) during the negative half of the input

Figure 7.34 shows the input and output waveforms of a full-wave rectifier which uses ideal diodes. Notice that the output contains both halves of the input with the negative halves inverted to become positive. Since the output waveform is always positive, the output is a DC voltage. By inverting the negative halves of the input, the full-wave rectifier has converted an AC to a DC.

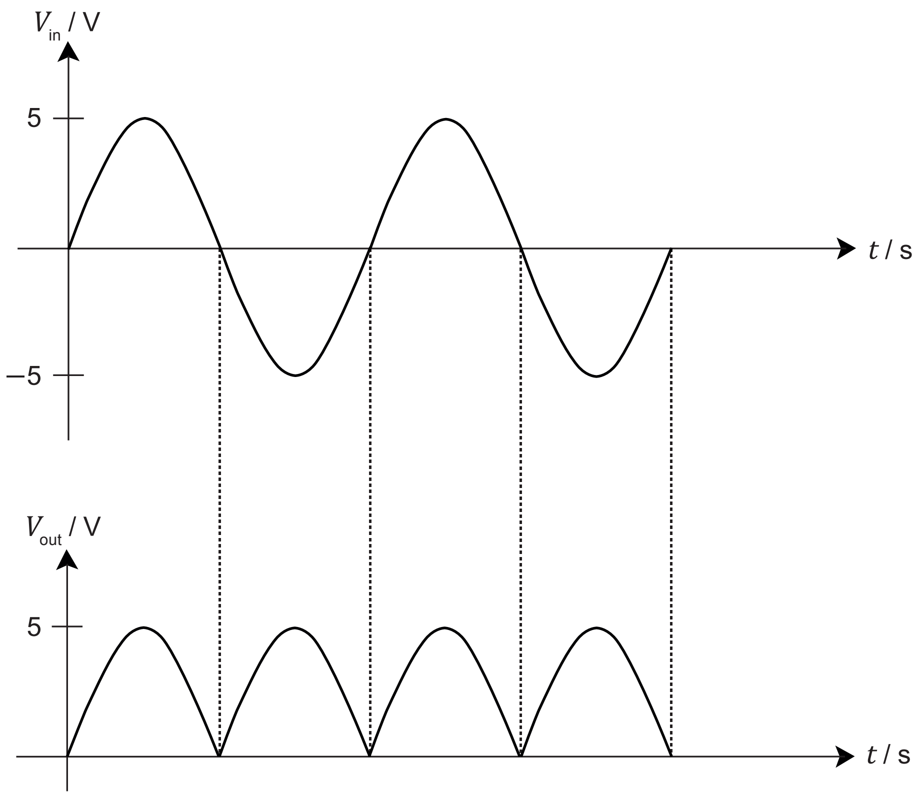


Figure 7.34 Input and output waveforms of a full-wave rectifier (ideal diode)

Simplified diode model with $V_F = 0.7$ V

The equivalent circuit during the positive half of the input is shown in Figure 7.35. There are two differences compared to the ideal diode:

- The input needs to be 1.4 V or higher (to overcome the V_F of the two diodes) in order to produce an output voltage.
- The output is 1.4 V lower than the input due to the voltage drop of V_F across each of the two diodes when they are forward-biased.

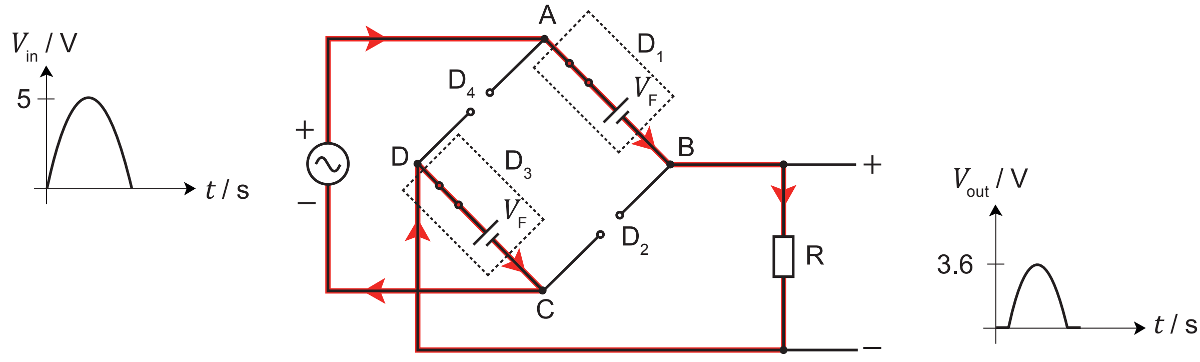


Figure 7.35 Equivalent circuit of a full-wave rectifier (simplified diode model) during the positive half of the input

The explanation is similar for the negative half of the input, except that D_2 and D_4 are forward-biased instead. Figure 7.36 shows the input and output waveforms of a full-wave rectifier which uses the simplified diode model.

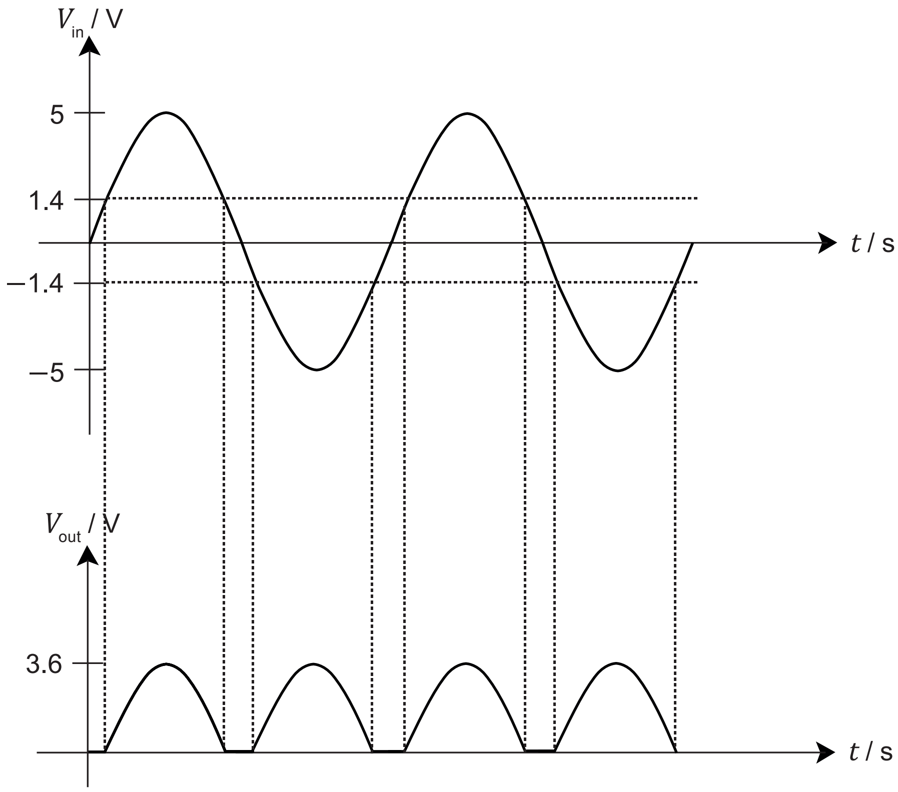


Figure 7.36 Input and output waveforms of a full-wave rectifier (simplified diode model)

Although both the half-wave and full-wave rectifiers are able to convert AC to DC, their outputs are both pulsating DC voltages with varying levels. In Section 7.7, we will learn how to use a capacitor and Zener diode to turn the pulsating DC voltages into steady DC voltages.

Review Questions 7.4

1. Draw the circuit diagrams of a half-wave and a full-wave rectifier.

2. Draw the output waveform of the full-wave rectifier in Figure 7.31 when a sine wave with a peak voltage of 8 V is used as the input. Use the simplified diode model with $V_F = 0.7$ V.

7.5 How do we connect light-emitting diodes correctly?

Learning Outcomes

- Describe the benefits of using LEDs for lighting as compared to incandescent bulbs.
- Explain why a resistor should be connected in series with an LED in a circuit and calculate its resistance value.

Key Ideas

- LEDs are an energy-efficient source of lighting.
- LEDs need to be connected in series with a resistor to prevent damage.

Light-emitting diodes (LEDs) are a special type of diode that can give off light. They come in a range of sizes, shapes and colours as shown in Figure 7.37.

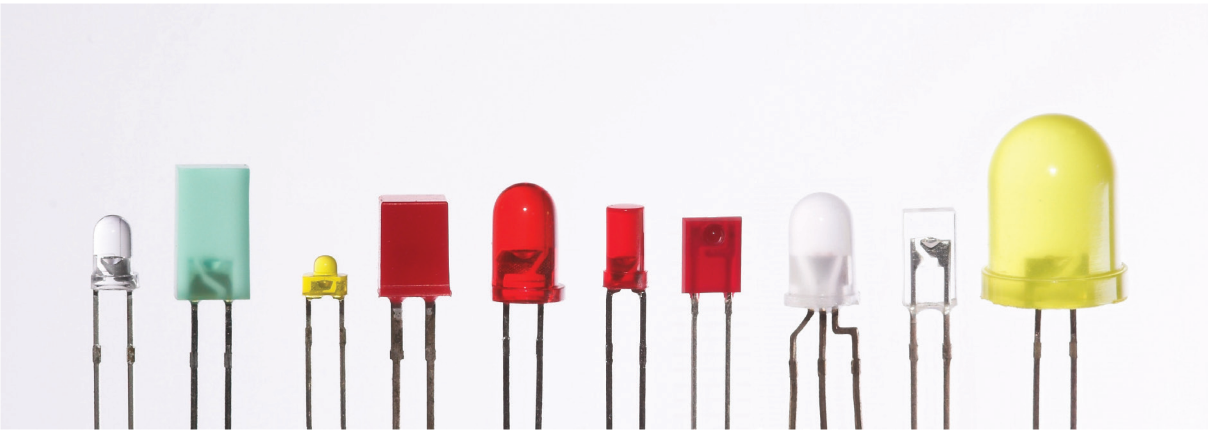


Figure 7.37 Different types of LEDs

LEDs are popularly used in home lighting, portable torches and traffic lights. Many mobile phones use LEDs in the flashlights of their built-in cameras. LEDs are also used in optical fibres to transmit information at high speeds.

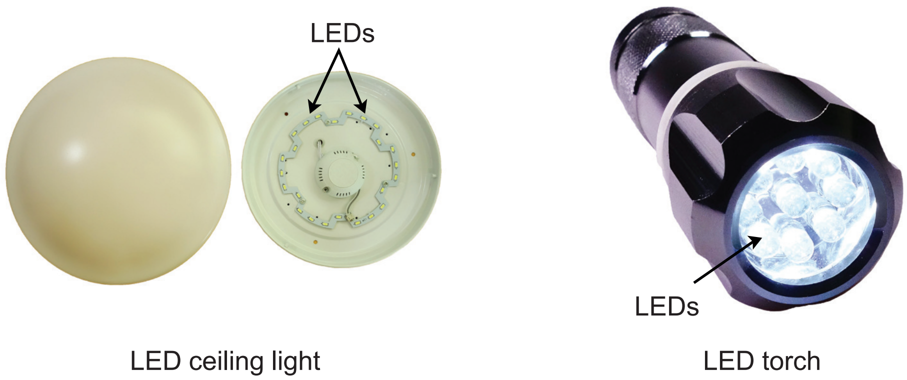


Figure 7.38 Common applications of LEDs

The two main reasons for the increasing use of LEDs for lighting are their long lifespan and energy efficiency. Compared to incandescent light bulbs, LEDs consume significantly less energy (< 20%) for the same amount of light produced. However, LEDs usually cost more than incandescent light bulbs.

The symbol of an LED is shown in Figure 7.39. It is similar to that of a diode except for two additional arrows.

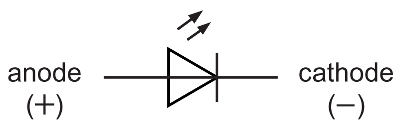


Figure 7.39 Symbol of an LED

Figure 7.40 shows three possible ways of identifying the anode and cathode of an LED:

- Look inside the LED for two plates – the terminal connected to the smaller plate is the anode while the terminal connected to the larger plate is the cathode.
- Look at the connecting leads – the longer lead is the anode and the shorter one is the cathode.
- Look for a flat edge – the terminal on the same side as the flat edge is the cathode.

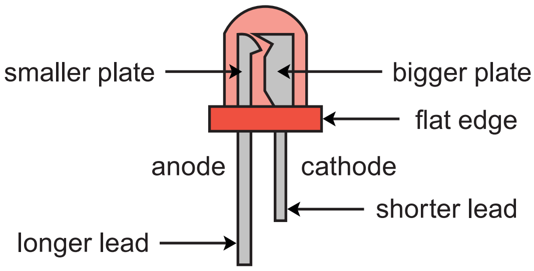


Figure 7.40 Features that help to identify the anode and cathode of an LED

Figure 7.41 shows a simple circuit that can be used to light up an LED.

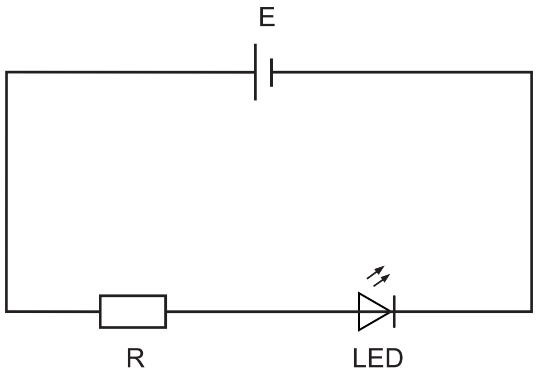


Figure 7.41 Circuit to light up an LED

There are a number of considerations when connecting the circuit shown in Figure 7.41.

- As a type of diode, LEDs allow current to flow in one direction only. As such, it is important to connect the LED in the forward-biased state.
- To turn on the LED, the voltage of the DC source must be higher than the V_F of the LED (using the simplified diode model). Depending on the type and colour of the LED, the value of V_F can range from 1.7 V to approximately 4.0 V.
- When the LED is forward-biased, it will have a voltage drop of V_F.
- To avoid damaging the LED, a current-limiting resistor is connected in series with the LED. The current rating of a standard 5 mm LED is around 20 mA.

  For the circuit shown in Figure 7.41, if $E = 9.0$ V, $V_F = 2.0$ V and the current rating of the LED is 20 mA, the minimum value of R can be determined by:

$$R = \frac{E - V_F}{I_{max}}$$

$$= \frac{9.0\text{ V} - 2.0\text{ V}}{20\text{ mA}}$$

$$= 350\ \Omega$$

Worked Example 7.3

Calculate the current through the LED in the circuit shown in Figure 7.42. Assume that $V_F = 2.0$ V.

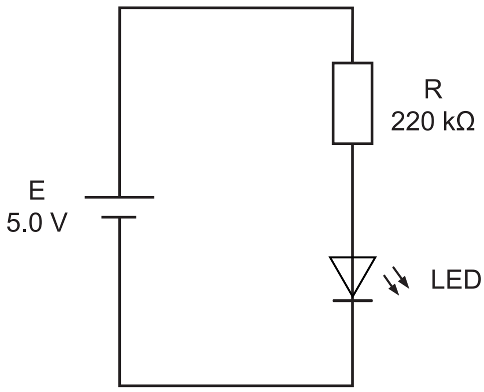


Figure 7.42

Solution

Since the LED is forward-biased and the voltage of the DC source is higher than V_F, the voltage drop across the LED $= V_F = 2.0$ V.

Using KVL, voltage across resistor, $V_R = 5.0\text{ V} - 2.0\text{ V}$
$= 3.0\text{ V}$

Current through resistor, $I_R = \dfrac{V_R}{R}$

$$= \frac{3.0\text{ V}}{220\ \Omega}$$

$$= 0.014\text{ A}$$

$$= 14\text{ mA}$$

Since the LED is connected in series with the resistor, the current through the LED is also 14 mA.

Review Question 7.5

1. For the circuit in Figure 7.43:
   (a) Explain the need to connect a resistor in series with the LEDs.
   (b) Calculate the current through the circuit, assuming that both LEDs are identical with $V_F = 2.0$ V.

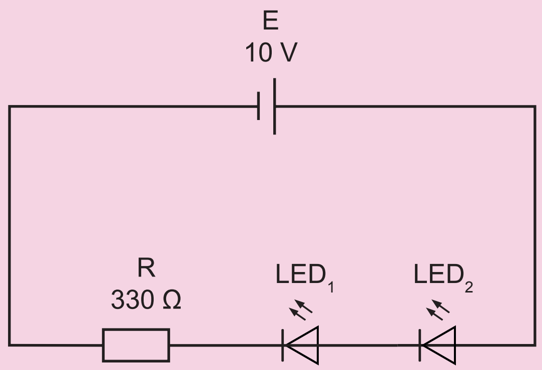


Figure 7.43

7.6 How does a 7-segment display work?

Learning Outcomes

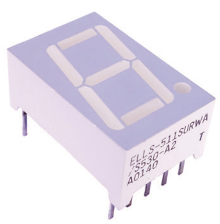
- State that a 7-segment display is made up of 7 LEDs which can be individually controlled.
- Describe the difference between the structure and operation of a common-anode and common-cathode 7-segment display.

Key Ideas

- By lighting up selected LEDs of a 7-segment display, different digits can be displayed.
- The anodes of all the LEDs of a common-anode 7-segment display are connected together; likewise for the cathodes of a common-cathode 7-segment display.

Many applications require the display of numerical figures. For example, the digital tally counter in Figure 1.5 shows the tally counted while the carpark display in Figure 14.2 shows the number of carpark lots available.

Figure 7.44 shows a single-digit **7-segment LED display** that can be used for this purpose. It consists of seven segments with a decimal point. The decimal point and each of the segments are LEDs that can be individually switched on or off. Each of the segments is identified by the letters *a* to *g* while the decimal point is identified by *dp*.



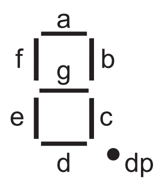


Figure 7.44 Single-digit 7-segment LED display (left) and segment identification (right)

By switching on different segments, the digits '0' to '9' can be displayed as shown in Figure 7.45.

Figure 7.45 Digits '0' to '9' as displayed on a 7-segment LED display

Table 7.3 shows the segments that need to be switched on or off to display the different digits.

Table 7.3 Segments to be lit for different digits

Number	Segment						
	a	b	c	d	e	f	g
0	on	on	on	on	on	on	off
1	off	on	on	off	off	off	off
2	on	on	off	on	on	off	on
3	on	on	on	on	off	off	on
4	off	on	on	off	off	on	on
5	on	off	on	on	off	on	on
6	on	off	on	on	on	on	on
7	on	on	on	off	off	off	off
8	on	on	on	on	on	on	on
9	on	on	on	on	off	on	on

To use a 7-segment display, we need to understand its pin configuration and internal circuitry. There are two types of 7-segment displays: **common-anode** and **common-cathode**.

Common-anode 7-segment display

Figure 7.46 shows the pin configuration and internal circuitry of a common-anode 7-segment display. Notice that it is made up of eight LEDs and that the anodes of these LEDs are connected together (thus the name 'common anode').

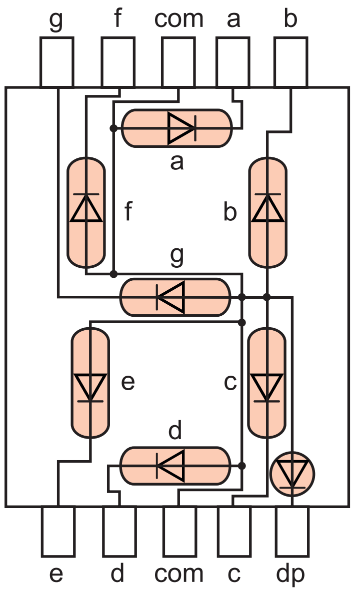


Figure 7.46 Pin configuration and internal circuitry of a common-anode 7-segment display

To display numbers on a common-anode 7-segment display, connect:

- the two common-anode pins (labelled as 'com' in Figure 7.46) to a suitable positive voltage (e.g., 5 V);
- the segments to be lit to 0 V through current-limiting resistors; and
- the segments to be switched off to the same positive voltage through current-limiting resistors.

Figure 7.47 shows how a common-anode 7-segment display should be connected to display the digit '0'.

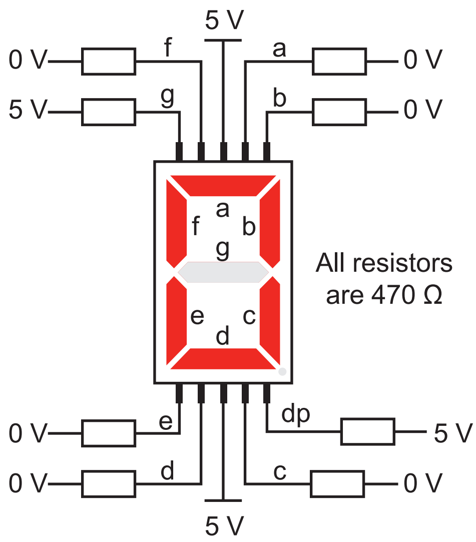


Figure 7.47 Connecting a common-anode 7-segment display to display the digit '0'

Common-cathode 7-segment display

Common-cathode 7-segment displays are similar to common-anode 7-segment displays, except that the cathodes of the LEDs are connected together as shown in Figure 7.48.

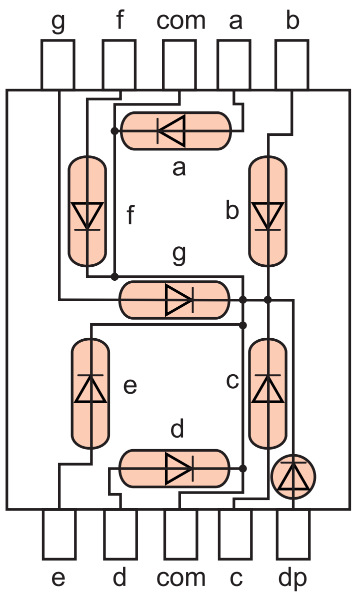


Figure 7.48 Pin configuration and internal circuitry of a common-cathode 7-segment display

To display numbers on a common-cathode 7-segment display, connect:

- the two common-cathode pins to 0 V;
- the segments to be lit to a suitable positive voltage (e.g., 5 V) through current-limiting resistors; and
- the segments to be switched off to 0 V through current-limiting resistors.

Figure 7.49 shows how a common-cathode 7-segment display should be connected to display the number '0'.

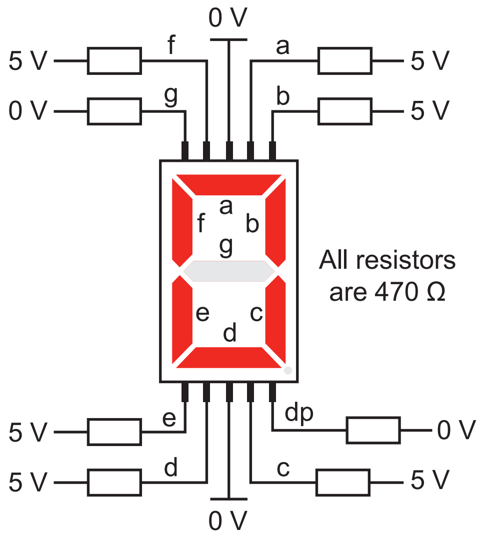


Figure 7.49 Connecting a common-cathode 7-segment display to display the digit '0'

Review Questions 7.6

1. List the segments that need to be lit to display the digit '3' on a 7-segment display.
2. Fill in '0 V' or '5 V' in each of the white boxes in Figure 7.50 so that the digit '5' is displayed on the common-anode 7-segment display.

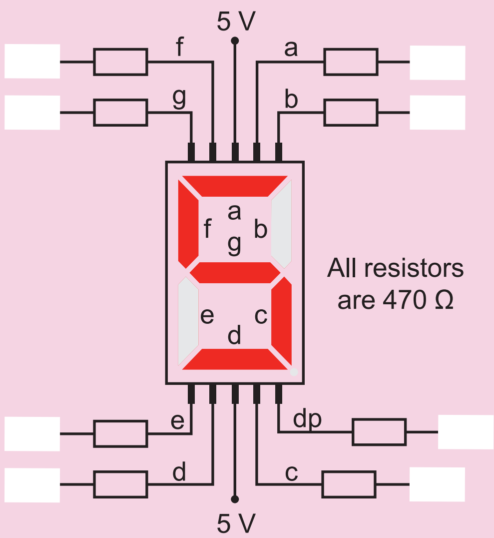


Figure 7.50

7.7 How do we use a Zener diode to regulate voltage?

Learning Outcomes

- Describe the *I-V* characteristics of a Zener diode.
- Explain the use of Zener diodes to regulate voltage.

Key Idea

- Zener diodes are used in the breakdown region to produce a steady voltage.

Basic operation of a Zener diode

We learnt in Section 7.2 that we should avoid driving a diode into its breakdown region as this might damage the diode. However, there is a special type of diode called the **Zener diode** that is designed to work in its breakdown region.

Figure 7.51 shows the symbol of a Zener diode. Like the general-purpose diode we learnt about earlier, the voltage across the Zener diode, V_D, is measured with reference to the cathode. I_D is the current flowing in the forward direction.

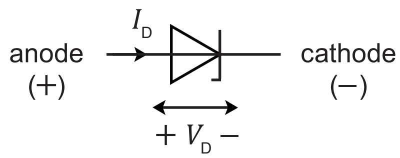


Figure 7.51 Symbol of a Zener diode

When the Zener diode operates in the breakdown region, it is convenient to label the reverse current as I_Z as shown in Figure 7.52 to avoid having to deal with negative values of current. Here, $I_Z = -I_D$.

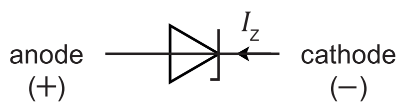


Figure 7.52 Zener diode operating in the breakdown region

Figure 7.53 shows the characteristic graph of a Zener diode. When forward-biased, the behaviour of the Zener diode is similar to a general-purpose diode. When the magnitude of the reverse voltage exceeds a value called the Zener voltage, V_Z, the Zener diode enters the breakdown region. In this region, the voltage across the Zener diode will be held constant at V_Z.

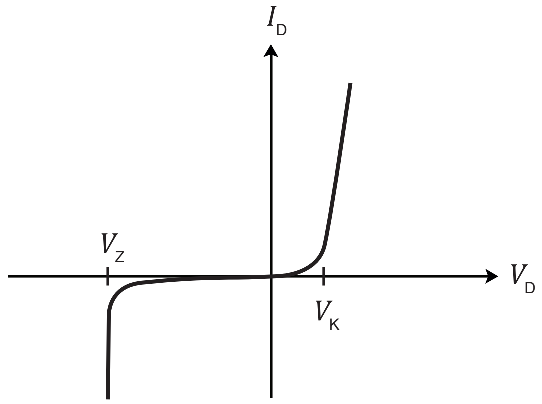


Figure 7.53 Characteristic graph of a Zener diode

The Zener voltage of Zener diodes is usually much lower than the breakdown voltage of general-purpose diodes. For example, the 1N4733 Zener diode has a breakdown voltage of 5.1 V as compared to the 1N4001 general-purpose diode, which has a breakdown voltage of 50 V.

Voltage regulation using Zener diodes

The ability of Zener diodes to hold a voltage at a constant level makes them useful for regulating voltage. Figure 7.54 shows a simple voltage-regulation circuit consisting of a resistor and a Zener diode. Notice that the Zener diode is reverse-biased. As long as E is higher than V_Z of the Zener diode, the voltage across it will be held constant at V_Z.

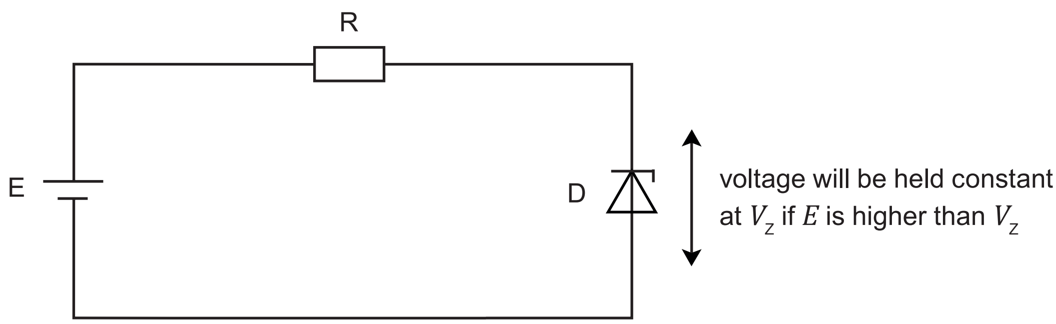


Figure 7.54 Basic voltage-regulation circuit

In practice, a load is usually present across the Zener diode as shown in Figure 7.55.

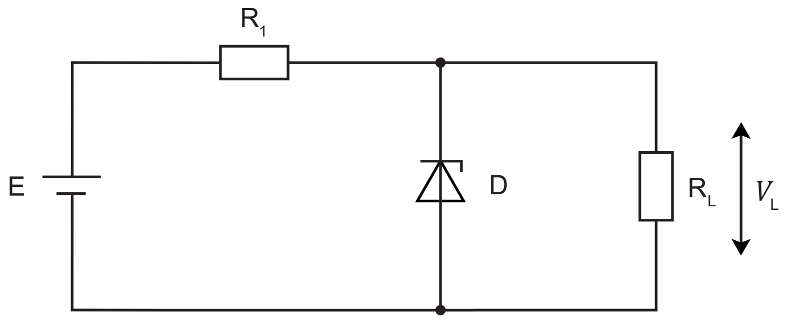


Figure 7.55 Basic voltage-regulation circuit with load

To analyse the circuit, we will first ignore the Zener diode by removing it as shown in Figure 7.56 and calculate the voltage across the open terminals using the voltage-divider formula:

$$V = \frac{R_L}{R_1 + R_L} \times E$$

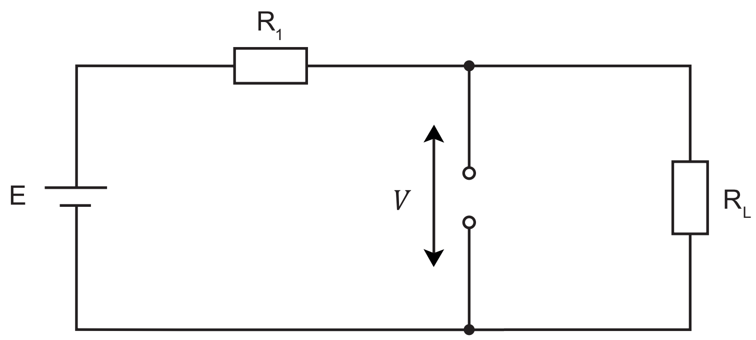


Figure 7.56 Basic voltage-regulation circuit (ignoring the Zener diode)

- If this calculated value is lower than V_Z, the Zener diode will act like an open circuit (based on the simplified diode model). The voltage across both the Zener diode and load resistor is equal to the calculated value (see Worked Example 7.4) and the current through the diode is zero.
- If this calculated value is equal to or higher than V_Z, the Zener diode is operating in the breakdown region. The voltage across the Zener diode will be held constant at V_Z. Since the load resistor is connected in parallel with the Zener diode, V_L will be equal to V_Z (see Worked Example 7.5).

Worked Example 7.4

The Zener diode in Figure 7.57 has a V_Z of 5.1 V. Determine (a) V_L and (b) the current through the Zener diode.

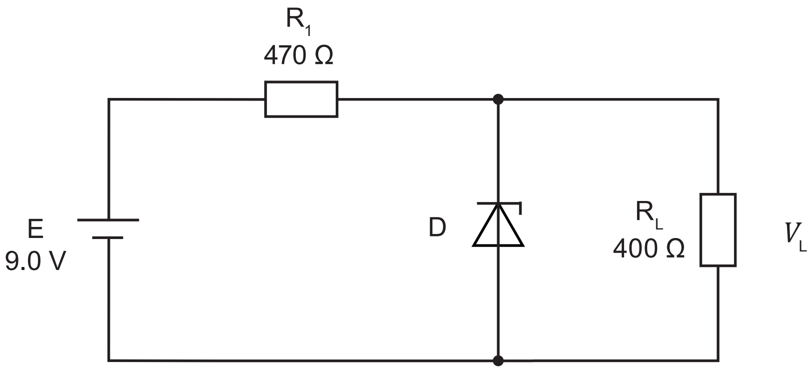


Figure 7.57

Solution

(a) Ignoring the Zener diode and using the voltage-divider formula,

$$V = \frac{R_L}{R_1 + R_L} \times E$$

$$= \frac{400\ \Omega}{470\ \Omega + 400\ \Omega} \times 9.0\ \text{V}$$

$$= 4.1\ \text{V}$$

As this voltage is smaller than V_Z, the Zener diode acts as an open circuit (see Figure 7.58). The voltage across R_L is thus 4.1 V.

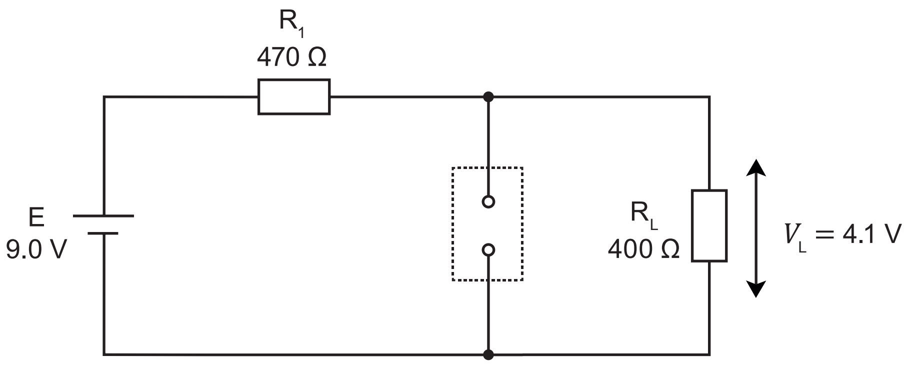


Figure 7.58

(b) Since the Zener diode acts as an open circuit, the current through the diode is zero.

Worked Example 7.5

Repeat Worked Example 7.4 using $R_L = 1.0\ \text{k}\Omega$.

Solution

(a) Ignoring the Zener diode and using the voltage-divider formula,

$$V = \frac{R_L}{R_1 + R_L} \times E$$

$$= \frac{1.0\ \text{k}\Omega}{470\ \Omega + 1.0\ \text{k}\Omega} \times 9.0\ \text{V}$$

$$= 6.1\ \text{V}$$

As this voltage is larger than V_Z, the voltage across the Zener diode will be held constant at V_Z which is 5.1 V. Since R_L is connected in parallel with the Zener diode, V_L is also 5.1 V.

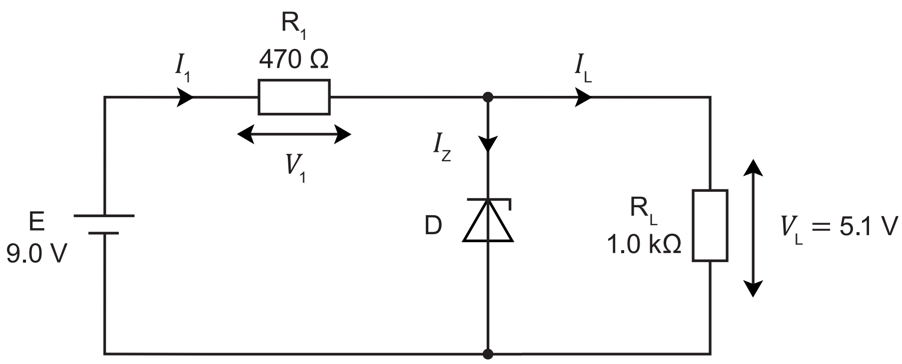


Figure 7.59

(b) Using KVL, voltage across R_1, $V_1 = 9.0\ \text{V} - 5.1\ \text{V}$
$= 3.9\ \text{V}$

Current through R_1, $I_1 = \dfrac{V_1}{R_1}$

$$= \frac{3.9\ \text{V}}{470\ \Omega}$$

$$= 8.3\ \text{mA}$$

Current through R_L, $I_L = \dfrac{V_L}{R_L}$

$$= \frac{5.1\ \text{V}}{1.0\ \text{k}\Omega}$$

$$= 5.1\ \text{mA}$$

Using KCL, current through Zener diode, $I_Z = 8.3\ \text{mA} - 5.1\ \text{mA}$
$= 3.2\ \text{mA}$

A Zener diode can be used to convert the pulsating DC voltage produced by a rectifier into a steady DC voltage.

Figure 7.60 shows the pulsating DC output from the full-wave rectifier discussed in Section 7.4. As we can see, the voltage level varies continuously.

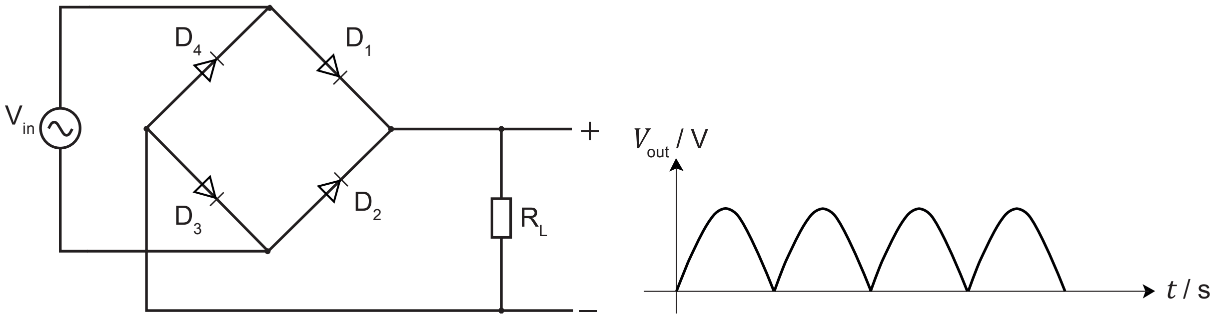


Figure 7.60 Pulsating output voltage from a full-wave rectifier

In Figure 7.61, a capacitor is added to the circuit shown in Figure 7.60. As the capacitor takes time to charge and discharge, the voltage across it will not be able to follow the fast-changing output of the rectifier. This causes the output voltage to vary over a much smaller range compared to the circuit in Figure 7.60. Thus, the capacitor is called a **voltage-smoothing capacitor**.

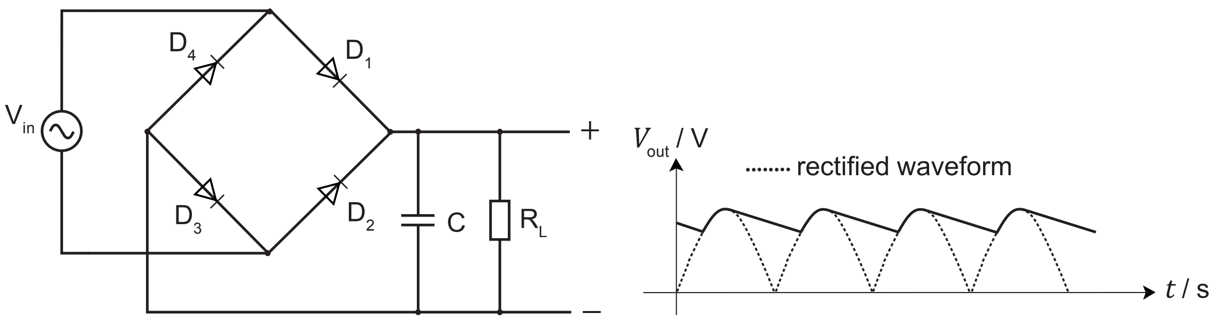


Figure 7.61 Output voltage smoothed with a capacitor

In Figure 7.62, a resistor, R_1, and a Zener diode are added to the circuit shown in Figure 7.61. If the voltage across the capacitor, V_C, is high enough such that $\frac{R_L}{R_1 + R_L} \times V_C$ is larger than the V_Z of the Zener diode, the voltage across the load, i.e., the output voltage, will be held constant at V_Z. Notice that the original pulsating DC voltage has now been regulated into a steady DC voltage.

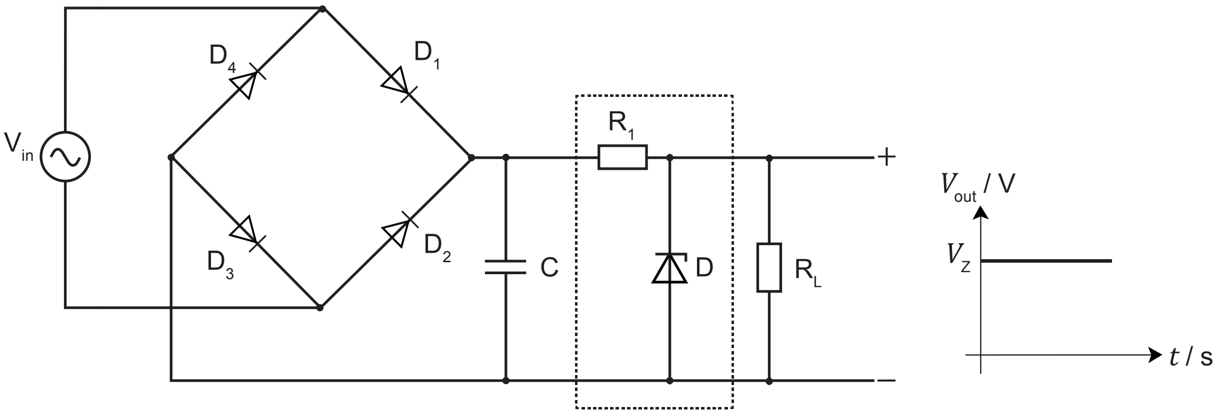


Figure 7.62 A steady output voltage is obtained after a Zener diode is added

Power dissipation

The power dissipated in a Zener diode can also be calculated using the equation $P = V \times I$.

Worked Example 7.6

Calculate the power dissipated in the Zener diodes used in Worked Examples 7.4 and 7.5.

Solution

(a) From Worked Example 7.4, the Zener diode acts as an open circuit. The voltage across it is equal to 4.1 V and the current through it is zero.

Power dissipated in Zener diode, $P = V \times I$
$= 4.1 \text{ V} \times 0 \text{ A}$
$= 0 \text{ W}$

(b) From Worked Example 7.5, the voltage across the Zener diode is 5.1 V and the current through the Zener diode is 5.3 mA.

Power dissipated in Zener diode, $P = V \times I$
$= 5.1 \text{ V} \times 3.2 \text{ mA}$
$= 16.3 \text{ mW}$

Review Questions 7.7

1. The Zener diode in Figure 7.63 has a Zener voltage, V_Z, of 5.1 V. Determine the voltage across R_L when the DC supply is set to (a) 6.0 V and (b) 12 V.

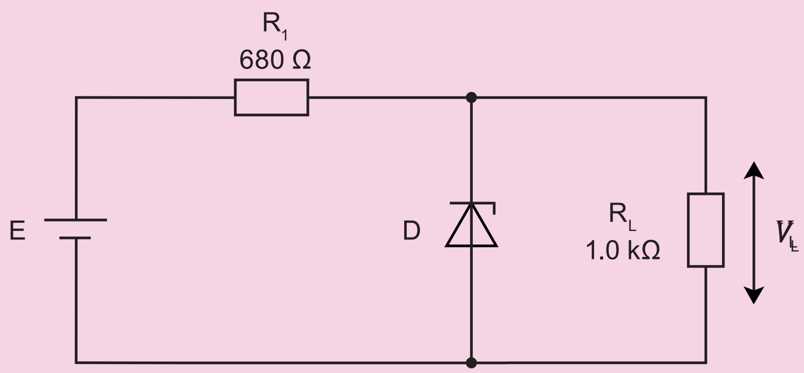


Figure 7.63

2. Calculate the power dissipated in the Zener diode in Figure 7.63 when the DC supply is set to (a) 6.0 V and (b) 12 V.

8 INPUT AND OUTPUT TRANSDUCERS

How do we select and use a suitable transducer?

We learnt in Chapter 1 that electronic systems can only process electrical signals. However, information about the environment exists in the form of non-electrical quantities. For example, the brightness of an environment is determined by the amount of light energy present. To convert between electrical and non-electrical quantities, we use a group of devices called transducers.

An example of a transducer is the motion sensor shown in Figure 8.1. When the sensor detects movement, it converts information about the movement (a non-electrical quantity) into an electrical signal. The electrical signal can then be used to activate the necessary action (e.g., sounding an alarm).

Figure 8.1 The motion sensor is an example of a transducer

In this chapter, we will learn about different types of transducers and how to use them.

8.1 What is the difference between input and output transducers?

Learning Outcomes

- Explain what is meant by an input and an output transducer.
- Give examples of input and output transducers.

Key Ideas

- Input transducers convert non-electrical information or quantities into electrical signals or quantities.
- Output transducers convert electrical signals or quantities into non-electrical information or quantities.

Transducers are devices that convert information or quantities from non-electrical to electrical form, or vice versa. Transducers can be classified as input and output transducers.

Input transducers

Input transducers convert non-electrical information or quantities into electrical signals or quantities as shown in Figure 8.2.

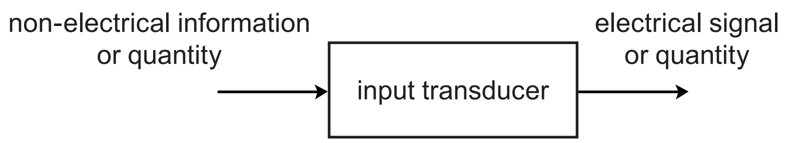


Figure 8.2 Conversion performed by an input transducer

Some examples of input transducers and their descriptions are shown in Figure 8.3.

thermistors convert temperature into electrical signals

light-dependent resistors (LDRs) convert light intensity into electrical signals

microphones convert sound energy into electrical signals

Figure 8.3 Examples of input transducers and the conversions they perform

Many input transducers also act as **sensors** as they can be used to detect certain conditions. For example, a thermistor can be used as a temperature sensor while a light-dependent resistor (LDR) can be used as a light sensor.

Output transducers

Output transducers convert electrical signals or quantities into non-electrical information or quantities as shown in Figure 8.4.

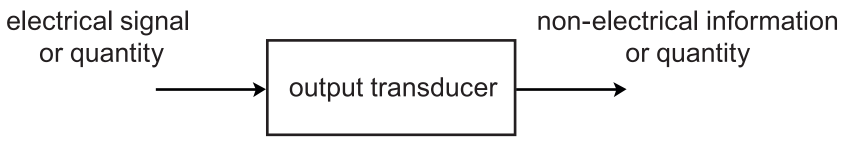
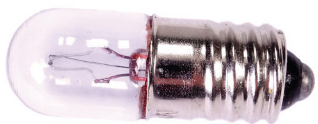


Figure 8.4 Conversion performed by an output transducer

Some examples of output transducers and their descriptions are shown in Figure 8.5.

LEDs convert electrical energy into light energy



filament bulbs convert electrical energy into light energy

loudspeakers (above) and buzzers (below) convert electrical signals into sound energy

motors convert electrical energy into mechanical energy

Figure 8.5 Examples of output transducers and the conversions they perform

Electronic systems usually have both input and output transducers. For example, Figure 8.6 shows the block diagram of an automatic cooling system that switches on a fan when the temperature of the surroundings exceeds a certain level. Here, the thermistor is an input transducer while the motor of the fan is an output transducer.

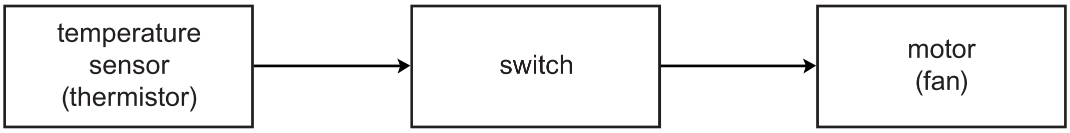


Figure 8.6 Block diagram of an automatic cooling system

Review Questions 8.1

1. Describe the functions of input and output transducers.
2. Give three examples of input transducers and describe their respective functions.
3. Give three examples of output transducers and describe their respective functions.

8.2 How do we use a thermistor to sense temperature?

Learning Outcomes

- Recall and apply the effect of changes in temperature on the resistance of a thermistor to practical situations.
- Interpret the characteristic graphs of thermistors.

Key Idea

- The resistance of a thermistor changes in accordance with its temperature. This characteristic enables thermistors to be used as temperature sensors.

Thermistors

A **thermistor** is a resistor whose resistance changes with temperature. There are two types of thermistors:

- **Negative temperature coefficient (NTC) thermistors** have resistances that decrease with temperature. Figure 8.7a and Figure 8.7b show a photo of an NTC thermistor and its symbol, respectively.

Figure 8.7a An NTC thermistor

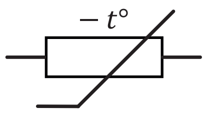


Figure 8.7b Symbol of an NTC thermistor

- **Positive temperature coefficient (PTC)** thermistors have resistances that increase with temperature. Figure 8.8a and Figure 8.8b show a photo of a PTC thermistor and its symbol, respectively.

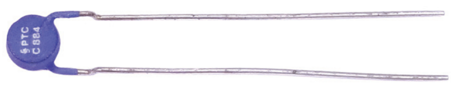


Figure 8.8a A PTC thermistor

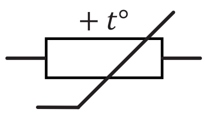


Figure 8.8b Symbol of a PTC thermistor

Since NTC thermistors are more commonly used, we will study them in greater detail in this course. However, we can apply the same understanding on PTC thermistors as well. Figure 8.9 shows the characteristic graph of an NTC thermistor. Notice that its resistance is high when the temperature is low. Its resistance then decreases in a non-linear manner as the temperature increases. We can determine the resistance of an NTC thermistor at a particular temperature from its characteristic graph. For example, from Figure 8.9, we can tell that its resistance is 10 kΩ at 25 °C.

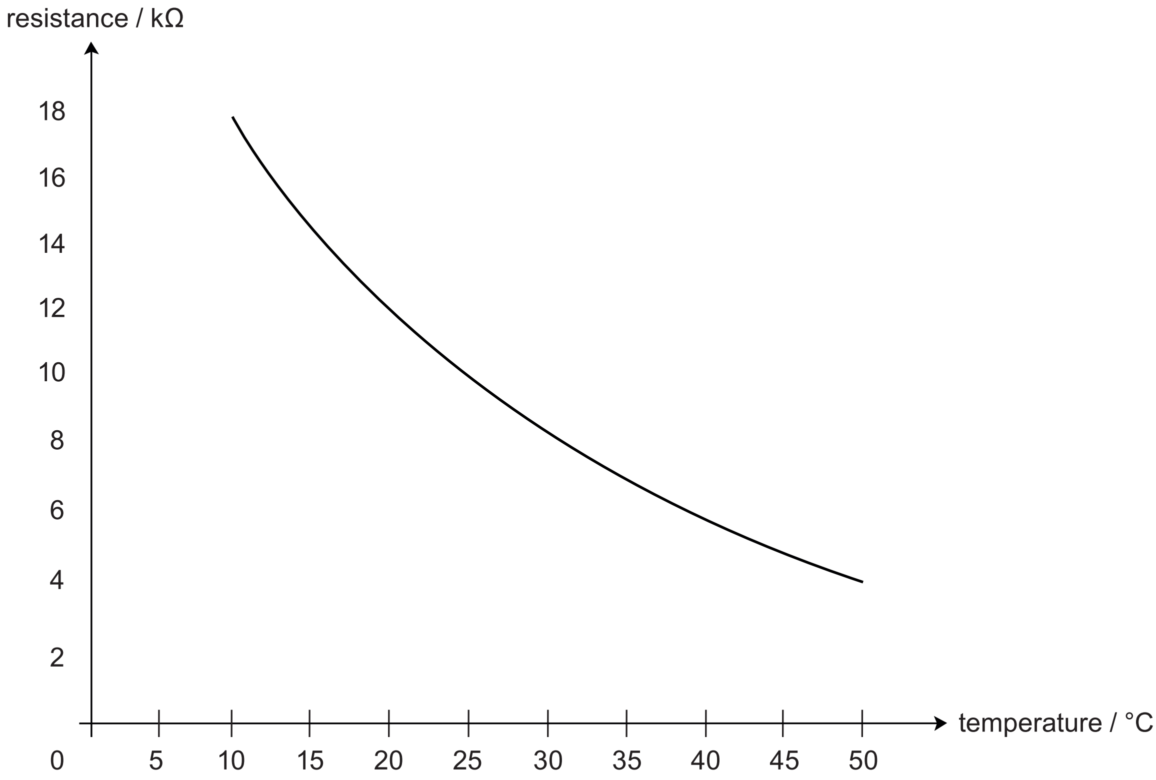


Figure 8.9 Characteristic graph of an NTC thermistor

Using thermistors as temperature sensors

This characteristic of thermistors enables them to be used as temperature sensors to convert information about temperature into electrical signals. As such, thermistors are commonly used in applications that require temperature control, such as refrigerators and air-conditioners.

Figure 8.10 Thermistors are used in refrigerators to control the temperature

Thermistors are often connected as part of a voltage-divider circuit, as shown in Figure 8.11. The output voltage, V_{out}, is the voltage across R_1.

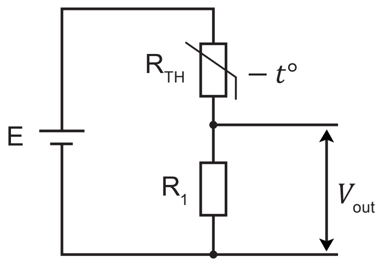


Figure 8.11 Voltage-divider circuit with an NTC thermistor

Using the voltage-divider formula, we can obtain an equation for V_{out}:

$$V_{out} = \frac{R_1}{R_1 + R_{TH}} \times E$$

V_{out} changes with temperature in the following manner:

- When the temperature increases, R_{TH} decreases, causing V_{out} to increase.
- When the temperature decreases, R_{TH} increases, causing V_{out} to decrease.

For applications that require V_{out} to decrease with temperature, we can swap the positions of R_1 and R_{TH} in the circuit.

Determining the value of R_1

To obtain the required output voltage at a particular temperature, the value of R_1 needs to be carefully selected. We need to first determine the resistance of the thermistor at that temperature either from the characteristic graph or by measurement.

Consider a situation where we need V_{out} to be 5.0 V when the temperature is 40 °C. Assume $E = 9.0$ V and R_{TH} is found to be 6.0 kΩ at 40 °C. Substituting the values into the equation, we obtain:

$$5.0\ \text{V} = \frac{R_1}{R_1 + 6.0\ \text{k}\Omega} \times 9.0\ \text{V}$$

$$R_1 = 7.5\ \text{k}\Omega$$

We can use a 0–10 kΩ variable resistor for R_1 and adjust its resistance until 7.5 kΩ is obtained.

Worked Example 8.1

An NTC thermistor has the following resistances at 20 °C and 50 °C:

Temperature	Resistance
20 °C	10 kΩ
50 °C	4.0 kΩ

The thermistor is used in the circuit shown in Figure 8.12. Determine the change in the output voltage as the temperature increases from 20 °C to 50 °C.

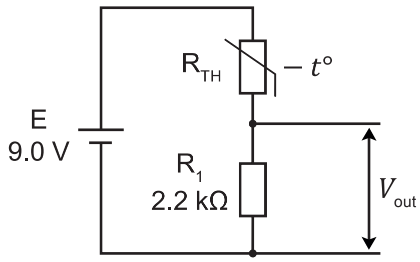


Figure 8.12

Solution

At 20 °C, $R_{TH} = 10\,000\ \Omega$

$$V_{out} = \frac{R_1}{R_1 + R_{TH}} \times E$$

$$= \frac{2200\ \Omega}{2200\ \Omega + 10\,000\ \Omega} \times 9.0\ \text{V}$$

$$= 1.6\ \text{V}$$

At 50 °C, $R_{TH} = 4000\ \Omega$

$$V_{out} = \frac{R_1}{R_1 + R_{TH}} \times E$$

$$= \frac{2200\ \Omega}{2200\ \Omega + 4000\ \Omega} \times 9.0\ \text{V}$$

$$= 3.2\ \text{V}$$

As the temperature increases from 20 °C to 50 °C, the output voltage increases from 1.6 V to 3.2 V.

Worked Example 8.2

Figure 8.13 shows a voltage-divider circuit consisting of an NTC thermistor and a variable resistor. The resistance of the thermistor, R_{TH}, is found to be 8.0 kΩ at 30 °C. Determine a suitable value of R_1 if an output voltage of 4.0 V is needed at 30 °C.

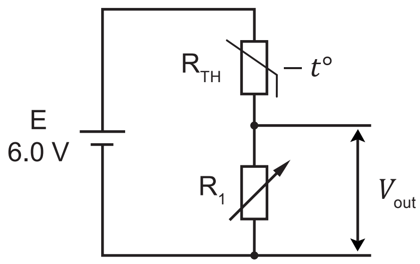


Figure 8.13

Solution

$$V_{out} = \frac{R_1}{R_1 + R_{TH}} \times E$$

$$4.0\ \text{V} = \frac{R_1}{R_1 + 8000\ \Omega} \times 6.0\ \text{V}$$

$$R_1 = 16\ \text{k}\Omega$$

We can use a 0–50 kΩ variable resistor and adjust its resistance to 16 kΩ.

Review Questions 8.2

1. An NTC thermistor is connected as shown in Figure 8.14. Explain what happens to the output voltage when the temperature of the surroundings increases.

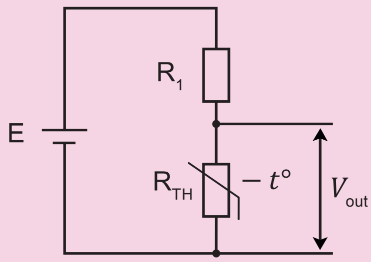


Figure 8.14

2. For the circuit in Figure 8.15, calculate the resistance of the NTC thermistor if the output voltage is 3.0 V.

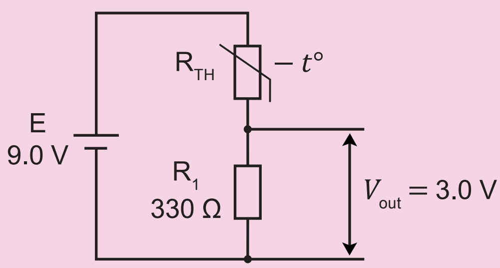


Figure 8.15

8.3 How do we use a light-dependent resistor to sense the brightness of our surroundings?

Learning Outcomes

- Recall and apply the effect of changes in light intensity on the resistance of an LDR to practical situations.
- Interpret the characteristic graphs of LDRs.

Key Idea

- The resistance of an LDR changes in accordance with the intensity of light that falls on it. This characteristic enables LDRs to be used as light sensors.

Light-dependent resistors

A **light-dependent resistor (LDR)** is a resistor whose resistance changes with the intensity of the light that falls on it.

Figure 8.16a and Figure 8.16b show a photo of an LDR and its symbol, respectively.

Figure 8.16a An LDR

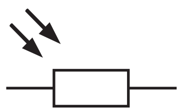


Figure 8.16b Symbol of an LDR

Figure 8.17 shows the characteristic graph of an LDR. Notice that the resistance of the LDR is high when the light intensity is low (dark). The resistance then decreases in a non-linear manner as the light intensity increases.

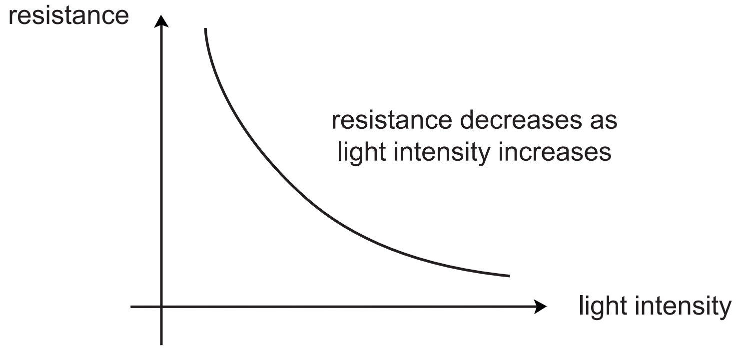


Figure 8.17 Characteristic graph of an LDR

In this course, we will mainly use the type of LDR shown in Figure 8.16a, which comes in various sizes. In general, under the same light intensity, a bigger LDR will have lower resistance than a smaller one. Table 8.1 shows their approximate range of resistances under different light intensities.

Table 8.1 Resistance of an LDR under different light intensities

Light intensity	Resistance of LDR
Total darkness	≥100 kΩ
Indoors	1–5 kΩ
Bright sunlight	≤500 Ω

Using LDRs as light sensors

This characteristic of LDRs enables them to be used as light sensors to convert information on light intensity into electrical signals. Light sensors can thus be used for automatic brightness control, which has become an increasingly common feature for smartphones, street lights and digital alarm clocks.

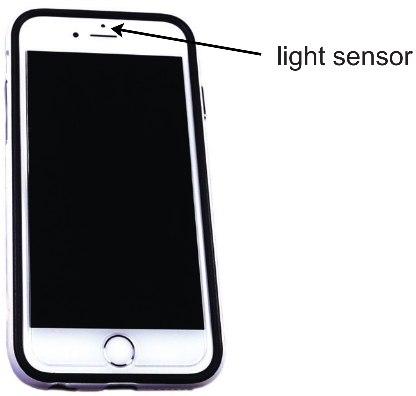


Figure 8.18 The light sensor in this smartphone allows the brightness of its screen to be adjusted automatically according to the brightness of the surroundings

Figure 8.19 The light sensor in this digital alarm clock allows the brightness of its display to be dimmed automatically at night for more comfortable viewing

Similar to the thermistor, LDRs are often connected as part of a voltage-divider circuit as shown in Figure 8.20. The output voltage, V_{out} , is the voltage across R_1.

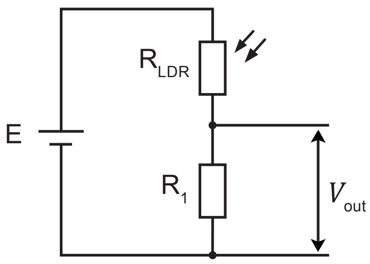


Figure 8.20 Voltage-divider circuit with LDR

Using the voltage-divider formula, we can obtain an equation for V_{out}:

$$V_{out} = \frac{R_1}{R_1 + R_{LDR}} \times E$$

V_{out} changes with light intensity in the following manner:

- When light intensity increases, R_{LDR} decreases, causing V_{out} to increase.
- When light intensity decreases, R_{LDR} increases, causing V_{out} to decrease.

For applications that require V_{out} to decrease with light intensity, we can swap the positions of R_1 and R_{LDR} in the circuit.

Like the case of the thermistor, the value of R_1 needs to be carefully selected to obtain the required output voltage. The same method used to determine the value of R_1 for the thermistor circuit in Figure 8.11 can be applied here.

Worked Example 8.3

An LDR has the following resistances:

Brightness of surroundings	Resistance
Bright	1.0 kΩ
Dark	20 kΩ

Design a circuit using the above LDR to provide an output voltage of:

- 3.0 V or higher when the surroundings are bright; and
- 1.0 V or lower when the surroundings are dark.

A 5.0 V DC source is available.

Solution

A possible solution is to use a voltage-divider circuit shown in Figure 8.20. We need to determine a suitable value of R_1.

When bright:

$$V_{\text{out}} = \frac{R_1}{R_1 + R_{\text{LDR}}} \times E$$

$$3.0\ \text{V} = \frac{R_1}{R_1 + 1000\ \Omega} \times 5.0\ \text{V}$$

$$R_1 = 1.5\ \text{k}\Omega \text{ or larger}$$

When dark:

$$V_{\text{out}} = \frac{R_1}{R_1 + R_{\text{LDR}}} \times E$$

$$1.0\ \text{V} = \frac{R_1}{R_1 + 20\,000\ \Omega} \times 5.0\ \text{V}$$

$$R_1 = 5.0\ \text{k}\Omega \text{ or smaller}$$

We need R_1 to be between 1.5 kΩ and 5.0 kΩ. We can choose a suitable resistance value from the E24 resistor series, e.g., 3.3 kΩ. Alternatively, we can use a 0–10 kΩ variable resistor and adjust its value until it falls within the required range.

Review Questions 8.3

1. For the circuit in Figure 8.21, calculate the resistance of the LDR when the output voltage is 5.0 V.

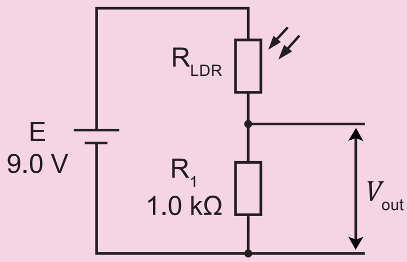


Figure 8.21

2. An LDR is connected as shown in Figure 8.22. Explain what happens to the output voltage when the brightness of the surroundings decreases.

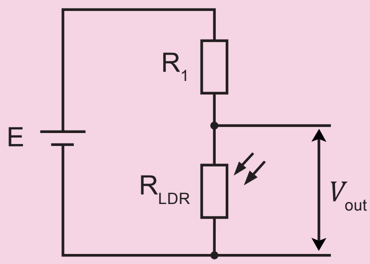


Figure 8.22

8.4 What are some examples of common transducers and their functions?

Learning Outcomes

- Describe the use of infrared diodes as transmitting and receiving devices.
- Describe the function of the following transducers: microphone, loudspeaker, buzzer, low-voltage DC motor and electromechanical relay.

Key Ideas

- Infrared (IR) diodes are input transducers that convert electrical energy into IR rays.
- Microphones are input transducers that convert sound energy into electrical signals.
- Buzzers and loudspeakers are output transducers that convert electrical signals into sound energy.
- DC motors are output transducers that convert electrical energy into mechanical energy.
- Electromechanical relays are switches operated by a small current that can turn on or off a much larger current.

Infrared diodes and photodiodes

Figure 8.23 shows a television remote control unit. Did you notice an LED at the edge of the remote control unit? This LED is an infrared diode.

Figure 8.23

An **infrared (IR) diode** is an LED that emits infrared instead of visible light rays. Both infrared and visible light rays are part of a group of energy waves called **electromagnetic waves**. Human eyes are not able to see infrared rays.

Figure 8.24a and Figure 8.24b show an IR diode and its symbol, respectively.

Figure 8.24a An IR diode

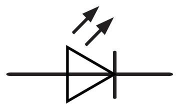


Figure 8.24b Symbol of an IR diode

Notice that the symbol is the same as that of a normal LED. Because human eyes cannot see IR rays, we would not be able to tell by visual inspection whether an IR diode is switched on or off. Instead, we use a photodiode.

When reverse-biased, a **photodiode** only allows a current to pass through easily when it is exposed to IR rays. The size of the current through a photodiode increases with the intensity of IR radiation it is exposed to.

Figure 8.25a and Figure 8.25b show a photodiode and its symbol, respectively. Notice that the symbol is the same as that of a normal LED except the arrows are pointing towards the diode instead.

Figure 8.25a A photodiode

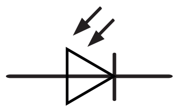


Figure 8.25b Symbol of a photodiode

Figure 8.26 shows two circuits – the one on the left has an IR diode (D_1) and the one on the right has a photodiode (D_2). The output voltage, V_{out}, is the voltage across R_2. Notice that D_1 is forward-biased but D_2 is reverse-biased.

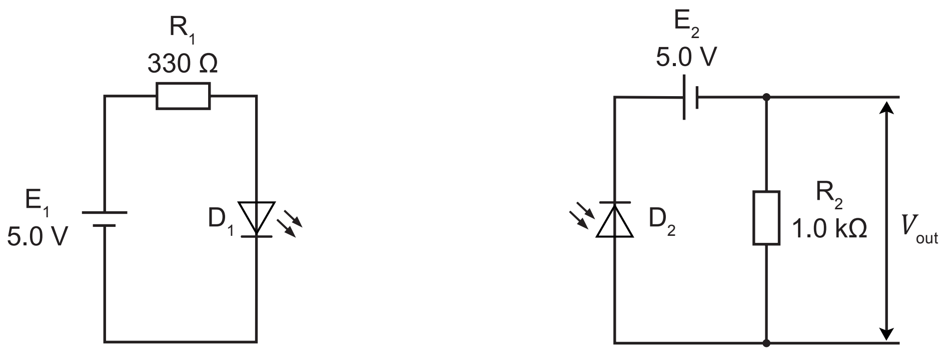


Figure 8.26 Using an IR diode and a photodiode to detect passing objects

When there is no object between D_1 and D_2, some of the IR rays emitted by D_1 will fall on D_2. Thus, there will be a current through D_2 and the output voltage will be more than 0 V. When an object comes in between D_1 and D_2, no IR rays will fall on D_2. There will be no current through D_2 and the output voltage will be zero. This setup can be used for a number of applications, such as a counter keeping track of the number of people who have walked past a particular point.

Microphones

A **microphone** is an input transducer that converts sound energy into electrical signals. Figure 8.27 shows a common type of microphone. All microphones have a thin sheet of material (usually plastic or paper) called a diaphragm which vibrates according to the sound waves that it receives. The vibration causes the relative positions of a coil of wire and a magnet in the microphone to change, which generates electrical output signals.

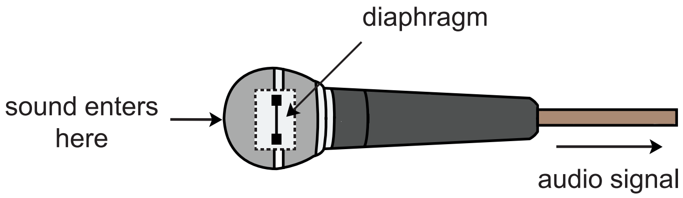


Figure 8.27 Basic operation of a microphone

Many electronic devices, such as mobile phones, laptops and guitar tuners, have built-in microphones to pick up sound, as shown in Figure 8.28.

Figure 8.28 Examples of devices with built-in microphones

Figure 8.29 shows the symbol of a microphone.

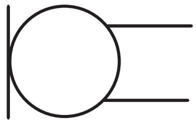


Figure 8.29 Symbol of a microphone

The electret microphone shown in Figure 8.30 is a type of low-cost microphone commonly used in electronics. This small-bodied microphone consists of a flat front that receives the sound waves and two terminals for connecting to an external circuit.

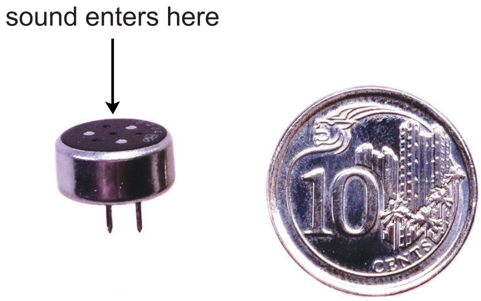


Figure 8.30 An electret microphone, shown with a 10-cent coin for comparison

To connect an electret microphone correctly, we should first identify its positive and negative terminals. The most reliable way would be to measure the resistance between the casing and each terminal with a multimeter as shown in Figure 8.31. Since the negative terminal is connected to the metal casing, a much lower resistance reading would be obtained compared to the measurement between the positive terminal and the metal casing.

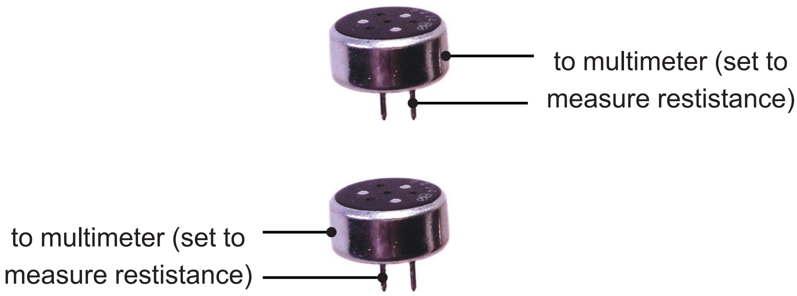


Figure 8.31 Using a multimeter to determine the terminals of an electret microphone – the terminal that gives a lower reading is the negative terminal

Once the terminals have been identified, we can connect the electret microphone to a circuit. A possible way is shown in Figure 8.32 where the positive terminal of the electret microphone is connected to a DC source through a resistor. The voltage at the positive terminal of the microphone varies with the sound that enters the microphone. The capacitor acts as a coupling capacitor (see Section 9.3) which allows the electrical signal from the microphone to pass through but blocks the DC voltage from reaching the output terminals.

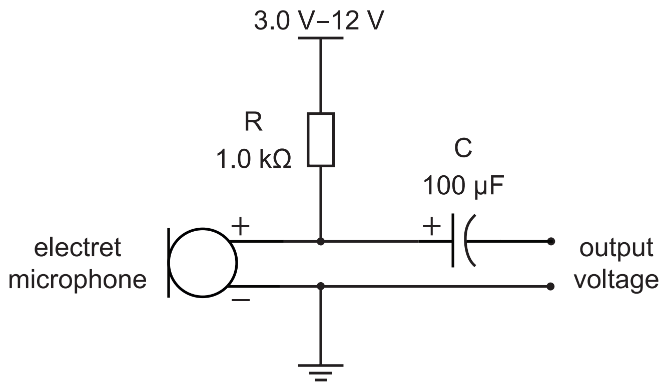


Figure 8.32 Connecting an electret microphone

Buzzers

A **buzzer** is an output transducer which converts an electrical signal into a beeping or buzzing sound. Buzzers can be found in many appliances such as microwave ovens and washing machines to alert their users of certain events.

In this course, we will mainly be using piezoelectric buzzers which come in different sizes as shown in Figure 8.33.

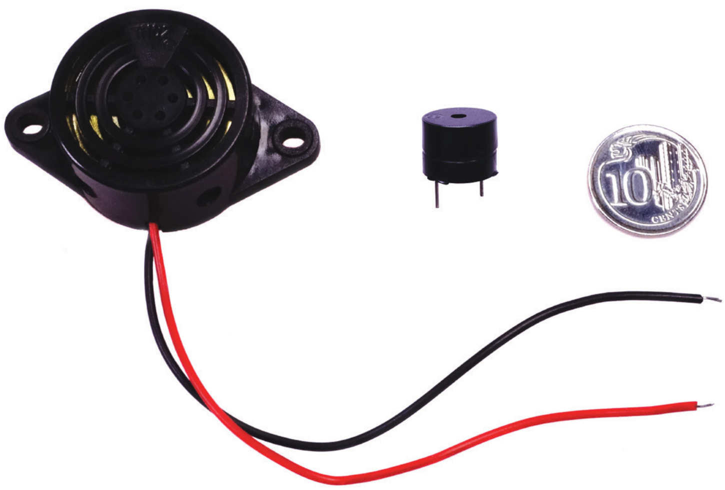


Figure 8.33 Two piezoelectric buzzers of different sizes, shown next to a 10-cent coin for comparison

Figure 8.34 shows the symbol of a buzzer.

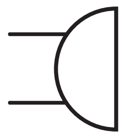


Figure 8.34 Symbol of a buzzer

Figure 8.35 shows the internal structure of a piezoelectric buzzer. When a DC voltage is applied across the terminals, the piezoelectric plate will bend back and forth to produce a vibration which in turn produces a sound.

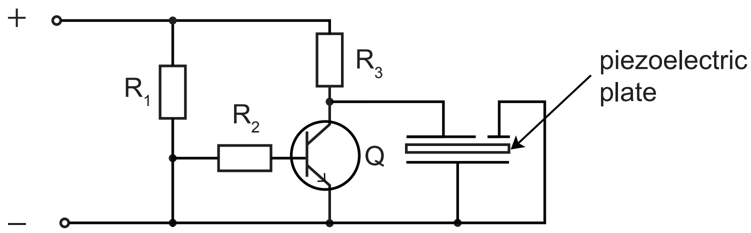


Figure 8.35 Internal structure of a piezoelectric buzzer

To connect a buzzer correctly, we should first identify its negative and positive terminals. The positive terminal can be identified by a red wire or a '+' sign marked on the buzzer.

Once the terminals have been identified, we can connect the buzzer to a circuit. A possible way is shown in Figure 8.36. When the buzzer is connected to the voltage source, it will produce a beeping sound. Most piezoelectric buzzers will work with a supply voltage of 3.0–12 V, but we should always refer to the datasheet to be certain.

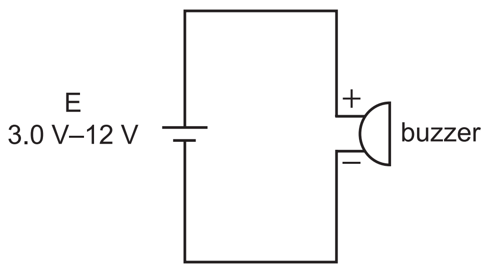


Figure 8.36 Connecting a buzzer

Loudspeakers

A **loudspeaker** is an output transducer that converts electrical signals into sound energy. Figure 8.37 shows the front and back views of a simple loudspeaker. It has two terminals for connecting to an external circuit.

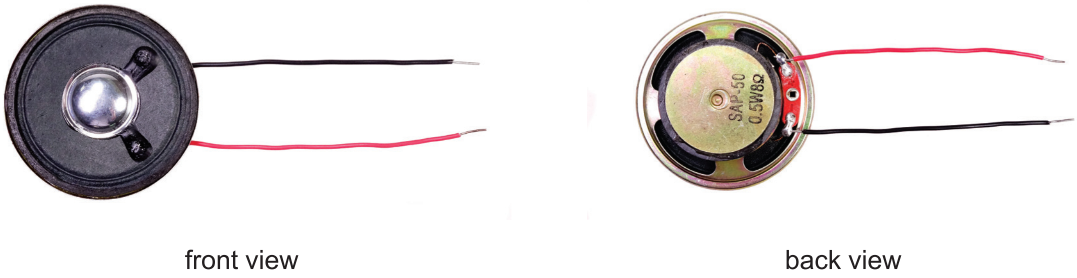


Figure 8.37 Front and back view of a loudspeaker

Figure 8.38 shows the structure of a simple loudspeaker, which consists of a cone, a coil and a magnet. When electrical signals (in the form of currents) pass through the coil, the cone will vibrate accordingly and produce sound. Unlike buzzers, which can only produce beeping or buzzing sounds, loudspeakers can produce more complex sounds such as music and human voices.

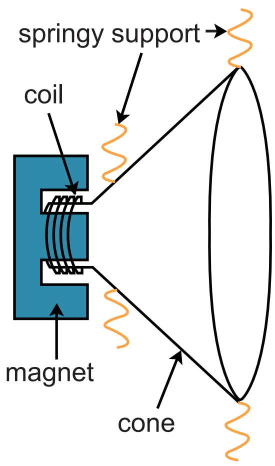


Figure 8.38 Basic structure of a simple loudspeaker

Figure 8.39 shows the symbol of a loudspeaker.

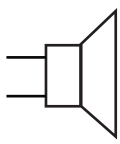


Figure 8.39 Symbol of a loudspeaker

To produce sound with a loudspeaker, we usually need an amplifier circuit, which will be covered in greater detail in Chapter 9. Figure 8.40 shows how the sound received by a microphone is played by a loudspeaker through an amplifier. The electrical signals produced by a microphone are too weak to drive a loudspeaker on their own. Hence, an amplifier is needed to increase the electrical power of the signal.

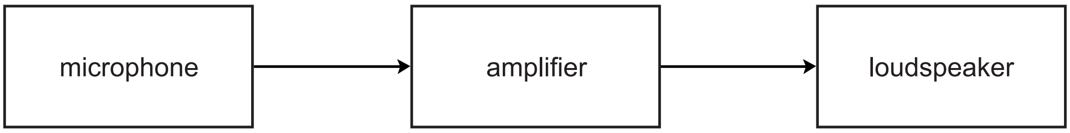


Figure 8.40 Driving a loudspeaker using an amplifier

DC motors

A **motor** is an output transducer that converts electrical energy into mechanical energy. Figure 8.41 shows two examples of low-voltage DC motors. A motor has two terminals for connecting to an external circuit.

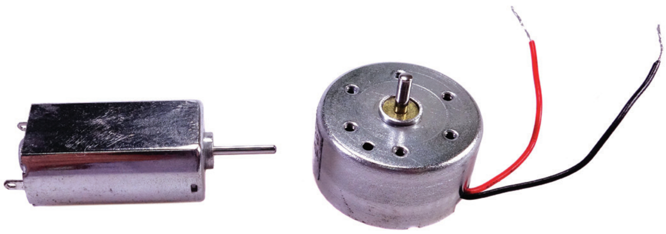


Figure 8.41 Two examples of low-voltage DC motors

Figure 8.42 shows the symbol of a motor.

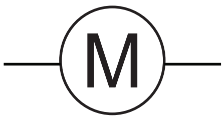


Figure 8.42 Symbol of a motor

Figure 8.43 shows the basic structure of a DC motor. When a current flows into the coil of wire, a magnetic field is produced. This magnetic field interacts with the magnetic field of the magnet to produce a force that rotates the coil and the shaft.

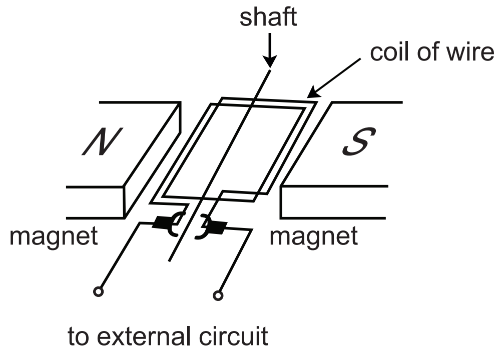


Figure 8.43 Basic structure of a DC motor

In this course, we will mainly be using low-voltage DC motors that work with a DC voltage that is between 3 V and 12 V. We can connect a DC motor directly to a DC source. However, if the DC motor is used with a transistor (see Chapter 9), we need to connect a reverse-biased diode in parallel with the motor as shown in Figure 8.44.

Without this diode, the magnetic field of the coil in the motor will produce a large negative voltage spike each time the motor is switched off. This will likely damage the transistor. When used for this purpose, the diode is known as a **'flyback' diode** or **'flywheel' diode**.

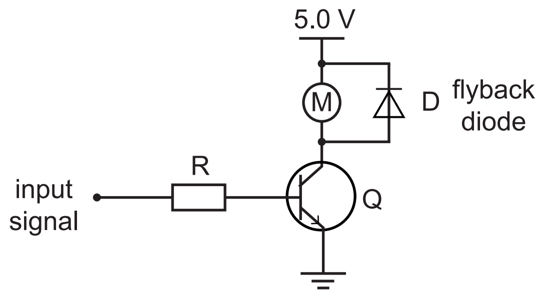


Figure 8.44 Using a flyback diode to protect a transistor that is connected to a DC motor

Electromechanical relays

The mechanical switches in Section 4.1 are opened and closed with a physical force. An **electromechanical relay** is a special type of mechanical switch that is opened and closed by a current instead.

Figure 8.45 shows the basic structure of a simple electromechanical relay. When no current flows through the coil, the contacts are opened.

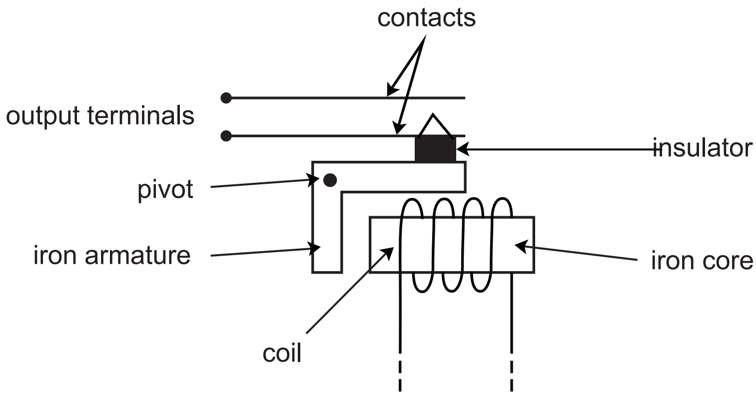


Figure 8.45 Basic structure of an electromechanical relay

When a current flows through the coil as shown in Figure 8.46, the iron core becomes an electromagnet and attracts the iron armature, which in turn closes the contacts. Only a small current is needed to magnetise the iron core. However, the current through the contacts can be much larger.

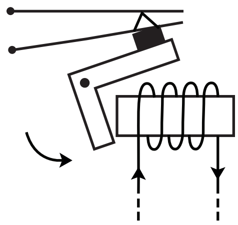


Figure 8.46 The contacts of the relay close when a current flows through its coil

Figure 8.47 shows two common types of electromechanical relays. We need to consider the voltage and current ratings when choosing a relay. For example, the '24 V' printed on the label of the relay on the left indicates the maximum DC voltage that should be applied across the coil of the relay. Hence, this relay should not be used for applications with voltages that exceed 24 V.

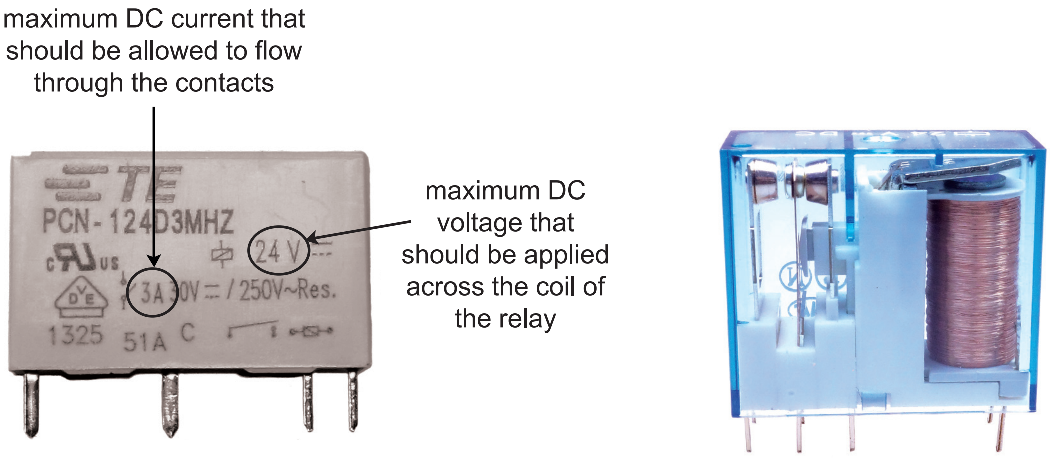


Figure 8.47 Two examples of electromechanical relays

Like other mechanical switches, electromechanical relays also come in SPST and SPDT forms. Their respective symbols are shown in Figure 8.48. The rectangular box in the symbols represents the coil in the relay.

Notice the terms 'NO' and 'NC' indicated on the symbol of the SPDT relay. NO stands for 'normally open' while NC stands for 'normally closed'. When the NO terminal is used, the switch will be open when no current flows through the coil and closed when a current flows through the coil. The opposite will happen if the NC terminal is used.

SPST electromechanical relay

SPDT electromechanical relay

Figure 8.48 Symbols of SPST and SPDT electromechanical relays

An important benefit of using relays is to allow low-power electronic circuits (e.g., digital circuits) that use small currents and low voltages to switch on devices that require much larger currents. Figure 8.49 shows how a 5 V circuit is able to switch on a 24 V motor through a relay.

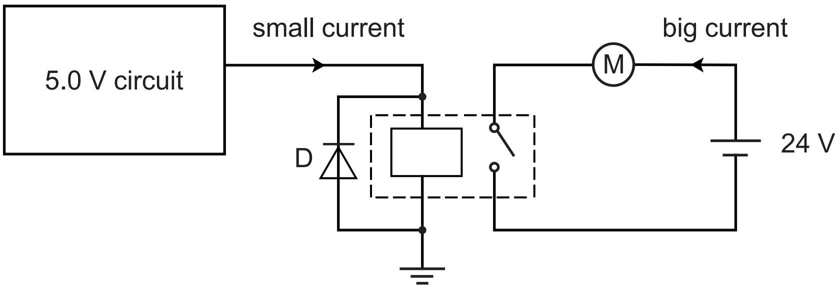


Figure 8.49 A relay allows a low-power circuit to switch on a high-power device

Like the motor, a flyback diode is also needed to prevent a voltage spike from damaging the 5 V circuit when the current to the relay is suddenly cut off.

Review Questions 8.4

1. Describe the functions of the following transducers:
   (a) NTC thermistor
   (b) LDR
   (c) Microphone
   (d) Buzzer
   (e) Loudspeaker
   (f) Motor

2. Draw the symbols of the following transducers:
   (a) Thermistor
   (b) LDR
   (c) Microphone
   (d) Buzzer
   (e) Loudspeaker
   (f) Motor

3. Suggest a suitable transducer for the following applications:
   (a) A lighting system that automatically becomes dimmer as the brightness of the surroundings increases
   (b) A sensor that can detect when the temperature of the surroundings exceeds 40 °C
   (c) A device that produces a sound in the presence of an electric signal
   (d) A device that uses a small current to switch on a high-current motor

9 BIPOLAR JUNCTION TRANSISTORS

How do we select and use a suitable bipolar junction transistor?

Besides the diode, another important semiconductor device is the transistor. Transistors are used in small quantities to perform useful functions such as switching, amplification, driving electrical loads and making logic decisions.

They are also used in larger quantities (ranging from tens to even billions) as part of integrated circuits (ICs). The microprocessors and memory chips found in computers and mobile phones are examples of such ICs.

Figure 9.1 A microprocessor IC contains millions or even billions of transistors

In this chapter, you will learn about the most basic transistor – the bipolar junction transistor – how it works and how to use it to perform switching, drive loads and amplify signals.

9.1 What is the structure of a bipolar junction transistor?

Learning Outcome

- Describe the structures of the two types of bipolar junction transistor.

Key Ideas

- Bipolar junction transistors consist of three layers of semiconductors arranged either in the order NPN or PNP.
- Every bipolar junction transistor has three terminals: base, emitter and collector. To identify the terminals correctly, we should refer to the datasheet of the transistor.

Bipolar junction transistors (BJTs) come in a range of packaging. Figure 9.2 shows some common types of BJT packaging. In general, the smaller BJTs (e.g., the TO-92 types) are used for low-power applications such as signal amplification while the larger ones (e.g., the TO-3 types) are used for high-power applications such as driving powerful loudspeakers in cinemas.

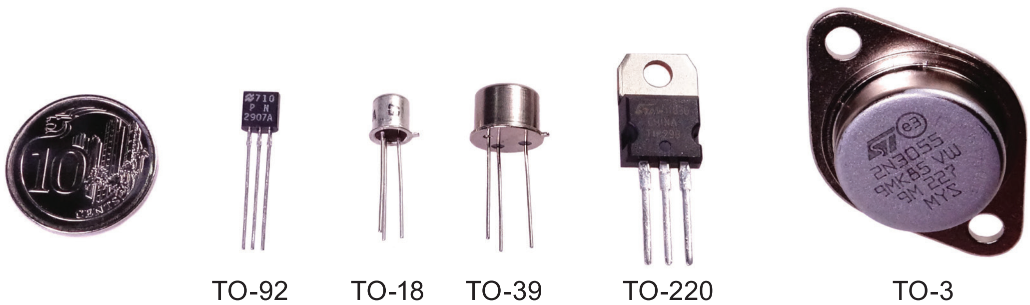


Figure 9.2 Common types of BJT packaging and their sizes as compared to a 10-cent coin

BJTs can be classified into two main types: **NPN** and **PNP**.

Figure 9.3 shows an NPN BJT, which consists of a thin layer of p-type semiconductor sandwiched between two thicker layers of n-type semiconductor. The centre layer is called the **base** while the two thicker layers at the ends are called the **collector** and the **emitter**, respectively. These three layers are connected to three external terminals (also called base, collector and emitter) as shown in Figure 9.3.

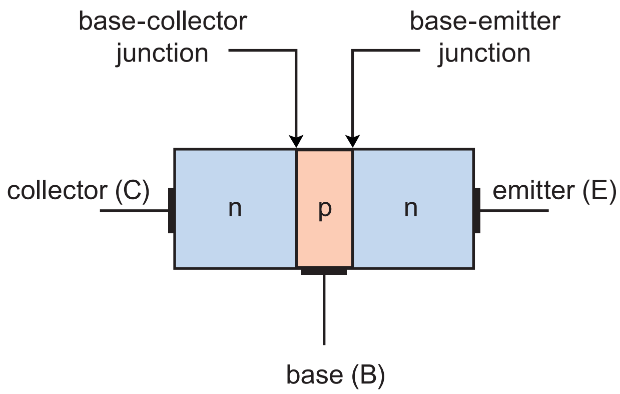


Figure 9.3 Basic structure of an NPN BJT

Notice that the base and emitter form a diode while the base and collector form another diode. The PN junction between the base and collector is called the **base-collector junction** while the PN junction between the base and emitter is called the **base-emitter junction**.

A PNP BJT consists of a thin layer of n-type semiconductor sandwiched between two thicker layers of p-type semiconductor as shown in Figure 9.4.

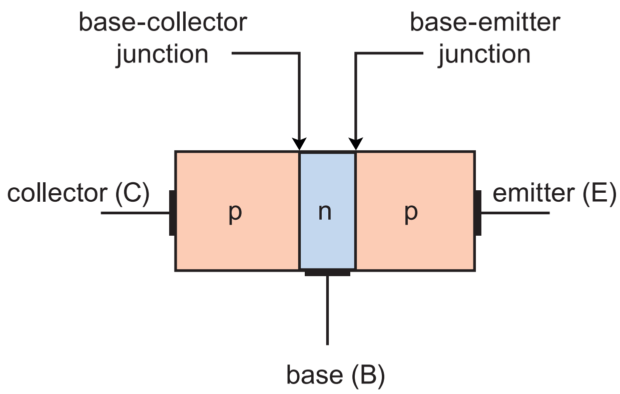


Figure 9.4 Basic structure of a PNP BJT

The symbols for NPN and PNP BJTs are shown in Figure 9.5. Notice that the arrow in the NPN symbol is pointing outwards while the arrow in the PNP symbol is pointing inwards.

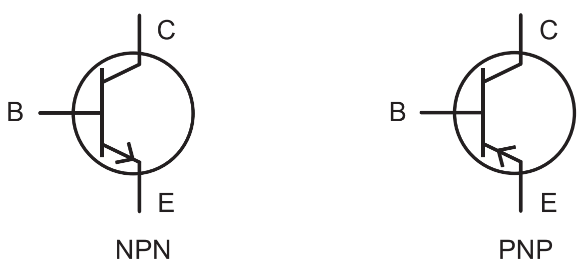


Figure 9.5 Symbols of NPN and PNP BJTs

As BJTs can be damaged if they are wrongly connected, it is important to identify their terminals correctly by referring to their respective datasheets. Figure 9.6 shows an extract from the datasheet of the 2N3904 NPN BJT in TO-92 packaging. For this type of packaging, the flat face of the BJT is used as the reference point. It is important to note that the arrangement of the pins can vary between different models of BJTs even if they have similar types of packaging. Hence, we should always refer to their datasheets to be sure.

Semiconductor Technical Data

2N3904

NPN General Purpose Transistor

Description

The device is designed as a general purpose switch and amplifier.

TO-92
CASE 29
STYLE 1

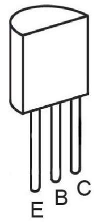


Figure 9.6 Extract from the datasheet of a 2N3904 NPN BJT

Figure 9.7 shows an extract from the datasheet of the 2N2222A BJT in TO-18 packaging. For this type of packaging, the protrusion of the BJT is used as the reference point.

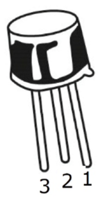
Semiconductor Technical Data

2N2222A

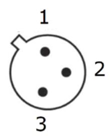
NPN General Purpose Transistor

Description

The device is designed for high speed switching at a collector current of up to 500 mA. It also provides useful current gain for medium power amplification.



1. Emitter
2. Base
3. Collector



bottom view

Figure 9.7 Extract from the datasheet of a 2N2222A NPN BJT

Both the 2N3904 and 2N2222A BJTs are widely used, low-cost and easily available. The semiconductor used to make them is silicon.

Review Questions 9.1

1. State the three terminals of a BJT.
2. State the two main types of BJTs and draw their respective symbols.
3. Describe how the terminals of a BJT can be correctly identified.

9.2 How does a BJT work?

Learning Outcomes

- Describe the working principle of a BJT.
- Describe the different operating regions of BJTs.
- Relate the operating regions to the different segments of an I_C-V_{CE} characteristic graph.
- Relate the operating regions to the use of a BJT as a switch and amplifier.
- Interpret the typical specifications of a BJT (β, $I_{C(max)}$, V_{BE}, $V_{CE(sat)}$) by referring to its datasheet.

Key Ideas

- A small current going in or out of the base of a BJT controls a bigger current between its collector and emitter.
- The BJT has three regions of operation: cutoff, active and saturation.
- When working as a switch, the BJT alternates between the cutoff and saturation region. When working as an amplifier, the BJT works in the active region.

How a BJT works

A BJT uses a small current at its base to control a larger current flowing between its collector and emitter. Figure 9.8 illustrates this operation. For NPN BJTs, the current flowing *into* the base determines the current flowing from the collector to the emitter. For PNP BJTs, the current flowing *out of* the base determines the current flowing from the emitter to the collector.

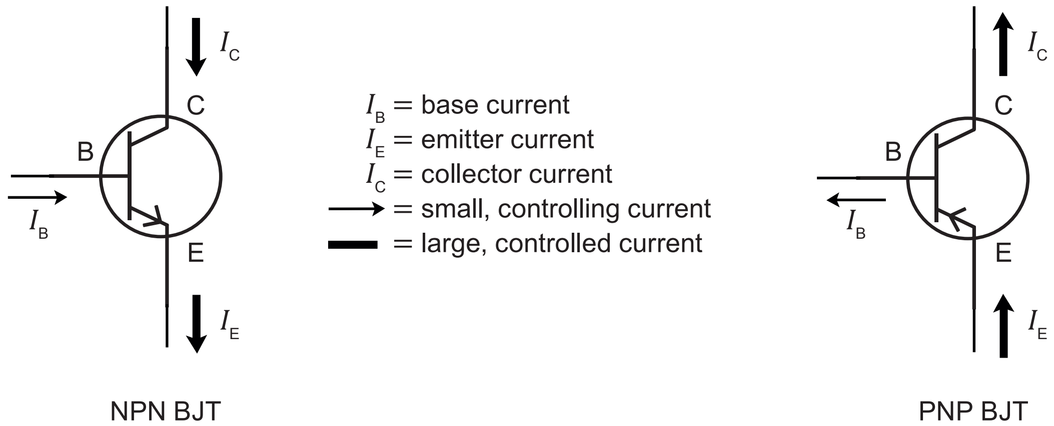


Figure 9.8 How a BJT works

In this textbook, we will focus our discussion on NPN BJTs. However, the ideas are applicable to PNP BJTs as well since they work in a similar way except that the polarities of the voltages and directions of the currents are reversed.

The water system shown in Figure 9.9 is an analogy for the NPN BJT. Water flowing down path B will push a flap which causes a stopper along path C to be lifted. The water from path B will then merge with the water from path C to flow down path E. In other words, the volume of the water flowing down path E is equal to the sum of the volume of water from paths B and C.

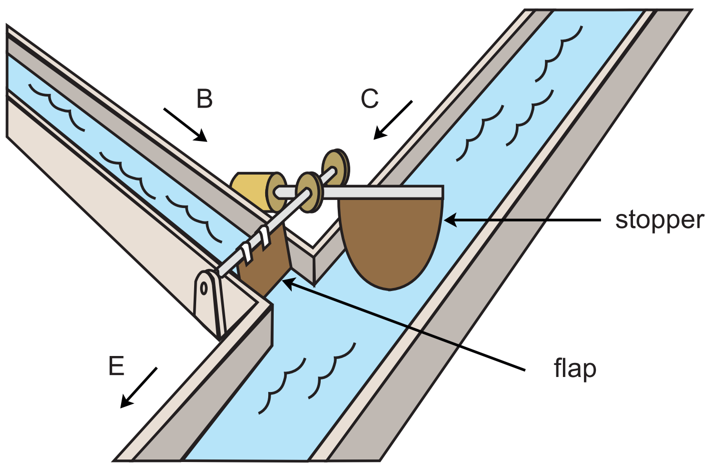


Figure 9.9 Using a water system to explain how a BJT works

This is how the water system works:

- When there is no water flowing down path B, the stopper is not lifted at all and blocks path C completely. No water is able to flow from path C to path E. You will learn later that this corresponds to the 'cutoff' region of a BJT.
- When a small water current flows down path B, the stopper is lifted slightly. This allows water to flow from path C to path E. If the rate of water flow along path B is increased, the stopper will be lifted higher. This increases the rate of water flow from path C to path E. You will learn later that this corresponds to the 'active' region of a BJT.
- When the rate of water flow along path B increases to a certain level, the stopper will be fully lifted and the water flow from path C to path E will reach a maximum rate. When this happens, increasing the rate of water flow along path B will not increase the rate of water flow from path C to path E further. You will learn later that this corresponds to the 'saturation' region of the BJT.

Figure 9.10 shows a circuit that can be used to investigate the operation of an NPN BJT. The circuit consists of three ammeters which measure the current at the base (I_B), collector (I_C) and emitter (I_E).

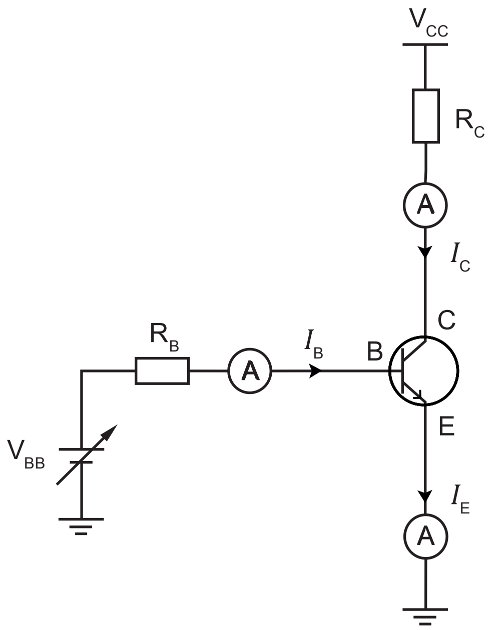


Figure 9.10 Circuit to investigate the operation of an NPN BJT

V_{CC} is the voltage supply. The size of I_B is adjusted using the variable DC voltage source, V_{BB}, connected to the base. R_B is a current-limiting resistor which prevents I_B from becoming large enough to damage the BJT. We will notice the following as we increase I_B from zero:

- When I_B is zero, I_C and I_E are nearly zero.
- As I_B increases from zero, I_C and I_E increase with I_B.
- After I_B exceeds a certain level, I_C and I_E will remain nearly constant at a maximum value.
- Throughout the experiment, I_E is the sum of I_B and I_C.

Notice the similarities between the operation of the water system in Figure 9.9 and the circuit in Figure 9.10.

The relationship between I_E, I_C and I_B of a BJT can be expressed as:

$$I_E = I_C + I_B$$

Equation 9.1

The ratio of I_C to I_B is called the **DC current gain (β_{DC})**, which is given by:

$$\text{DC current gain, } \beta_{DC} = \frac{I_C}{I_B}$$

Equation 9.2

The typical values of β_{DC} range from 20 to 300. This value can vary significantly from device to device, even between two BJTs of the same model.

We can obtain the β_{DC} of a BJT from its datasheet. In most datasheets, β_{DC} is denoted by h_{FE}. Figure 9.11 shows an extract from the datasheet of a 2N3904 NPN BJT. Notice that the β_{DC} (denoted as h_{FE}) varies from 30 to 300 depending on the operating conditions.

MAXIMUM RATINGS

Parameter	Symbol	Value	Unit
Collector-Emitter Voltage	V_{CEO}	40	V
Collector-Base Voltage	V_{CBO}	60	V
Emitter-Base Voltage	V_{EBO}	6.0	V
Collector Current - continuous	I_C	200	mA
Operating and Storage Junction Temperature Range	T_J, T_{STG}	50	°C

ELECTRICAL CHARACTERISTICS (T_A = 25 °C unless otherwise noted)

Parameter	Symbol	Conditions	Min.	Max.	Unit
OFF CHARACTERISTICS					
Collector-Emitter Breakdown Voltage	$V_{(BR)CEO}$	I_C = 1.0 mA, I_B = 0	40	-	V
Collector-Base Breakdown Voltage	$V_{(BR)CBO}$	I_C = 10 μA, I_E = 0	60	-	V
Emitter-Base Breakdown Voltage	$V_{(BR)EBO}$	I_E = 10 μA, I_C = 0	6.0	-	V
Base Cutoff Current	I_{BL}	V_{CE} = 30 V, V_{EB} = 3V	-	50	nA
Collector Cutoff Current	I_{CEX}	V_{CE} = 30 V, V_{EB} = 3V	-	50	nA
ON CHARACTERISTICS (Note 1)					
DC Current Gain	h_{FE}	I_C = 0.1 mA, V_{CE} = 1.0 V	40	-	-
		I_C = 1.0 mA, V_{CE} = 1.0 V	70	-	
		I_C = 10 mA, V_{CE} = 1.0 V	100	300	
		I_C = 50 mA, V_{CE} = 1.0 V	60	-	
		I_C = 100 mA, V_{CE} = 1.0 V	30	-	
Collector-Emitter Saturation Voltage	$V_{CE(sat)}$	I_C = 10 mA, I_B = 1.0 mA	-	0.2	V
		I_C = 50 mA, I_B = 5.0 mA	-	0.3	
Base-Emitter Saturation Voltage	$V_{BE(sat)}$	I_C = 10 mA, I_B = 1.0 mA	0.65	0.85	V
		I_C = 10 mA, I_B = 1.0 mA	-	0.95	

1. Pulse Test: Pulse width ≤ 300 μs ; Duty Cycle ≤ 2%

Figure 9.11 Extract from the datasheet of a 2N3904 NPN BJT

When using a BJT, we must make sure that the maximum ratings of the BJT are not exceeded. For example, from the datasheet, the maximum I_C that should be used for the 2N3904 is 200 mA. If a higher I_C is needed, we can consider using the 2N2222A BJT, which can take an I_C of up to 500mA.

Although the BJT is primarily a current-controlled device, we still need to consider the voltages related to the BJT as shown in Figure 9.12 as:

- they have a direct effect on the currents in a BJT; and
- they provide information about the operating point of the BJT.

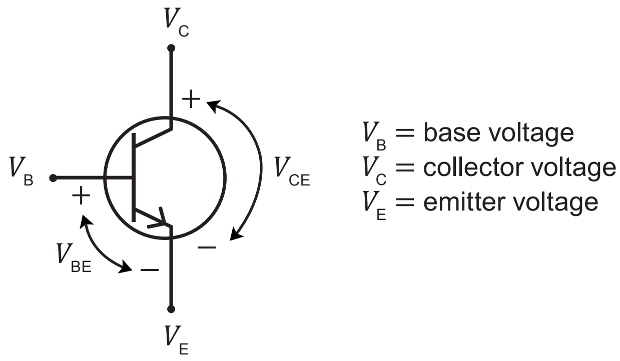


Figure 9.12 Voltages related to an NPN BJT

Base-emitter voltage, V_{BE}

This is the voltage between the base and the emitter. As discussed in Section 9.1, the base and emitter form a diode. To allow current to flow from the base to the emitter, this diode needs to be forward-biased, which means that V_{BE} needs to be larger than the forward voltage of this diode. In BJTs, this forward voltage is called the **base activation voltage**, which is approximately 0.7 V for silicon BJTs. If V_{BE} is less than the base activation voltage, I_B will be nearly zero.

Like a practical diode, there is a voltage drop from the base to the emitter of an NPN BJT when the base-emitter junction is forward-biased. This voltage drop is approximately 0.7 V for silicon BJTs such as the 2N3904 and 2N2222A.

Collector-emitter voltage, V_{CE}

This is the voltage between the collector and the emitter. V_{CE} provides information on the operating point of the BJT (see Figure 9.14).

BJT operating regions

Figure 9.13 shows the I_C-V_{CE} graph, an important characteristic graph of a BJT which shows how I_C changes with V_{CE} for different values of I_B. From this graph, we can study the three main operating regions of a BJT: cutoff, active and saturation.

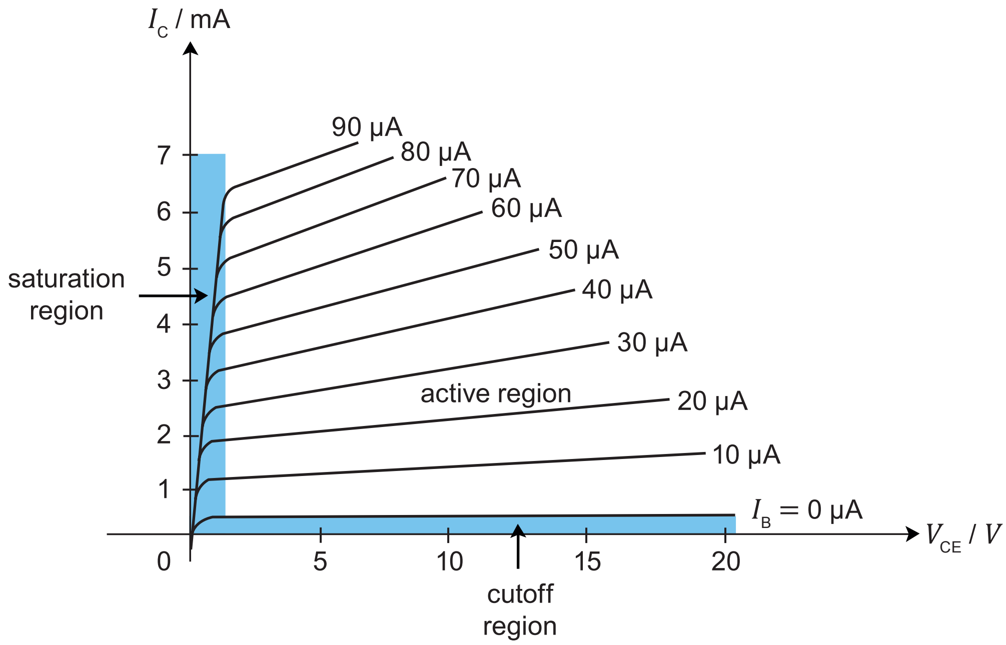


Figure 9.13 I_C-V_{CE} characteristic graph of a BJT

To apply this characteristic graph on a circuit, we need to draw an additional graph called the **DC load line** of the circuit onto the characteristic graph, as shown in Figure 9.14. The DC load line reflects the conditions which V_{CC} and R_C impose on the BJT:

- The DC load line intercepts the horizontal axis at V_{CC} (20 V in Figure 9.14).
- The DC load line intercepts the vertical axis at $\frac{V_{CC}}{R_C}$ (5 mA in Figure 9.14).

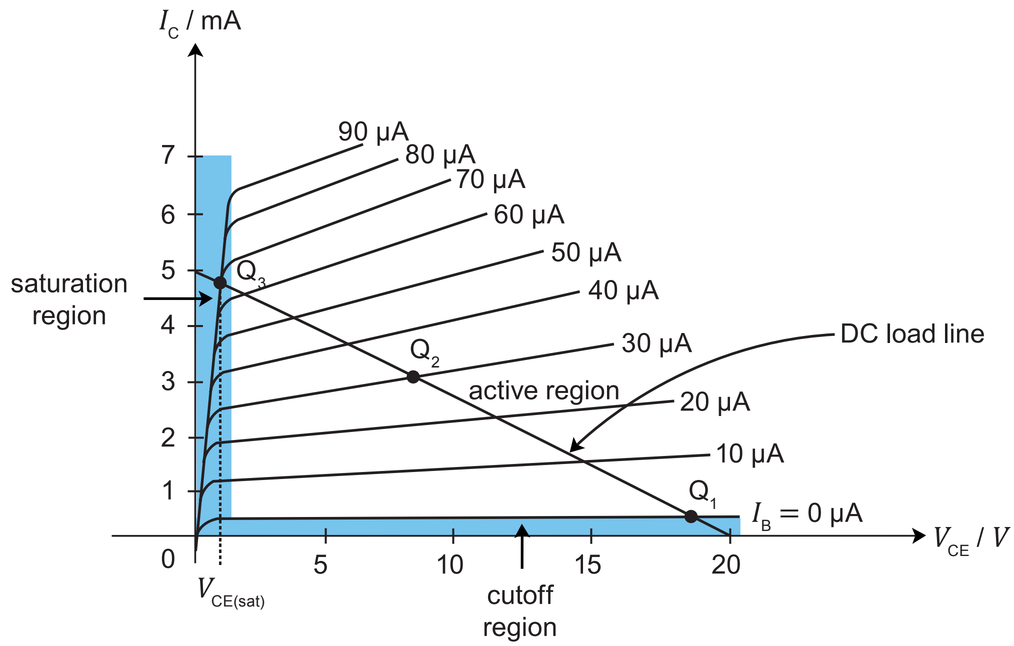


Figure 9.14 I_C-V_{CE} characteristic graph of BJT with DC load line

The DC load line intercepts the characteristic graph at different points for different values of I_B. The position of the intersection point determines the operating point of the BJT. We will now look at three examples:

- When $I_B = 0$, the BJT operates at point Q_1. This point lies in the **cutoff region** where I_C is nearly zero. V_{CE} is close to the supply voltage (20 V in this case). We can describe a BJT operating in this region as 'off'.
- When $I_B = 30$ μA, the BJT operates at point Q_2. This point lies in the **active region** where I_C changes linearly with the value of I_B. However, the value of I_C is usually 20 to 300 times larger than that of I_B.
- When $I_B = 70$ μA, the BJT operates at point Q_3. This point lies in the **saturated region** where I_C reaches a maximum value. Even if I_B is increased to a higher value, e.g., 80 μA, the operating point stays at Q_3. In this region, the value of V_{CE} is called $V_{CE(sat)}$. If we refer to the datasheet in Figure 9.11, $V_{CE(sat)}$ for the 2N3904 NPN BJT is approximately 0.2 V. We can describe a BJT operating in this region as 'on'.

In the next two sections, we will learn the two main applications of a BJT: switching and amplification. When used for switching, a BJT will alternate between the cutoff region (no current) and the saturation region (maximum current). When used for amplification, a BJT will operate in the active region.

Review Questions 9.2

1. Describe briefly how a BJT works.
2. State the three main operation regions of a BJT.
3. Write down an equation that relates base current, collector current and emitter current.

9.3 How do we connect a BJT to work as a switch and a driver?

Learning Outcomes

- Explain how a BJT can be biased to operate as a switch.
- Apply the relationship between the current, voltage and power of a transistor to solve related problems in circuits that use transistors as switches.

Key Idea

- When a BJT is working as a switch, the base current must be large enough to drive the BJT into the saturation region.

Figure 9.15 shows a circuit with a mechanical switch that is used to turn a bulb on or off. A physical force is needed to open or close the switch.

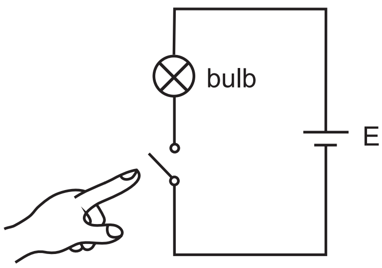


Figure 9.15 Simple switching circuit

A BJT can be used as an electronic switch as shown in Figure 9.16. Unlike mechanical switches, a BJT switch is closed and opened with a current instead of a physical force. This is how the BJT switch works:

- If V_{BB} is smaller than the base activation voltage (about 0.7 V for silicon BJTs), I_B will be zero. The BJT will operate in the cutoff region and no current is allowed to flow from the collector to the emitter. Hence, the BJT acts like an open switch.
- If V_{BB} is larger than the base activation voltage, depending on the value of R_B, I_B may become large enough to drive the BJT into the saturation region and current is allowed to flow almost freely from the collector to the emitter. Hence, the BJT acts like a closed switch.

R_B acts as a current-limiting resistor to prevent I_B from becoming too large and damaging the BJT. An appropriate value of R_B must be determined to ensure that I_B is large enough to drive the BJT into the saturation region when we want the switch to be closed.

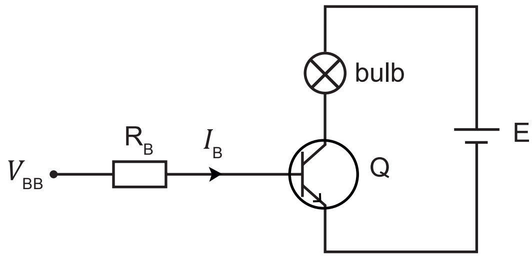


Figure 9.16 Switching circuit using a BJT

Compared to mechanical switches, BJT switches have the following advantages:

- faster switching speeds as the switching is performed by currents instead of physical forces
- no wear and tear as there are no moving parts
- no contact bounce (see Section 13.3)

Biasing a BJT to work as a switch

Biasing is the process of setting up a BJT to work at a particular operating point. It is done by adjusting the values of resistors according to the voltage of the source.

We will now learn how to bias the simple BJT switching circuit shown in Figure 9.17. The load, R_L, is connected to the collector of the BJT. V_{in} is the input signal used to switch the BJT on and off.

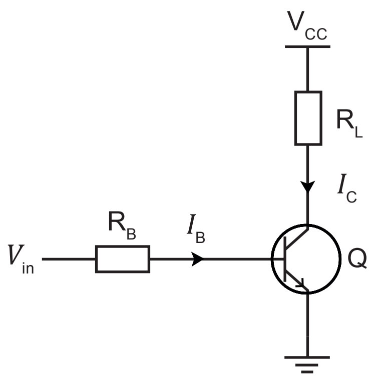


Figure 9.17 Using a BJT as a switch

To bias a BJT, follow these steps:

Step 1: Choose a suitable value for the voltage supply (V_{CC}).

In most situations, V_{CC} is usually set at a value that is equal to the operating voltage of the load. For example, if the load is a 5 V bulb, the chosen voltage supply would also be 5.0 V. The actual voltage across the load will be about 0.2 V lower due to the voltage drop of $V_{CE(sat)}$ when the BJT enters the saturation region.

Step 2: Determine the value of $I_{C(sat)}$ which is the maximum value of I_C.

Using KVL, $V_{CC} - I_C R_C - V_{CE} = 0$

When $I_C = I_{C(sat)}$, $V_{CE} = V_{CE(sat)}$. Rearranging this equation, we obtain:

$$I_{C(sat)} = \frac{V_{CC} - V_{CE(sat)}}{R_C}$$

Equation 9.3

Step 3: Determine the value of I_B using Equation 9.2.

$$I_B = \frac{I_C}{\beta_{DC}}$$

Equation 9.2 (rearranged)

To ensure that I_B is large enough to drive the BJT into the saturation region, use the minimum value of β_{DC} described in the datasheet.

Step 4: Determine the value of R_B.

Using KVL, $V_{in} - I_B R_B - V_{BE} = 0$

Rearranging this equation, we obtain:

$$R_B = \frac{V_{in} - V_{BE}}{I_B}$$

Equation 9.4

V_{BE} is approximately 0.7 V for silicon BJTs. We then choose a resistor from the E24 series with a resistance that is lower than this calculated value of R_B. If we choose a higher value, I_B may not be large enough.

Worked Example 9.1

In the circuit shown in Figure 9.18, a 2N3904 NPN BJT is used as a switch for a bulb rated 5 V. The bulb has a resistance of 250 Ω. The bulb should reach near-full brightness when V_{in} = 3.0 V. Determine suitable values for V_{CC} and R_B.

Take the value of $\beta_{DC(min)}$, $V_{CE(sat)}$ and V_{BE} to be 40, 0.2 V and 0.7 V, respectively.

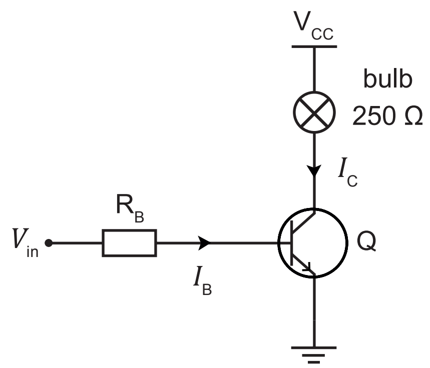


Figure 9.18

Solution

The bulb is the load in the circuit. Since the bulb is rated 5 V, we will set V_{CC} at 5.0 V so that the bulb will achieve near-full brightness when V_{in} = 3.0 V.

Using Equation 9.3, $$I_{C(sat)} = \frac{V_{CC} - V_{CE(sat)}}{R_C} = \frac{5.0\ \text{V} - 0.2\ \text{V}}{250\ \Omega} = 19.2\ \text{mA}$$

Using Equation 9.2, $$I_B = \frac{I_C}{\beta_{DC(min)}} = \frac{19.2\ \text{mA}}{40} = 0.48\ \text{mA}$$

Using Equation 9.4, $$R_B = \frac{V_{in} - V_{BE}}{I_B} = \frac{3.0\ \text{V} - 0.7\ \text{V}}{0.48\ \text{mA}} = 4.8\ \text{k}\Omega$$

We can choose a 4.7 kΩ resistor from the E24 series.

BJTs as drivers

From Worked Example 9.1, we can see that a small current of 0.48 mA is used to switch on a current that is many times larger than itself. On its own, the 0.48 mA current is too small to drive the load (in this case, a bulb) by itself. It needs to work through a BJT in order to drive the load.

A BJT is said to act as a **driver** when it is used in an application to allow a smaller current to drive a load that needs a larger current.

... Review Question 9.3

1. In the circuit shown in Figure 9.19, a BJT is used to switch an LED on and off. Determine a suitable value of R_B if the LED is to be switched on by an input signal of 3.3 V.

   You can use the following values:

   $\beta_{DC(min)} = 30$

   $V_{BE} = 0.7$ V

   V_F of LED = 2.0 V

   $V_{CE(sat)} = 0.2$ V

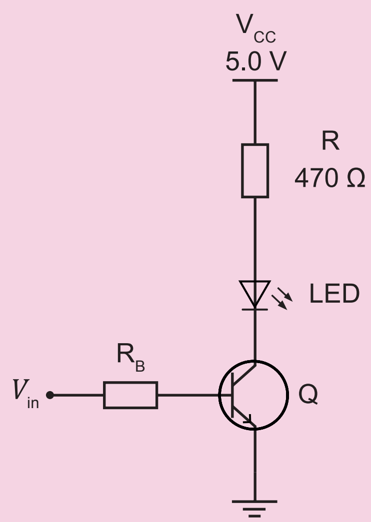


Figure 9.19

9.4 How do we connect a BJT to work as an amplifier?

Learning Outcomes

- Explain how a BJT can be biased to operate as an amplifier.
- Apply the relationship between the current, voltage and power of a transistor to solve related problems in common emitter circuits.
- Explain the function of coupling and bypass capacitors in transistor amplifier circuits.

Key Ideas

- When a BJT is working as an amplifier, it must be biased to operate in the active region.
- Coupling capacitors allow AC signals to pass through but block DC voltages.

Besides switching, another important use of BJTs is to amplify electronic signals. **Amplification** increases the magnitude of a signal.

To connect a BJT to work as an amplifier, we need to bias it to work in the active region. One way of doing so is through the **voltage-divider bias** configuration shown in Figure 9.20.

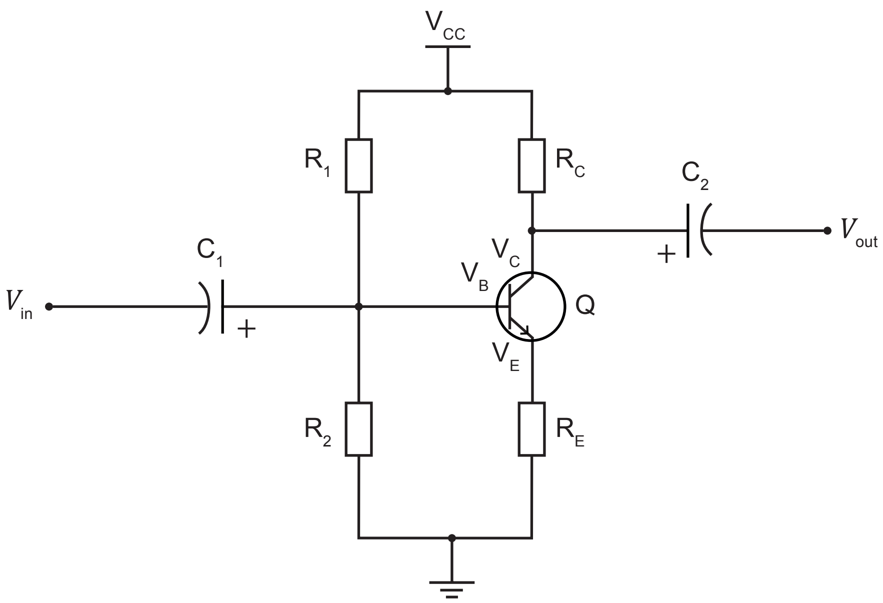


Figure 9.20 Voltage-divider bias amplifier

In this configuration, the base is connected to a voltage divider formed by two resistors, R_1 and R_2. The collector is connected to the positive voltage supply through the resistor R_C while the emitter is connected to the ground through the resistor R_E. The input signal is applied at the base through the capacitor C_1, while the output signal is taken from the collector through the capacitor C_2.

Capacitors C_1 and C_2 are called **coupling capacitors**. Their function is to allow AC signals to pass through but block DC voltages. In Figure 6.3 of Chapter 6, we saw that a capacitor connected to a DC source will become fully charged and eventually act as an open circuit. Hence, the capacitor blocks the voltage from the DC source. However, when a capacitor is connected to an AC source, it will continuously charge and discharge, thus acting as a conducting path and allowing AC signals to pass through.

In Figure 9.21, an AC sine signal with a DC level of 5.0 V is connected to a coupling capacitor. The signal is allowed to pass through the capacitor but its 5.0 V DC voltage is blocked. After passing through the capacitor, the sine signal will take on the DC level of point B which is 6.0 V.

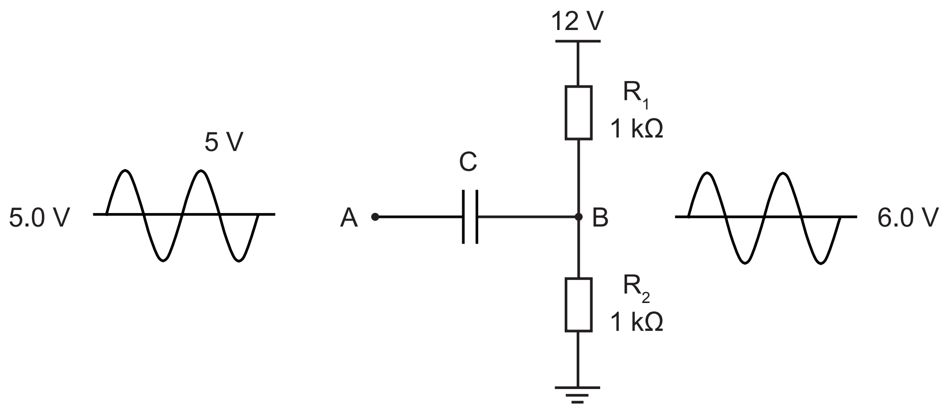


Figure 9.21 Coupling capacitor

After a BJT has been properly biased, V_B, V_C and V_E will be set at the required DC voltage levels. Without C_1, the DC voltage of the input signal will affect V_B and, thus, the biasing of the BJT. Likewise, without C_2, V_C will be affected.

We will perform a simplified analysis of the circuit in Figure 9.20 by making two assumptions:

1. R_2 is much smaller (at least 10 times) than the value of $\beta_{DC} \times R_E$. V_B can then be calculated using the voltage-divider formula:

$$V_B = \frac{R_2}{R_1 + R_2} \times V_{CC} \qquad \textbf{Equation 9.5}$$

2. I_B is much smaller than I_C in the active region. Since $I_E = I_B + I_C$,

$$I_E \approx I_C \qquad \textbf{Equation 9.6}$$

   It is important to note that Equation 9.6 should only be used when the BJT is working in the active region.

V_E can be calculated using:

$$V_E = V_B - V_{BE} \qquad \textbf{Equation 9.7}$$

Using the equation $I = \frac{V}{R}$, I_E can be calculated using:

$$I_E = \frac{V_E}{R_E} \qquad \textbf{Equation 9.8}$$

V_C can be calculated using:

$$V_C = V_{CC} - I_C R_C \qquad \textbf{Equation 9.9}$$

V_{CE} can be calculated using:

$$V_{CE} = V_C - V_E \qquad \textbf{Equation 9.10}$$

For sinusoidal signals, the magnitude of the **voltage gain**, $|A_V|$, of the amplifier is defined as the ratio of the peak voltage (V_{peak}) of the output signal to that of the input signal:

$$|A_V| = \frac{V_{peak} \text{ of output signal}}{V_{peak} \text{ of input signal}}$$

Figure 9.22 shows an input signal with a peak voltage of 1.0 V. After amplification, the output signal has a peak voltage of 3.0 V.

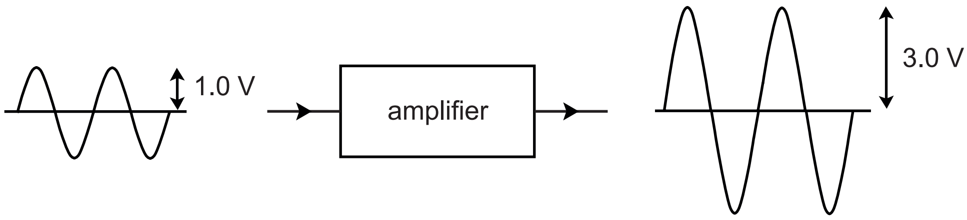


Figure 9.22 A signal with a peak voltage of 1.0 V is amplified to one with a peak voltage of 3.0 V

Therefore,

$$|A_V| = \frac{3.0 \text{ V}}{1.0 \text{ V}}$$
$$= 3.0$$

$|A_V|$ for the circuit shown in Figure 9.20 can also be estimated using:

$$|A_V| \approx \frac{R_C}{R_E}$$ **Equation 9.11**

The equation for the voltage gain of this circuit can also be expressed as $A_V \approx -\frac{R_C}{R_E}$.

The negative sign implies that the output voltage is 180° out of phase with the input voltage, which means that the negative half of the output voltage occurs during the positive half of the input voltage, and vice versa. For example, the two waveforms in Figure 9.25 are 180° out of phase.

Worked Example 9.2

For the voltage-divider biased amplifier circuit shown in Figure 9.23, determine the following:

(a) V_B

(b) V_E

(c) I_E

(d) I_C

(e) V_C

(f) V_{CE}

(g) $|A_V|$

You should use Equations 9.5 to 9.11, which were introduced earlier in the section.

Take the value of V_{BE} to be 0.7 V.

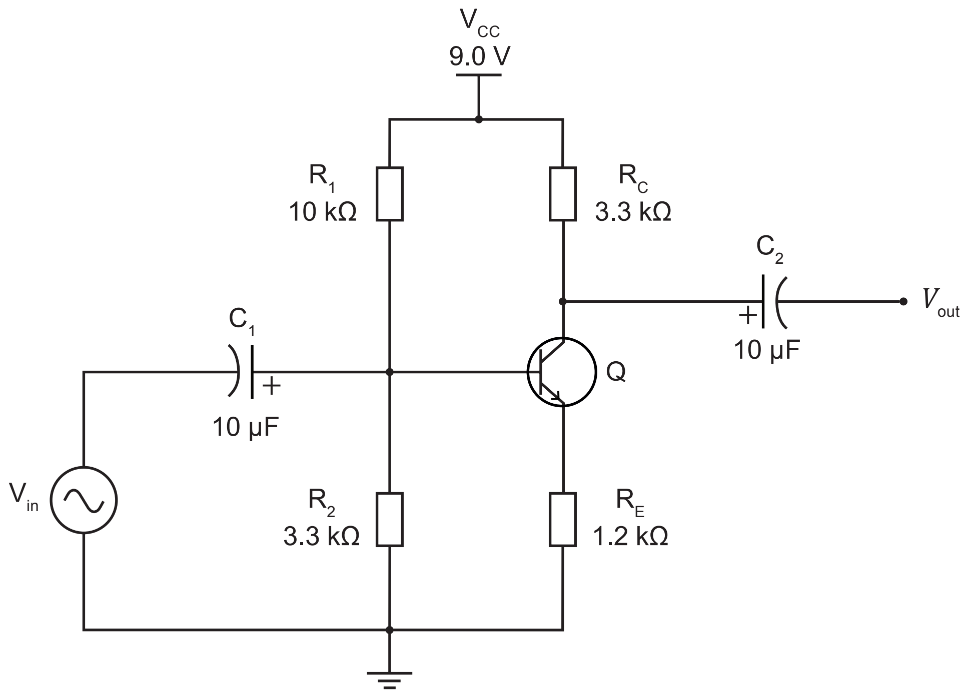


Figure 9.23

Solution

(a) Using Equation 9.5, $V_B = \frac{R_2}{R_1 + R_2} \times V_{CC}$

$$= \frac{3.3\text{ k}\Omega}{10\text{ k}\Omega + 3.3\text{ k}\Omega} \times 9.0\text{ V}$$
$$= 2.23\text{ V}$$

(b) Using Equation 9.7, $V_E = V_B - V_{BE}$

$$= 2.23\text{ V} - 0.7\text{ V}$$
$$= 1.53\text{ V}$$

(c) Using Equation 9.8, $I_E = \frac{V_E}{R_E}$

$$= \frac{1.53\text{ V}}{1.2\text{ k}\Omega}$$
$$= 1.28\text{ mA}$$

(d) Using Equation 9.6, $I_C \approx I_E = 1.28\text{ mA}$

(e) Using Equation 9.9, $V_C = V_{CC} - I_C R_C$

$$= 9.0\text{ V} - (1.28 \times 10^{-3})\text{ A} \times (3.3 \times 10^3)\ \Omega$$
$$= 4.78\text{ V}$$

(f) Using Equation 9.10, $V_{CE} = V_C - V_E$

$$= 4.78\text{ V} - 1.53\text{ V}$$
$$= 3.25\text{ V}$$

(g) Using Equation 9.11, voltage gain, $|A_V| \approx \frac{R_C}{R_E}$

$$\approx \frac{3.3\text{ k}\Omega}{1.2\text{ k}\Omega}$$
$$\approx 2.75$$

Alternatively, we can write $A_V \approx -2.75$

Worked Example 9.3

Repeat Worked Example 9.2 using computer simulation and compare the results.

Solution

The screen capture of the computer simulation with values of the voltage and current probes is shown in Figure 9.24.

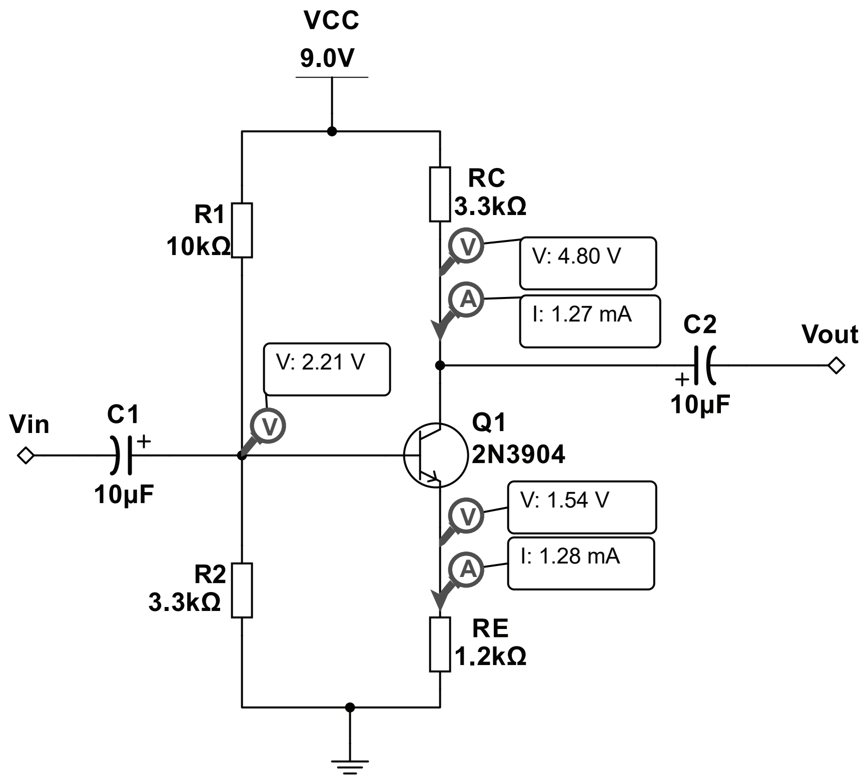


Figure 9.24

Using a 1 kHz input sine signal (red waveform) with peak voltage of 0.5 V, an output sine signal (blue waveform) with a peak voltage of about 1.25 V was obtained. The voltage gain is therefore 2.5. The screen capture of the virtual oscilloscope is shown in Figure 9.25.

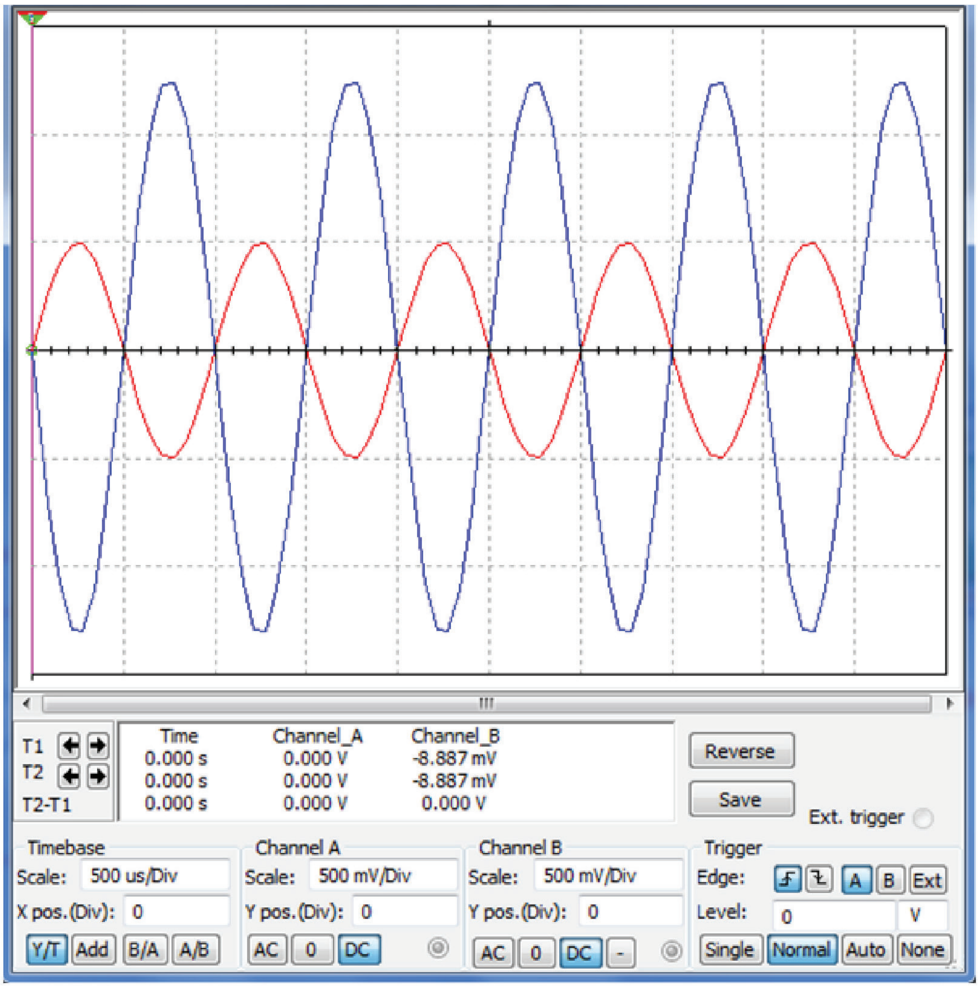


Figure 9.25

Table 9.1 Comparison of calculated and computer-simulated values

Values	Calculated values (from Worked Example 9.2)	Computer-simulated values (from Worked Example 9.3)
V_B	2.23 V	2.21 V
V_E	1.53 V	1.54 V
I_E	1.28 mA	1.28 mA
I_C	1.28 mA	1.27 mA
V_C	4.78 V	4.80 V
V_{CE}	3.25 V	3.26 V
$\|A_V\|$	2.75	2.5

We can see that the two sets of values are very close.

From Worked Examples 9.2 and 9.3, we can see the voltage gain for this amplifier is not large (only around 2.5). The voltage gain can be increased by connecting the capacitor C_3 across R_E as shown in Figure 9.26. This capacitor is called a **bypassed capacitor** as it allows AC signals to bypass R_E.

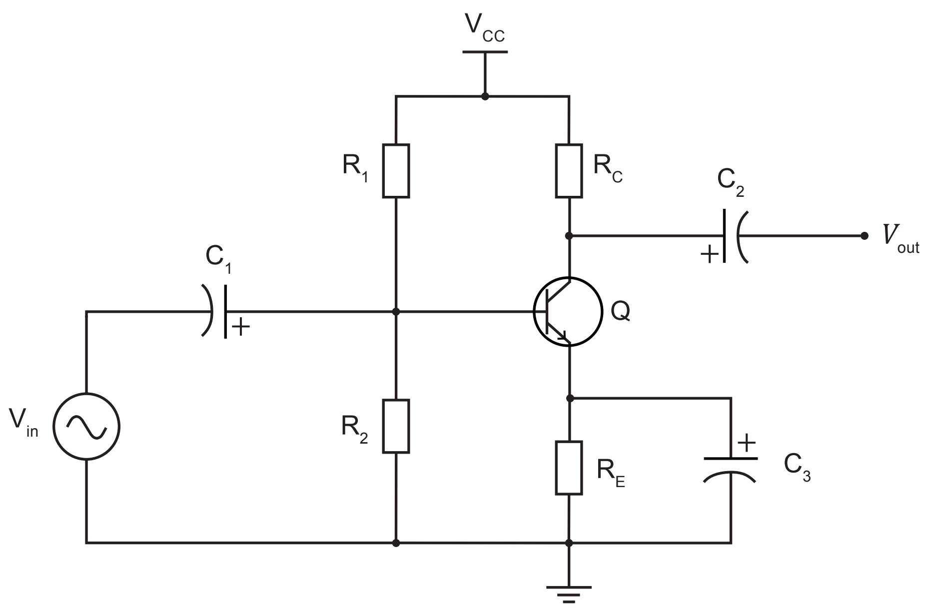


Figure 9.26 Voltage-divider amplifier with bypassed emitter resistor

Review Questions 9.4

1. For the voltage-divider biased amplifier circuit shown in Figure 9.27, calculate the following:
   (a) V_B
   (b) V_E
   (c) I_E
   (d) I_C
   (e) V_C
   (f) V_{CE}
   (g) $|A_V|$

Take the value of V_{BE} to be 0.7 V.

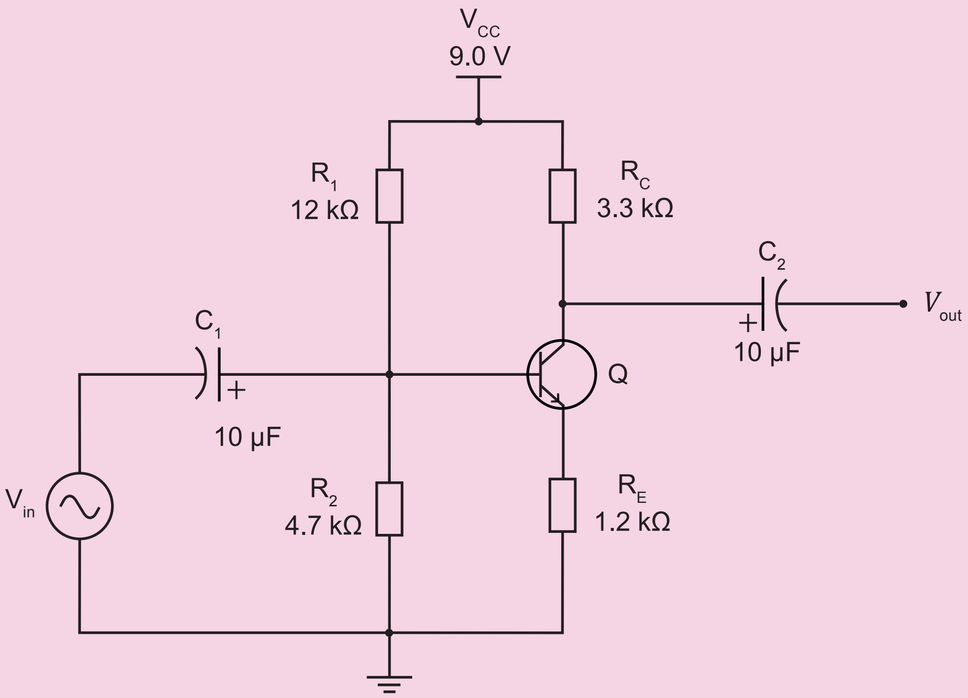


Figure 9.27

9.5 How do we identify the three different configurations of a BJT?

Learning Outcome

- Identify common base (CB), common collector (CC) and common emitter (CE) transistor circuits.

Key Idea

- The configuration of a BJT amplifier can be identified through its input and output terminals.

The BJT amplifier discussed in Section 9.4 is called the **common emitter (CE)** amplifier as the input is fed into the base and the output is taken from the collector. There are two other configurations: **common base (CB)** and **common collector (CC)** (also known as **emitter follower**). Figure 9.28 compares the three configurations while Table 9.2 summarises the terminals for input and output signals in each configuration.

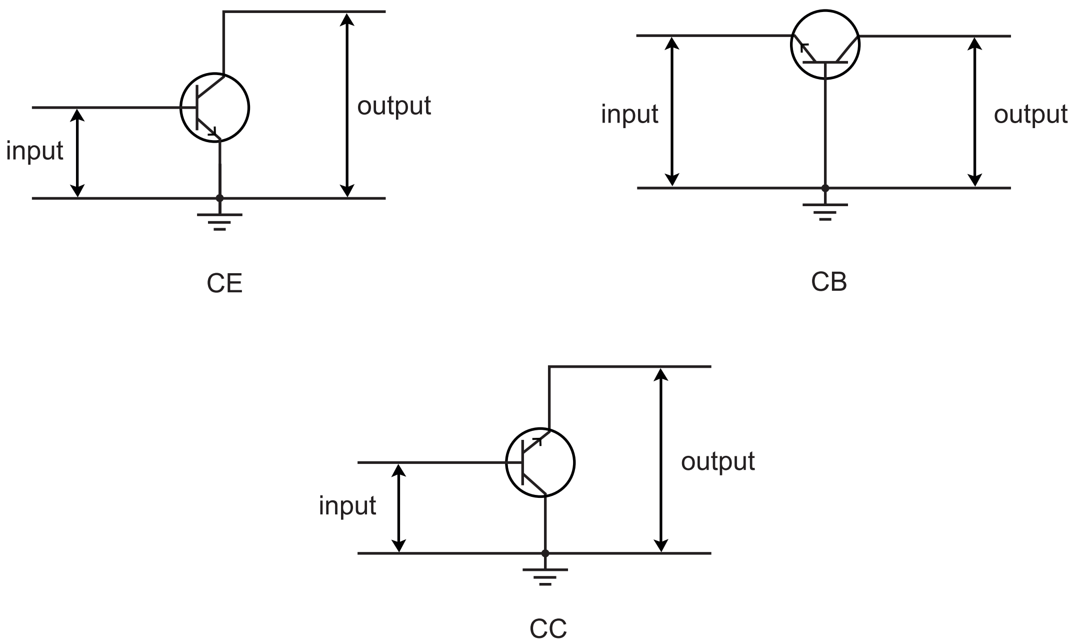


Figure 9.28 CE, CB and CC BJT configurations

Table 9.2 Input and output terminals of the CE, CB and CC configurations

Configuration	Input	Output
CE	base	collector
CB	emitter	collector
CC (also known as emitter follower)	base	emitter

CE amplifiers are the most commonly used amplifiers as they can provide good voltage and current gain. However, CE amplifiers are not good at driving loads with low resistance such as loudspeakers. If an 8 Ω loudspeaker is connected across the output terminal of a CE amplifier, the voltage gain is likely to drop significantly and we will not be able to obtain the amplification needed.

On the other hand, the voltage gain of CC amplifiers is close to 1 (i.e., no voltage gain) but they are very good at driving low-resistance loads.

We can tap on the strengths of both amplifiers by building a two-stage amplifier as shown in Figure 9.29. The first stage consists of a CE amplifier which provides good voltage gain. The second stage uses a CC amplifier to drive a low-resistance load such as a loudspeaker.

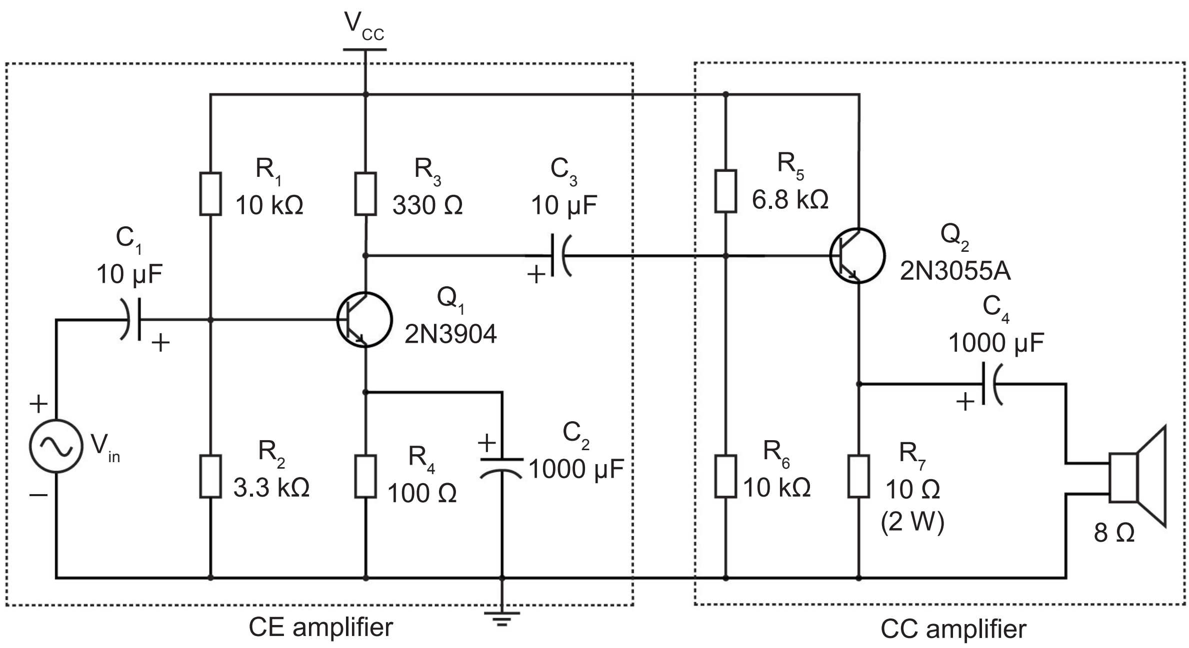


Figure 9.29 Two-stage amplifier

Review Questions 9.5

1. Describe the difference between CE, CB and CC amplifiers in terms of their input and output terminals.
2. Describe one advantage of a CC amplifier.

9.6 How do we use multiple transistors to increase current gain?

Learning Outcome

- Explain the advantage of a Darlington pair over a single transistor in driving an output transducer.

Key Idea

- The Darlington pair is made up of two BJTs with a much higher current gain than a single BJT.

Figure 9.30 shows a BJT acting as a switch and driver for a load. As mentioned in Section 9.3, I_B needs to be large enough to drive the BJT into the saturation region.

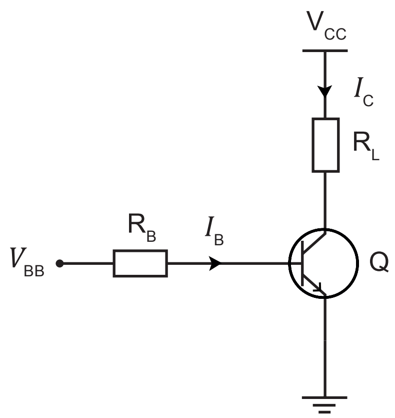


Figure 9.30 A BJT acting as both a switch and driver.

In some situations, I_B is too small to drive the BJT into the saturation region. A common solution is to connect two BJTs to form a **Darlington pair** as shown in Figure 9.31. The emitter of Q_1 is connected to the base of Q_2. The collectors of both BJTs are connected together. The Darlington pair can then be used in the same way as a single BJT, with the new collector, base and emitter points labelled as shown.

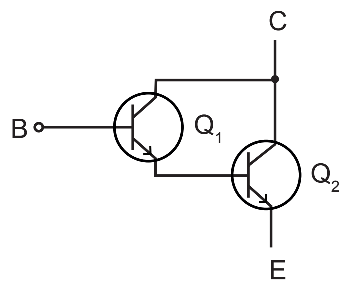


Figure 9.31 Darlington pair

The DC current gain of a Darlington pair is equal to the product of the β_{DC} values of its two component BJTs. This is much higher than the current gain of any one of its component BJTs.

DC current gain of Darlington pair = β_{DC} of $Q_1 \times \beta_{DC}$ of Q_2

Figure 9.32a shows a simple rain sensor circuit. When water is present between terminals A and B, a closed circuit is formed between the +9 V terminal and the base of the BJT. A current will then flow into the base. If this base current is large enough, the buzzer will sound. However, depending on the conductivity of the water, the base current may not be large enough to activate the buzzer. This problem can be solved by replacing the BJT with a Darlington pair as shown in Figure 9.32b.

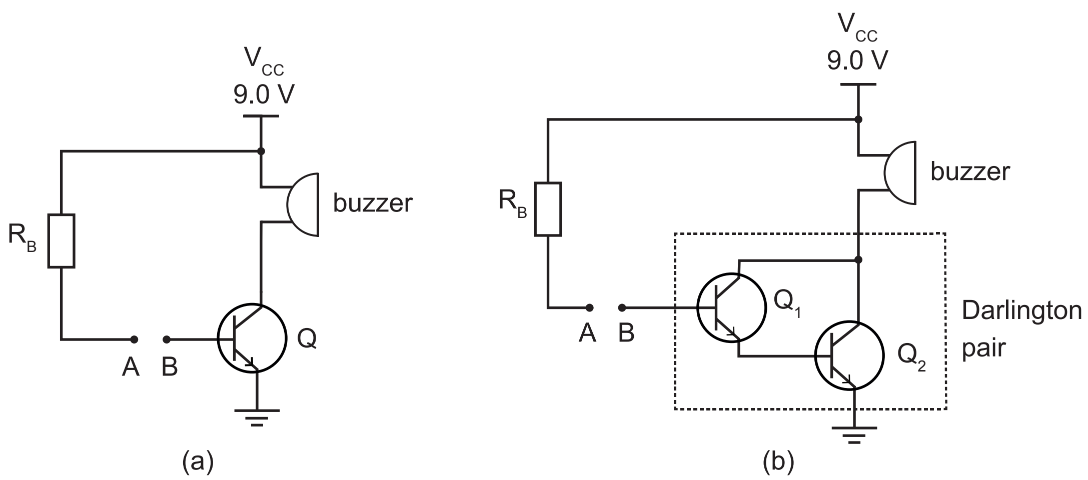


Figure 9.32 A rain sensor circuit with (a) a single BJT and (b) a Darlington pair

Although a Darlington pair can provide a larger current gain than a single BJT, it has a number of disadvantages:

1. The switching speed will be slower as the base current needs to first switch on Q_1, which will then switch on Q_2. However, for applications such as rain sensors which do not require fast switching speeds, this will not be of much concern.
2. There are two PN junctions between the base of Q_1 and the emitter of Q_2. This means the base activation voltage required will be double that of a single BJT.
3. There is a bigger voltage drop across the collector and emitter in the saturation region. For a single BJT, $V_{CE(sat)}$ is around 0.2 V. However, for a Darlington pair, $V_{CE(sat)}$ will be around 0.9 V. Thus, there will be a lower voltage across the load. For example, the buzzer in Figure 9.32a can achieve a voltage of 8.8 V if the BJT is switched on, but the buzzer in Figure 9.32b will only achieve a voltage of 8.1 V.

Worked Example 9.4

A small current of 100 μA is available to drive a load rated 10 V 500 mA. The resistance of the load is 20 Ω. A student attempted to use a BJT with $\beta_{DC} = 100$ using the circuit shown in Figure 9.33. She found that the load did not perform as expected.

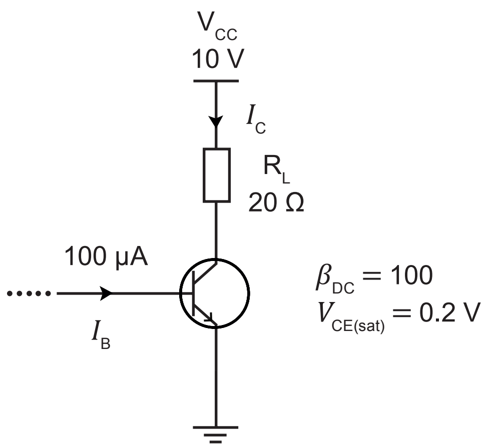


Figure 9.33

(a) Explain why the load did not perform as expected.

(b) Explain how the student can use two BJTs to provide the current needed by the load.

Solution

(a) Using Equation 9.5, $I_C = \beta_{DC} \times I_B$

$= 100 \times 100\ \mu A$

$= 10\ mA$

This is much lower than the 500 mA needed by the load, which explains why the load does not perform as expected.

(b) The student can connect the two BJTs as a Darlington pair as shown in Figure 9.34.

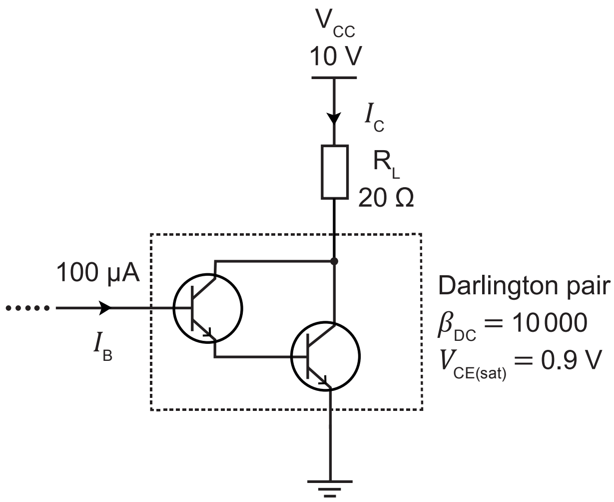


Figure 9.34

Using Equation 9.3 and using $V_{CE(sat)} = 0.9$ V, $I_{CE(sat)} = \dfrac{V_{CC} - V_{CE(sat)}}{R_C}$

$= \dfrac{10\ V - 0.9\ V}{20\ \Omega}$

$= 455\ mA$

Current gain of a Darlington pair $= \beta_{DC} \times \beta_{DC}$

$= 100 \times 100$

$= 10\,000$

Multiplying the base current with this current gain would give us a value of 1.0 A. However, as the Darlington pair would have entered the saturation region, the actual collector current will be 455 mA.

If 500 mA is needed for the load, a V_{CC} of 10.9 V can be used to compensate for the $V_{CE(sat)}$.

Review Question 9.6

1. For each circuit shown in Figures 9.35 and 9.36, determine if the 10 μA base current is enough to drive the BJT or Darlington pair into the saturation region. Use β_{DC} = 100 for each BJT.

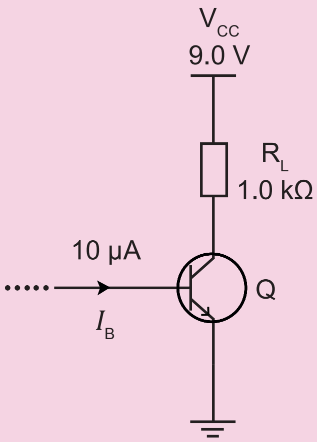


Figure 9.35

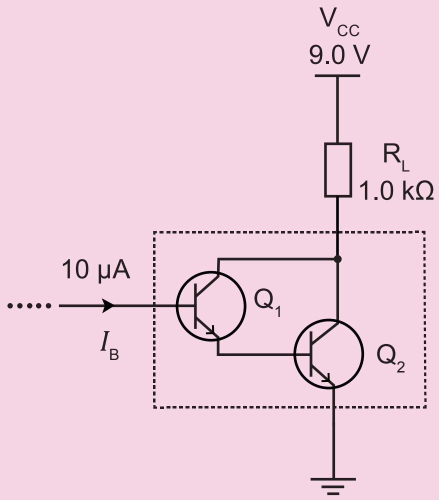


Figure 9.36

Further Reading

Besides BJTs, there is another group of transistors called the field-effect transistor (FET). FETs are further classified into junction FETs (JFETs) and metal oxide semiconductor FETs (MOSFETs), each with further subclasses as shown in Figure 9.37.

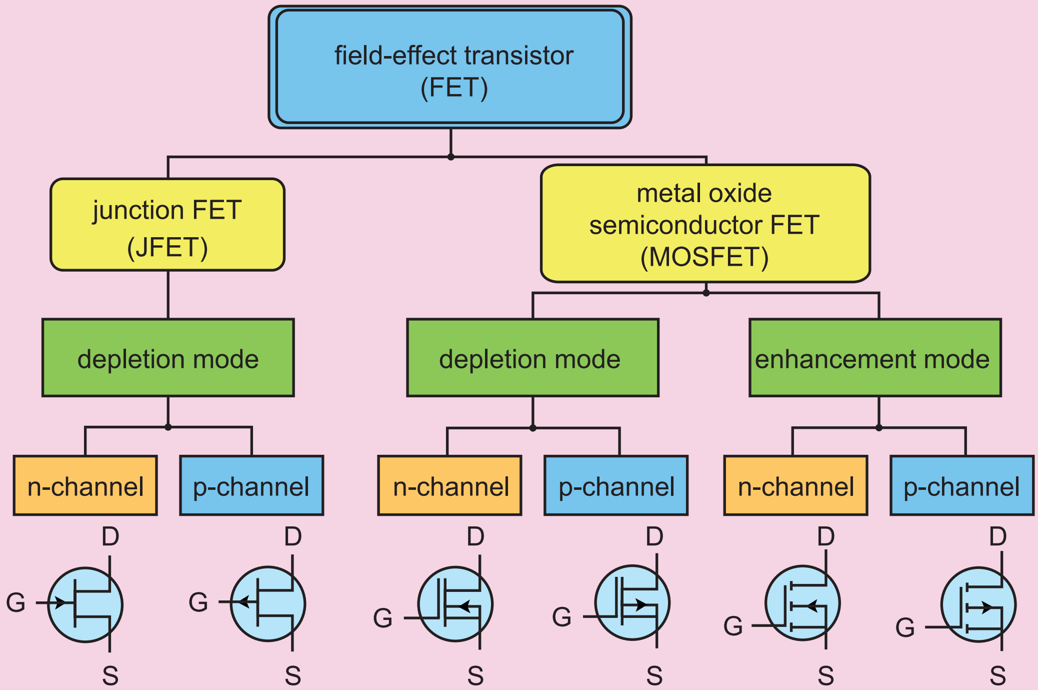


Figure 9.37 FETs and their classifications

Figure 9.38 shows the basic internal structure of an n-channel enhancement-mode MOSFET. It consists of a slab of p-type semiconductor (called the substrate) and two n-type regions. These two n-type regions form the source (S) and drain (D) terminals. When a positive voltage is applied at the gate (G) terminal, a conducting channel is formed in the substrate, linking S and D. A current can then flow from D to S.

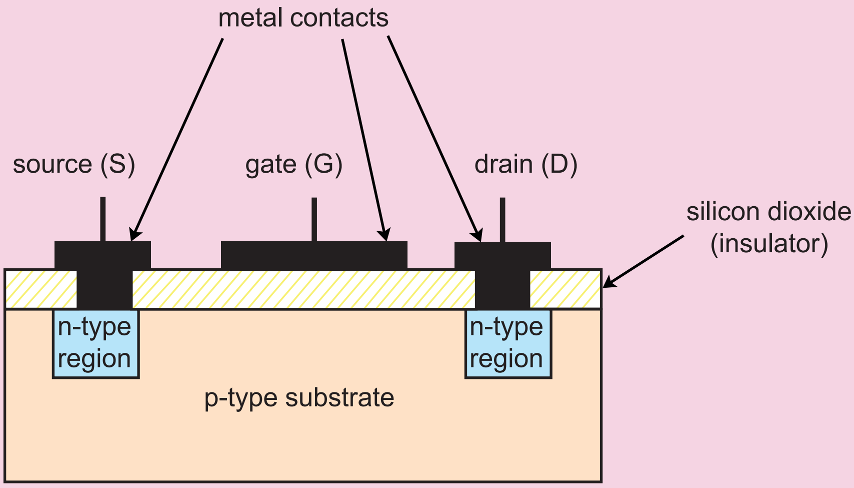


Figure 9.38 Basic internal structure of an n-channel MOSFET

Comparing BJTs and FETs:

- Both BJTs and FETs are made of n-type and p-type semiconductors.
- Both BJTs and FETs have three terminals but they are named differently. The three terminals of FETs are called the gate (G), drain (D) and source (S).
- The key advantage of FETs over BJTs is their very high input resistance. This means FETs only need a very small current from the circuit that supplies the input signal.
- BJTs are current-controlled devices – the base current controls the current between the collector and emitter. FETs are voltage-controlled devices – the voltage at the gate controls the current between the drain and source.
- In general, FETs are more temperature-stable than BJTs. In other words, circuits built using FETs are less affected by changes in temperature.
- In general, FETs are smaller than BJTs, which makes them suitable for forming complex integrated circuits.
- Both BJTs and FETs can be used in small quantities for switching and amplification. However, BJT amplifiers generally have a higher voltage gain due to their higher sensitivity to changes in the input signal.

10 INTRODUCTION TO DIGITAL ELECTRONICS

How do digital electronic systems work?

We hear the term 'digital' frequently. Do you know that many of the electronic devices we use today, such as mobile phones and computers, run on digital systems? Digital systems process digital signals, which are made up of a series of 0s and 1s. For example, the mobile phone shown in Figure 10.1 sends and receives voice calls and text messages in the form of digital signals to and from mobile stations.

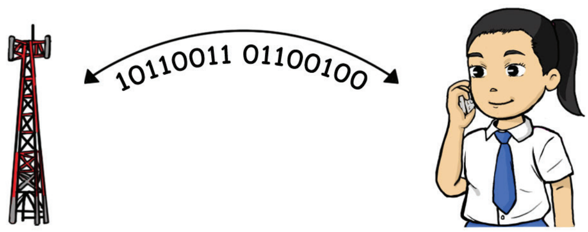


Figure 10.1 Mobile phones send and receive digital signals

In this chapter, we will learn about digital signals, how to represent them and the advantages and disadvantages of using digital systems.

10.1 How do we differentiate analogue and digital signals?

Learning Outcomes

- Identify analogue and digital signals from oscilloscope traces.
- State that digital signals can be represented by two logic states: logic 1 (high voltage, usually 5 V); logic 0 (low voltage, usually 0 V).

Key Ideas

- Analogue quantities vary continuously whereas digital quantities vary in steps.
- Digital signals can be represented by two logic states: 0 and 1.

Analogue and digital quantities

Analogue quantities vary continuously whereas digital quantities vary in steps. To illustrate the difference between these two types of quantities, consider two students tossing pebbles onto a ramp and a set of stairs as shown in Figure 10.2. The pebbles can land on any height along the ramp but only on one of the steps of the stairs. Thus, the heights of the pebbles on the ramp are analogue quantities as they can vary continuously. However, the heights of the pebbles on the stairs are digital quantities as they can only vary in steps.

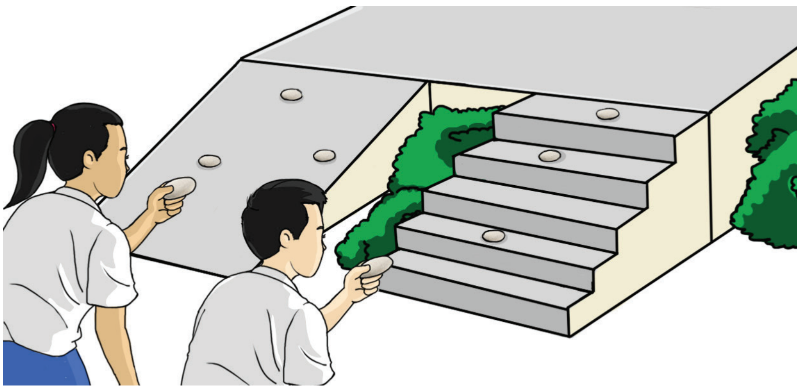


Figure 10.2 The heights of the pebbles on the ramp and the stairs are analogue and digital quantities, respectively

Figure 10.3 shows an analogue watch and a digital watch. The positions of the hour and minute hands of the analogue watch change continuously as they move around the dial, while the display of the digital watch changes in steps.

Figure 10.3 An analogue watch (left) and a digital watch (right)

Analogue and digital signals

We learnt in Section 1.3 that an electrical signal is an electrical voltage or current that carries information. Electrical signals can be analogue or digital. Figure 10.4 shows an analogue signal with continuously varying voltage levels.

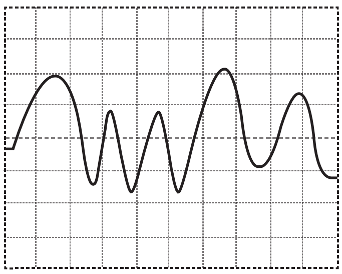


Figure 10.4 An analogue signal

Figure 10.5 shows a digital signal which takes on only two distinct voltage levels. The lower level is known as logic 0, LOW state, or OFF state. The higher level is known as logic 1, HIGH state, or ON state. In this course, we will use 0 V for logic 0 and +5 V for logic 1, although the actual voltage can vary for different digital circuits.

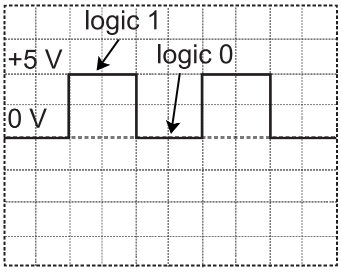


Figure 10.5 A digital signal

Review Questions 10.1

1. Classify the following into analogue and digital quantities:
   (a) Number of marbles in a bag
   (b) Temperature of a room
   (c) Volume of water in a pail
2. Describe the difference between an analogue signal and a digital signal.
3. State the two logic states that a digital signal can take on.

10.2 How do we build a logic switch?

Learning Outcome

- Explain the use of 'pull-up' and 'pull-down' resistors to provide the correct logic levels.

Key Ideas

- Logic switches can be used to provide input signals for digital systems.
- Logic switches use 'pull-up' or 'pull-down' resistors to provide the correct logic levels.

In Section 10.1, we learnt that a digital signal can only take on two levels – logic 0 or logic 1. A logic switch can be used to provide such a digital signal. Figure 10.6 shows a logic switch consisting of a resistor connected in series with a switch.

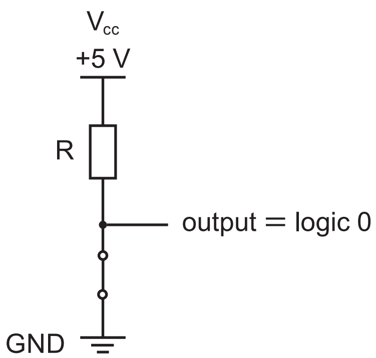


Figure 10.6a Logic switch with a 'pull-up' resistor. When the switch is closed, the output is logic 0.

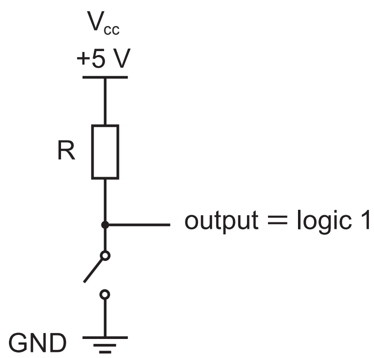


Figure 10.6b Logic switch with a 'pull-up' resistor. When the switch is open, the output is logic 1.

When the switch is closed as shown in Figure 10.6a, the output will be 0 V or logic 0 as it is connected to the ground. When the switch is open as shown in Figure 10.6b, the output will be +5 V or logic 1 as it is connected to V_{CC}. Thus, this resistor is called a **'pull-up' resistor** as it 'pulls' the output to +5 V when the switch is open. The resistance of the resistor is typically in the order of 10 kΩ.

Alternatively, we can swap the position of the resistor and switch as shown in Figure 10.7. Here, the resistor acts as a **'pull-down' resistor** because the output is 'pulled' down to 0 V or logic 0 when the switch is open. When the switch is closed, the output will be +5 V or logic 1.

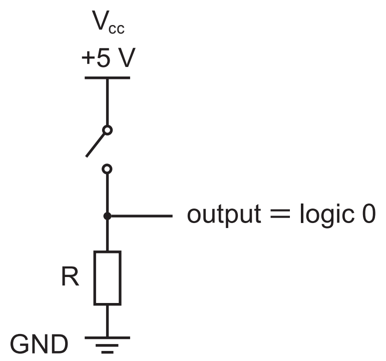


Figure 10.7a Logic switch with a 'pull-down' resistor. When the switch is open, the output is logic 0.

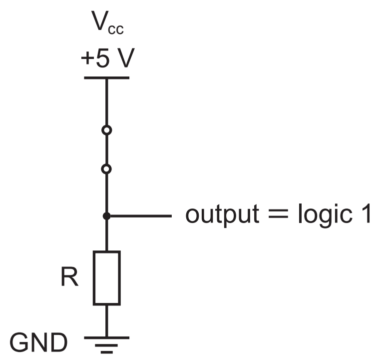


Figure 10.7b Logic switch with a 'pull-down' resistor. When the switch is closed, the output is logic 1.

The 'pull-up' and 'pull-down' resistors ensure that there is a valid output state when the switch is open. Without a 'pull-up' or 'pull-down' resistor, as shown in Figure 10.8, the logic switch will produce a 'floating' output when the switch is open. This means that the output terminal is left unconnected and the output state is uncertain. A **floating output** is undesirable as it can pick up unwanted electrical signals and take on either logic 0 or logic 1 in an unpredictable way.

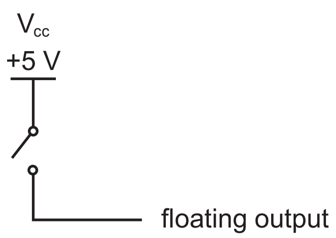


Figure 10.8 Logic switch with a 'floating' output

Review Questions 10.2

1. Draw circuit diagrams of:
   (a) a logic switch which uses a 'pull-up' resistor; and
   (b) a logic switch which uses a 'pull-down' resistor.
   Your diagrams should include the points from which the output is taken.
2. Explain why a resistor is required to provide the correct logic levels for the output of a logic switch.

10.3 What are the advantages and disadvantages of using digital systems over analogue systems?

Learning Outcomes

- List the advantages and disadvantages of digital systems over analogue systems.
- Describe the need to convert between analogue and digital signals.

Key Ideas

- Since real-world quantities are analogue in nature, there is a need to convert analogue signals to digital signals to exploit the advantages of digital systems.
- The advantages of digital systems are that they are less affected by electrical interference, more reliable, generally easier to design, easier to store data in and cheaper.
- The main disadvantage of digital systems is that additional steps are needed to convert between analogue and digital signals.

Analogue and digital systems

Electronic systems are classified into either analogue or digital systems according to the type of signal they can process. Figure 10.9 shows an analogue system that takes in analogue signals as input and produces analogue signals as output.

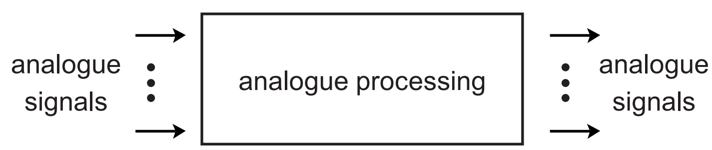


Figure 10.9 An analogue system

Figure 10.10 shows a digital system that takes in digital signals as input and produces digital signals as output.

Figure 10.10 A digital system

Over the last few decades, many applications that used to be performed by analogue systems are now performed by digital systems. Some advantages of digital systems over analogue systems are:

1. Digital systems are less affected by electrical interference. Figure 10.11 shows a digital signal that has been distorted by electrical interference during transmission. Since there is a fairly large difference (5 V) between the two voltage levels, the receiver is still able to tell logic 0 apart from logic 1 as long as the signal is not too badly distorted.

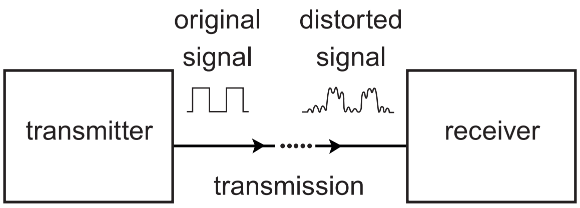


Figure 10.11 Digital signal distorted by noise during transmission

2. Digital signals can be restored to their original condition using repeaters as shown in Figure 10.12. This makes it possible to transmit information over long distances and makes digital systems more reliable.

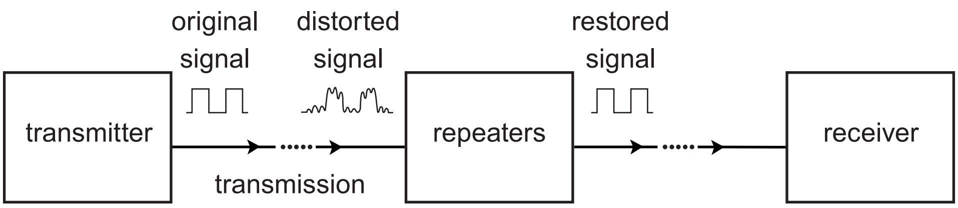


Figure 10.12 Restoring a distorted digital signal using repeaters

3. It is generally easier to design digital systems because digital signals only have two voltage levels. In addition, the exact values of these two levels are not crucial as long as the system is able to correctly identify the corresponding logic states. In analogue systems, the specific voltage levels of the analogue signals need to be considered, hence, they are generally more difficult to design.

4. It is easier to store information using digital systems. This is because the information is stored as a series of 0s and 1s unlike a continuous range of possible values in analogue systems.

5. Due to advancements in technology, a large number of digital components can be squeezed into a small area of a semiconductor material. This helps to reduce cost.

Despite their numerous advantages, digital systems have a key disadvantage. Digital systems can only process digital signals but many quantities in our daily lives, such as sound level and temperature, are analogue quantities. These analogue quantities need to be converted into digital signals for processing. If needed, the processed digital signals are then converted back into analogue signals. Hence, the disadvantage of using digital systems is that additional steps are needed to convert between analogue and digital signals.

Review Question 10.3

1. What are the advantages of digital systems over analogue systems?

10.4 How do we represent and display values in digital form?

Learning Outcomes

- Convert between binary, decimal and binary-coded decimal (BCD) systems.
- Describe the function of a BCD to 7-segment display module using a truth table.

Key Ideas

- To represent a decimal value in digital form, it needs to be converted into a binary value or a BCD.
- A 7-segment display module takes in a BCD and displays its decimal equivalent.

Number systems

We often use numbers to communicate quantities, for example, the number of people or the time taken to perform a task. The number system that is most commonly used is the decimal (base-10) system. However, many other number systems are also used in digital electronics. These include the binary (base-2), octal (base-8) and hexadecimal (base-16) systems.

Besides these number systems, other codes are used, such as the binary-coded decimal (BCD), the American Standard Code for Information Interchange (ASCII) code and the Gray code. In this section, we will learn how to convert numbers between binary, decimal and BCD.

The decimal system

The **decimal system** is made up of 10 distinct digits – 0 (smallest), 1, 2, 3, 4, 5, 6, 7, 8, 9 (biggest). Because the system has 10 digits, it is also called a base-10 system.

This is how we count using the decimal system:

$$0, 1, 2, \dots \underbrace{9, 10}_{\text{(i)}}, 11, 12, \dots \underbrace{19, 20}_{\text{(ii)}}, 21, \dots \dots \dots \underbrace{99, 100}_{\text{(iii)}}, 101, \dots$$

Figure 10.13 Counting in the decimal system

(i) When the biggest digit, 9, is reached, we add a digit 1 on the left and reset the original digit to 0.
(ii) When the digit on the right reaches 9 again, we increase the digit on the left by 1 and reset the digit on the right to 0.
(iii) When both digits reach 9, we add a digit 1 on the left and reset the two digits on the right to 0.

The position of a digit in a decimal number determines its **place value**, which is represented by 10^N. The place value starts from 10^0 for the rightmost digit with the power (N) increasing by 1 for each subsequent digit on the left, as shown in Figure 10.14.

2 3 4

place value $= 10^2$ | place value $= 10^1$ | place value $= 10^0$

Figure 10.14 Place values of a decimal number

In Figure 10.14, since the digit 2 has the highest place value, it is referred to as the most significant digit. Similarly, the digit 4 has the lowest place value and is referred to as the least significant digit.

Figure 10.15 shows the value of the decimal number 234, which is the sum of the product of each digit and its place value.

$$234 = (2 \times 10^2) + (3 \times 10^1) + (4 \times 10^0)$$

Figure 10.15 Value of a decimal number

The binary system

The **binary system** is made up of two distinct digits – 0 (smallest) and 1 (biggest). Because the system has two digits, it is also referred to as a base-2 system. In the binary system, the digits are also called **bits.**

This is how we count using the binary system:

0, 1, 10, 11, 100, 101, 111, 1000, 1001, 1010, 1011, ...

(i) (ii)

Figure 10.16 Counting in the binary system

(i) When the biggest digit, 1, is reached, we add a digit 1 on the left and reset the original digit to 0.
(ii) When both digits reach 1, we add a digit 1 on the left and reset the two digits on the right to 0.

The position of a digit in a binary number determines its place value, which is represented by 2^N. The place value starts from 2^0 for the rightmost digit with the power increasing by 1 for each subsequent digit on the left as shown in Figure 10.17.

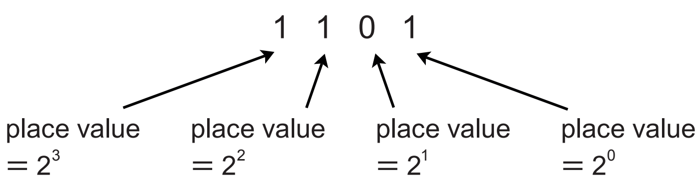


Figure 10.17 Place values of a binary number

Since the leftmost digit has the highest place value, it is referred to as the **most significant bit (MSB)**. Similarly, rightmost digit has the lowest place value and is referred to as the **least significant bit (LSB)**.

Recall that digital signals are represented by two levels: logic 0 and logic 1. Because of this, the binary system is often used to represent the values of digital signals.

Converting between binary and decimal

A binary number can be converted to its decimal equivalent by summing the product of each bit and its place value. Worked Example 10.1 illustrates how to convert a binary number to its decimal equivalent.

Worked Example 10.1

Convert the binary number 1100 to its decimal equivalent.

Solution

$$1100_2 = (1 \times 2^3) + (1 \times 2^2) + (0 \times 2^1) + (0 \times 2^0)$$
$$1100_2 = 8 + 4 + 0 + 0 = 12_{10}$$

Notice how subscripts (2 and 10) were used in Worked Example 10.1 to indicate the base of the number. This convention is used to avoid confusion whenever more than one number system is used.

To convert a decimal number to its binary equivalent, repeatedly divide the decimal number by 2. The remainder generated by each division produces the binary bits that form the binary number, with the first remainder being the LSB. Worked Example 10.2 illustrates how to convert a decimal number to its binary equivalent.

Worked Example 10.2

Convert the decimal number 12 to its binary equivalent.

Solution

$12 \div 2 = 6$ remainder of **0** (LSB)
$6 \div 2 = 3$ remainder of **0**
$3 \div 2 = 1$ remainder of **1**
$1 \div 2 = 0$ remainder of **1** (MSB)

Hence, the binary equivalent of 12_{10} is 1100_2.

For easy reference, Table 10.1 shows the first 16 decimal numbers and their binary equivalent.

Table 10.1 Decimal numbers and their binary equivalent

Decimal number	Binary equivalent
0	0
1	1
2	10
3	11
4	100
5	101
6	110
7	111
8	1000
9	1001
10	1010
11	1011
12	1100
13	1101
14	1110
15	1111

Binary-coded decimal (BCD)

The **binary-coded decimal (BCD)** uses groups of 4-bit binary code to represent the digits of a decimal number. Note that BCD is a coding system and not a number system.

Table 10.2 shows three decimal numbers and their BCD equivalent. Notice that a single-digit decimal number requires one group of 4-bit binary code, a double-digit decimal number requires two groups of 4-bit binary code, and so on. Each group of 4-bit binary code is the binary equivalent of the digit it represents.

Table 10.2 Decimal numbers and their BCD equivalent

Decimal number	BCD equivalent
5	0101
94	1001 0100
248	0010 0100 1000

Worked Example 10.3 illustrates how to convert a decimal number to its BCD equivalent.

Worked Example 10.3

Convert:

(a) 387_{10} to BCD; and

(b) $0101\ 0110\ 1001_{BCD}$ to decimal

Solution

(a) $387_{10} = \overset{3}{0011}\quad \overset{8}{1000}\quad \overset{7}{0111}_{BCD}$

(b) $\overset{5}{0101}\quad \overset{6}{0110}\quad \overset{9}{1001}_{BCD} = 569_{10}$

Although both BCD and binary numbers are stored as binary bits, it is easier to convert between decimal and BCD than between decimal and binary. This becomes more obvious as the decimal number gets bigger – it is very tedious to convert a big decimal number into its binary form but converting it to BCD remains relatively straightforward.

BCD is also useful for displaying decimal numbers. For example, the decimal number 25 is stored as 0010 0101 in BCD. The first 4-bit group (0010) can be readily sent out to the display system to be displayed as the digit 2 and the second 4-bit group (0101) as the digit 5. This would be more difficult to perform if the number 25 is stored as a binary number, 11001, instead.

A disadvantage of using BCD is the extra binary bits needed to represent the same number. Using the previous example, the decimal number 25 is represented by 11001 in binary and 0010 0101 in BCD. This would mean that more storage space is needed to store the same information.

BCD to 7-segment display module

We learnt in Section 7.6 that to display numbers on a 7-segment LED display, a 7-bit binary pattern is applied to segments *a* to *g* to turn each of them on or off.

In many instances, we need to display binary numbers stored in digital systems as decimal digits. A BCD to 7-segment display module is useful for this purpose. The module consists of a **BCD to 7-segment decoder** and a 7-segment display as shown in Figure 10.18.

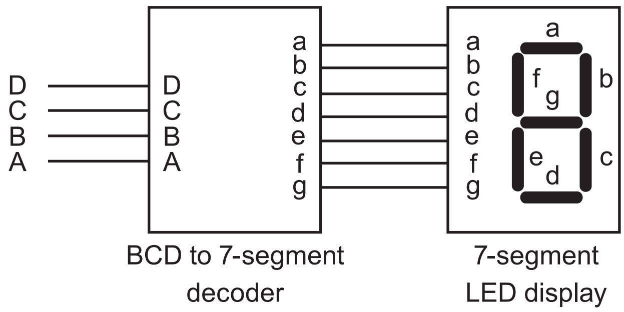


Figure 10.18 BCD to 7-segment display module

The BCD to 7-segment decoder converts a BCD input into a 7-segment code according to Table 10.3. This table is known as a truth table.

Table 10.3 Truth table of a BCD to 7-segment display module (common-cathode)

BCD	7-bit binary code							7-segment display (decimal digit)
	g	f	e	d	c	b	a	
0000	0	1	1	1	1	1	1	0
0001	0	0	0	0	1	1	0	1
0010	1	0	1	1	0	1	1	2
0011	1	0	0	1	1	1	1	3
0100	1	1	0	0	1	1	0	4
0101	1	1	0	1	1	0	1	5
0110	1	1	1	1	1	0	1	6
0111	0	0	0	0	1	1	1	7
1000	1	1	1	1	1	1	1	8
1001	1	1	0	1	1	1	1	9

Review Questions 10.4

1. For the following numbers, circle the most significant digit and state its place value.
   (a) 4296_{10}
   (b) 10111_2

2. Perform the following conversions.
   (a) $1001\ 0110_2$ to its decimal equivalent
   (b) 83_{10} to its binary equivalent
   (c) 45_{10} to its BCD equivalent
   (d) $1000\ 0011\ 0110\ 1001_{BCD}$ to its decimal equivalent

3. State one advantage and one disadvantage of BCD compared to the binary system.

4. Write down the 7-bit binary code needed to display the digit 6 on a 7-segment display module.

11 BASIC LOGIC GATES

How do we design and build a decision-making circuit?

We make many decisions each day based on the information we have about the situations we face. For example, a student may decide to take a taxi to school instead of a bus if he wakes up late and the weather is bad.

One useful application of electronics is to allow devices to make decisions without human intervention. In this chapter, we will learn about a group of digital systems called logic gates, which can make logic decisions. We will also learn how to use logic gates that come in the form of integrated circuits (ICs).

11.1 What is a logic gate?

Learning Outcomes

- State that a logic gate is a device with one output and at least one input; the output is either logic 1 or 0 depending on the input(s).
- Describe the truth table as a way to show the output of a digital circuit for different combinations of input(s).

Key Ideas

- A logic gate is a digital system with one logic output and at least one logic input.
- A truth table is a common way to show the relationship between the input(s) and output(s) of a digital system.

We learnt in Section 10.3 that a digital system takes digital signals as inputs and produces digital signals as outputs. The simplest digital systems are called **logic gates**, which are used to make logic decisions. They can have one or more inputs but only one output. Figure 11.1 shows the block diagrams of logic gates with one, two and three inputs.

Figure 11.1 From left: logic gates with one, two and three inputs

We can use a **truth table** to show the outputs of a logic gate for all possible input combinations. Figure 11.2 shows the truth tables of logic gates with one, two and three inputs. Notice that there is only one output column since logic gates have only one output. For digital systems with more than one output, additional columns need to be added. For example, the truth table for the BCD to 7-segment decoder in Section 10.4 has seven output columns.

A	X
0	
1	

Truth table of a 1-input logic gate

A	B	X
0	0	
0	1	
1	0	
1	1	

Truth table of a 2-input logic gate

A	B	C	X
0	0	0	
0	0	1	
0	1	0	
0	1	1	
1	0	0	
1	0	1	
1	1	0	
1	1	1	

Truth table of a 3-input logic gate

Figure 11.2 From left: truth tables of logic gates with one, two and three inputs

To construct a truth table, we need to:

- determine the number of rows in the truth table, which is equal to 2^N, where N is the number of inputs. For example, if there are three inputs, the number of rows will be $2^3 = 8$.
- fill in the input columns in ascending order using the binary system. For example, in a 3-input system, the inputs start from 000 in the first row, followed by 001 in the second, 010 in the third and so on, till 111 in the last row.

The output is determined by the type of logic gate, which will be covered in the next section.

Review Question 11.1

1. How many input combinations does a 3-input logic gate have?

11.2 How do we describe the processes of common logic gates?

Learning Outcomes

- Draw symbols and construct truth tables for NOT, AND, OR, NAND and NOR gates.
- Use Boolean notation ('$\overline{}$', '·' and '+') to write Boolean expressions for NOT, AND, OR, NAND and NOR gates.

Key Ideas

- Besides truth tables, we can also use Boolean expressions to describe the processes performed by logic gates.
- The NOT, AND, OR, NAND and NOR gates are five common types of logic gates and are each represented by a unique symbol.

Common logic gates

There are several types of logic gates. Each type performs a unique decision-making process called a **logic operation**. The logic operation can be represented by a truth table, a symbol or a **Boolean expression** (a type of mathematical expression). In this course, we will learn about five common types of logic gates: the **NOT**, **AND**, **OR**, **NAND** and **NOR** gates.

NOT gate

Figure 11.3 shows the symbol and truth table of a **NOT gate**.

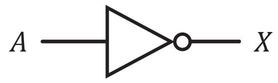


Figure 11.3a Symbol of a NOT gate

Input A	Output $X = \bar{A}$
0	1
1	0

Figure 11.3b Truth table of a NOT gate

The NOT gate (also known as an inverter gate) performs the NOT operation, which inverts an input to the opposite state. This means that the output will always be the opposite of the input. The small circle in the symbol represents this inversion.

The Boolean expression for the NOT gate is written as:

$$X = \bar{A}$$

The '‾' sign represents the NOT operation. We say that X is the complement of A.

AND gate

Figure 11.4 shows the symbol and truth table of an **AND gate**.

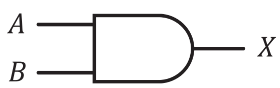


Figure 11.4a Symbol of an AND gate

Input A	Input B	Output $X = A \cdot B$
0	0	0
0	1	0
1	0	0
1	1	1

Figure 11.4b Truth table of an AND gate

The AND gate performs the AND operation, which gives an output of 1 only when both inputs are 1. If any of the inputs is 0, the output is 0.

The Boolean expression for the AND gate is written as:

$$X = A \cdot B$$

The '·' sign represents the AND operation.

The AND operation is useful in situations where an action is to be implemented only when all the conditions have been met. Figure 11.5 shows an example of a security system in which a door can be opened only when two sets of keys have been inserted.

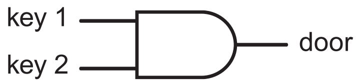


Figure 11.5 Security system using an AND gate

OR gate

Figure 11.6 shows the symbol and truth table of an **OR gate**.

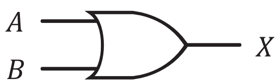


Figure 11.6a Symbol of an OR gate

Input A	Input B	Output $X = A + B$
0	0	0
0	1	1
1	0	1
1	1	1

Figure 11.6b Truth table of an OR gate

The OR gate performs the OR operation, which gives an output of 1 when one or both of the inputs is 1. The only case where the output is 0 is when both inputs are 0.

The Boolean expression for the OR gate is written as:

$$X = A + B$$

The '+' sign represents the OR operation.

The OR operation is useful in situations where an action is to be implemented when one or more conditions are met. Figure 11.7 shows an example of a fire alarm system in which the alarm will sound when the temperature is high, or when there is smoke, or both.

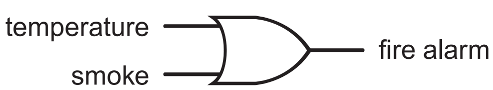
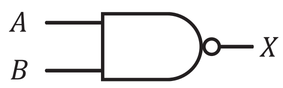


Figure 11.7 Fire alarm system using an OR gate

NAND gate

Figure 11.8 shows the symbol and truth table of a **NAND gate**.



Input A	Input B	Output $X = \overline{A \cdot B}$
0	0	1
0	1	1
1	0	1
1	1	0

Figure 11.8a Symbol of a NAND gate

Figure 11.8b Truth table of a NAND gate

The NAND gate performs the NAND operation, which gives an output of 0 only when both inputs are 1. If any of the inputs is 0, the output is 1.

A NAND gate operates like an AND gate followed by a NOT gate, as shown in Figure 11.9.

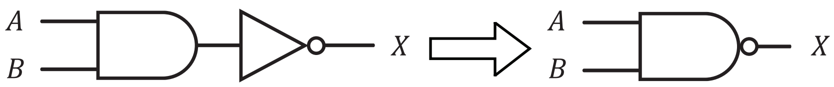


Figure 11.9 The NAND gate is equivalent to an AND gate followed by a NOT gate

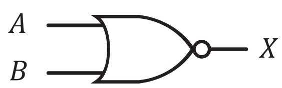
The Boolean expression for the NAND gate is written as:

$$X = \overline{A \cdot B}$$

Notice that the expression also indicates that A and B are first 'ANDed' and then inverted.

NOR gate

Figure 11.10 shows the symbol and truth table of a **NOR gate**.



Input A	Input B	Output $X = \overline{A + B}$
0	0	1
0	1	0
1	0	0
1	1	0

Figure 11.10a Symbol of a NOR gate

Figure 11.10b Truth table of a NOR gate

The NOR gate performs the NOR operation, which gives an output of 0 when one or both of the inputs is 1. The only case where the output is 1 is when both inputs are 0.

The NOR gate operates like an OR gate followed by a NOT gate, as shown in Figure 11.11.

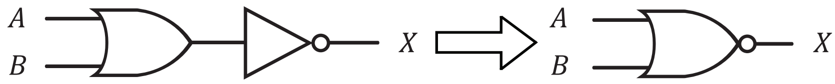


Figure 11.11 The NOR gate is equivalent to an OR gate followed by a NOT gate

The Boolean expression for the NOR gate is written as:

$$X = \overline{A + B}$$

Notice that the expression also indicates that A and B are first 'ORed' and then inverted.

Worked Example 11.1

Write down the Boolean expressions for each of the following logic gates:

(a) NOR

(b) NOT

(c) AND

(d) OR

(e) NAND

Solution

(a) $X = \overline{A + B}$

(b) $X = \overline{A}$

(c) $X = A \cdot B$

(d) $X = A + B$

(e) $X = \overline{A \cdot B}$

Worked Example 11.2

To attract customers during off-peak hours, an eatery has decided to waive its service charge from Mondays to Thursdays between 2.00 and 4.30 p.m.

Complete Figure 11.12 by drawing a suitable logic gate to describe the situation.

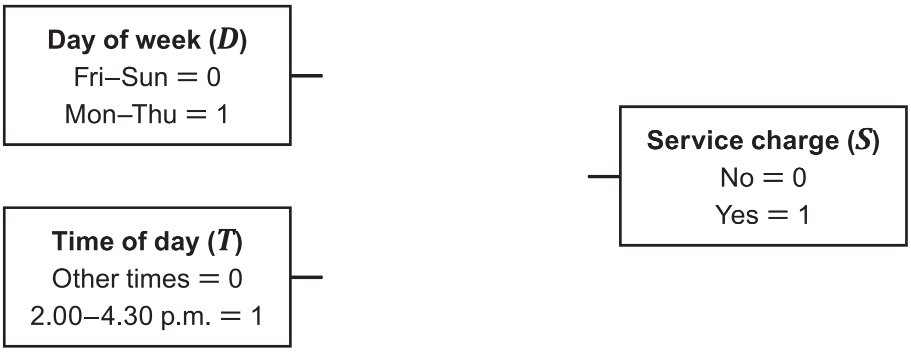


Figure 11.12

Solution

Step 1: Draw the truth table. S should only be 0 when $D = 1$ and $T = 1$.

Input D	Input T	Output S
0	0	1
0	1	1
1	0	1
1	1	0

Step 2: Determine the logic gate based on the truth table.

The truth table is that of a NAND gate.

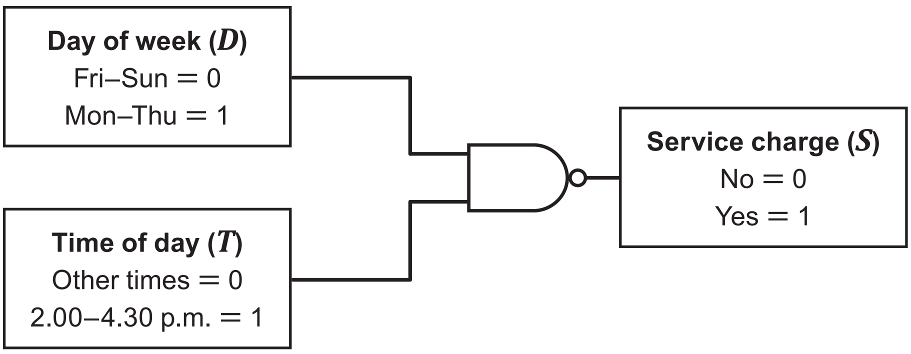


Figure 11.13

Review Questions 11.2

1. Draw the symbol and write the Boolean expression of the logic gate described by the following truth table.

Table 11.1 Truth table

Input A	Input B	Output X
0	0	1
0	1	0
1	0	0
1	1	0

2. For each of the two systems described below,
   (a) determine the inputs and output;
   (b) draw the truth table to describe its operation;
   (c) draw the corresponding logic gate; and
   (d) write down the corresponding Boolean expression.

   - The carpark exit barrier should rise if there is a car waiting to exit and the correct parking fee has been paid.
   - The green man traffic lights at a pedestrian crossing should light up if the buttons on the traffic light poles on either side of the road have been pressed.

11.3 How do we build logic gates using universal gates?

Learning Outcomes

- State that NAND and NOR gates are universal gates.
- Show how NOT, AND and OR gates can be made using NAND or NOR gates.

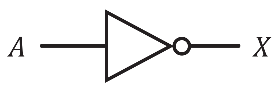
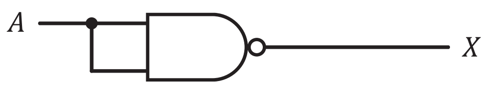
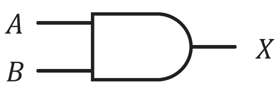
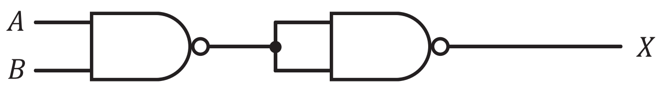
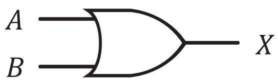
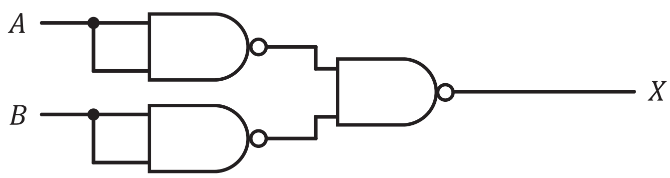
Key Idea

- Any logic system can be built using only NAND or NOR gates.

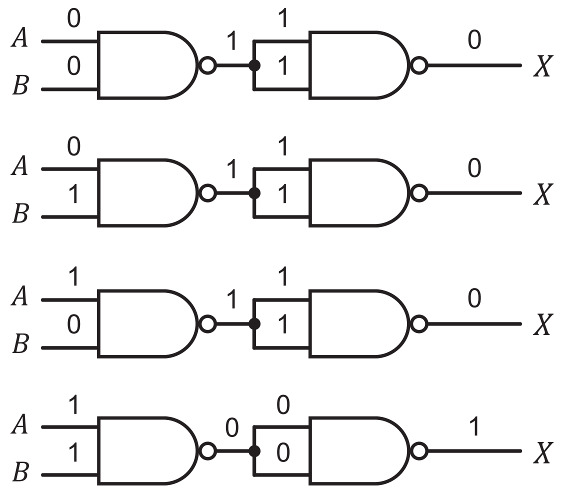
Of the five common logic gates discussed in Section 11.2, NAND and NOR gates are known as **universal gates**. This means that we can implement other logic gates using *only* NAND gates or NOR gates.

Table 11.2 shows how the AND, OR and NOT operations can be implemented using only the NAND gates.

Table 11.2 Using NAND gates to implement NOT, AND and OR operations

Logic operation	Equivalent circuit using only NAND gates
 NOT	
 AND	
 OR	

We can construct a truth table to verify the operation of the equivalent circuits. An example is given in Figure 11.14, which shows the construction of the truth table of the equivalent circuit of the AND operation. The resulting truth table is exactly the same as the AND gate truth table shown in Figure 11.4b.



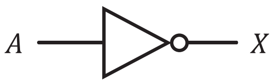
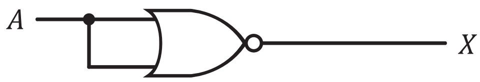
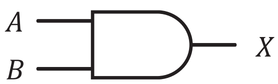
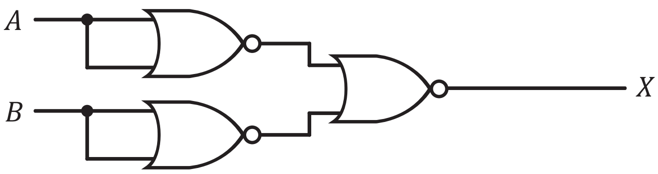
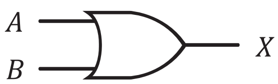
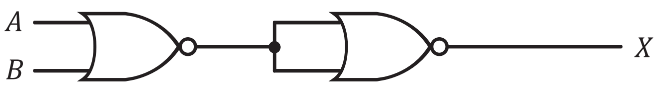
A	*B*	*X*
0	0	0
0	1	0
1	0	0
1	1	1

AND operation

Figure 11.14 Constructing a truth table to verify the equivalent circuit of the AND operation made from NAND gates

Table 11.3 shows how the NOT, AND and OR operations can be implemented using only NOR gates.

Table 11.3 Using NOR gates to implement NOT, AND and OR operations

Logic operation	Equivalent circuit using only NOR gates
 NOT	
 AND	
 OR	

Worked Example 11.3

Substitute each of the logic gates in Figure 11.15 using only NAND gates. Simplify your curcuit to use as few NAND gates as possible.

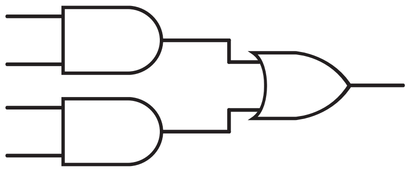


Figure 11.15

Solution

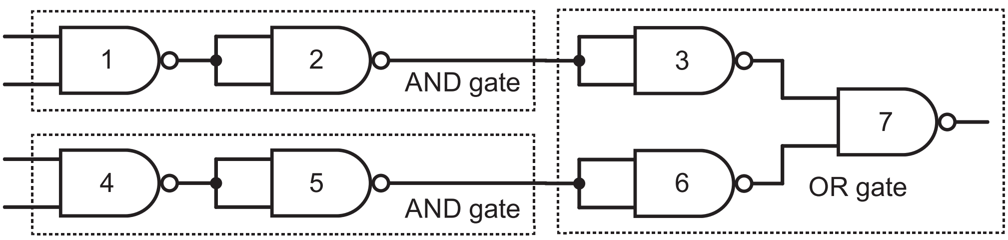


Figure 11.16

Notice that gates 2, 3, 5 and 6 are NOT gates. Since two NOT gates connected consecutively cancel out the action of each other, this circuit can be simplified by removing adjacent pairs of NOT gates (gates 2 and 3; gates 5 and 6).

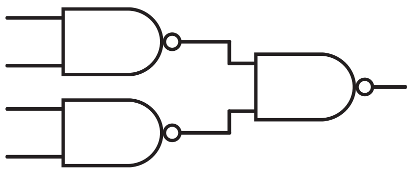


Figure 11.17

This results in a simpler equivalent circuit that contains only three NAND gates.

Review Questions 11.3

1. What are universal gates?

2. Substitute each of the logic gates in Figure 11.18 using only NAND gates. Simplify your circuit to use as few NAND gates as possible.

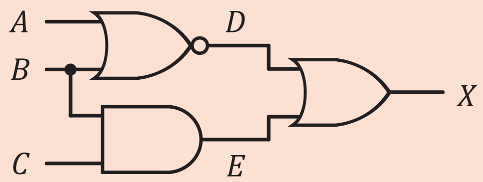


Figure 11.18

11.4 How do we read the datasheet of an integrated circuit?

Learning Outcomes

- Describe basic characteristics (e.g., general structure, pin configuration, common notation) of a dual in-line IC.
- Use datasheets to identify the pin connections of common logic gate ICs.

Key Idea

- Datasheets provide essential information on how to use ICs correctly and safely.

Integrated circuits

Figure 11.19a shows an AND gate built with diodes and Figure 11.19b shows an AND gate built with BJTs.

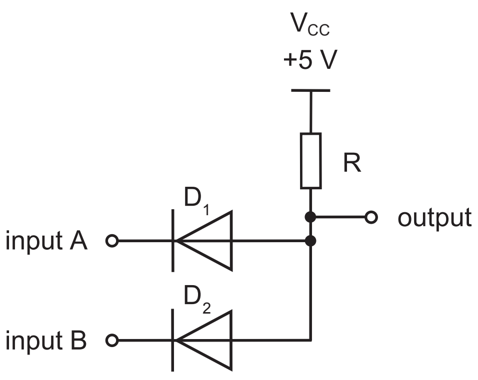


Figure 11.19a AND gate built with diodes

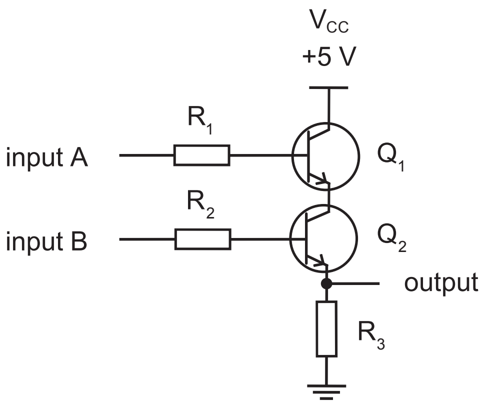


Figure 11.19b AND gate built with BJTs

Although logic gates can be built using separate diodes and BJTs, it is a lot easier to use logic gates that come in the form of **integrated circuits (ICs)** where all the components are integrated into a single package. This eliminates the need to build the circuit from scratch.

ICs are available in a variety of packaging types, which differ in terms of dimension, pin-count and mounting type (through-hole or surface-mount). Figure 11.20 shows two ICs that come in different packaging.

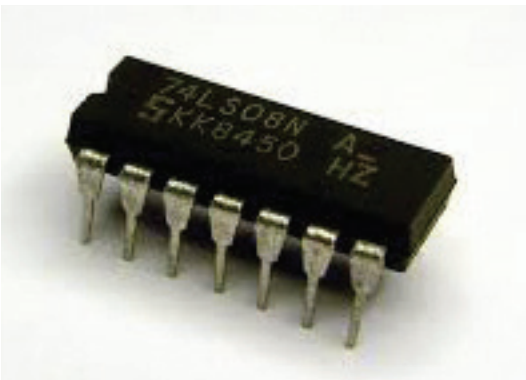


Figure 11.20a A 14-pin dual in-line through-hole IC

Figure 11.20b An 8-pin surface-mount IC

In this course, we will only use **dual in-line (DIL)** ICs, as shown in Figure 11.20a. DIL ICs consist of two parallel rows of pins extending perpendicularly from a black rectangular plastic housing. Each IC can be identified by the model number imprinted on it. Table 11.4 shows a list of ICs that we will be using in this course.

Table 11.4 Model numbers of common ICs

Model number	Description of IC
74LS00	quad 2-input NAND gates
74LS02	quad 2-input NOR gates
74LS04	hex inverting gates (NOT gates)
74LS08	quad 2-input AND gates
74LS11	triple 3-input AND gates
74LS32	quad 2-input OR gates
74LS47	BCD to 7-segment decoder
74LS390	dual 4-bit decade counter
NE555	555 timer
LM311	voltage comparator

To identify the pins of a DIL IC, we first place the IC in the orientation shown in Figure 11.21 with the notch and dot on top. Starting with the top left pin as pin 1, the pin number increases in an anticlockwise manner.

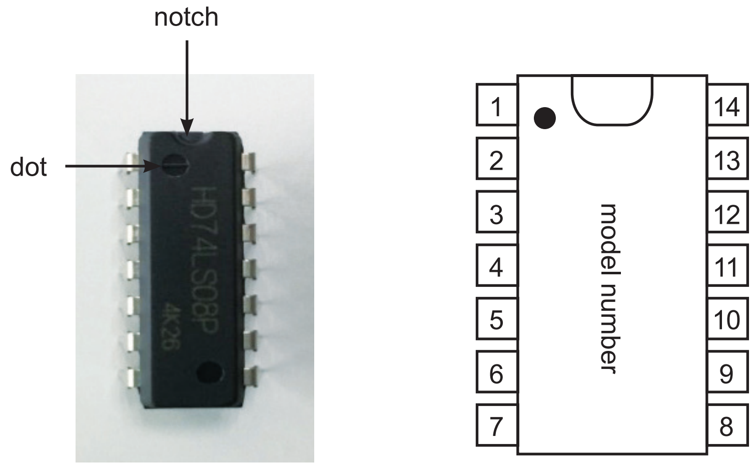


Figure 11.21 Top view of a 14-pin DIL IC (left) and its corresponding pin numbers (right)

Datasheet of a DIL IC

The **datasheet** of an IC contains important information such as the connection diagram, function table, absolute maximum ratings, recommended operating conditions and electrical characteristics. An extract of the datasheet of a 74LS08 quad 2-input AND gates IC is shown in Figure 11.22.

Semiconductor Technical Data

74LS08

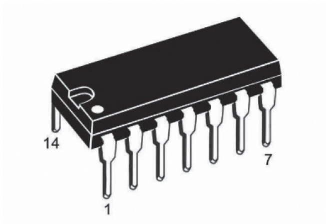
Quad 2-Input AND Gates

General Description

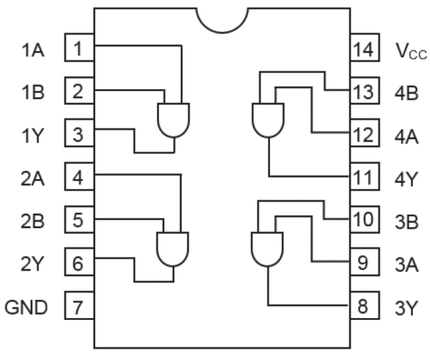
The device contains four independent AND gates.

Package

Standard 14-pin plastic dual in-line (DIL) package.



Connection Diagram



Function Table

$Y = A \cdot B$

Inputs		Output
A	***B***	***Y***
L	L	L
L	H	L
H	L	L
H	H	H

H = HIGH logic level
L = LOW logic level

ABSOLUTE MAXIMUM RATINGS (Note 1)

Parameter	Min.	Max.	Unit
Supply voltage		7	V
Input voltage		7	V
Operating free-air temperature range	0	70	°C
Storage temperature range	−65	150	°C

Note 1:
- The safety of the device cannot be guaranteed if the absolute maximum ratings are exceeded. The device should not be used at these limits.
- The values defined in the table of electrical characteristics are not guaranteed at these absolute maximum ratings.
- The values in the table of recommended operating conditions define the conditions for actual device usage.

Figure 11.22a Extract from a 74LS08 IC datasheet (page 1)

RECOMMENDED OPERATING CONDITIONS

Parameter	Symbol	Min.	Nom.	Max.	Unit
Supply voltage	V_{CC}	4.75	5	5.25	V
HIGH level input voltage	V_{IH}	2			V
LOW level input voltage	V_{IL}			0.8	V
HIGH level output current	I_{OH}			−0.4	mA
LOW level output current	I_{OL}			8	mA
Operating free-air temperature	T_A	0		70	°C

ELECTRICAL CHARACTERISTICS over recommended operating free-air temperature range

Parameter	Symbol	Conditions	Min.	Typ.	Max.	Unit
Input clamp voltage	V_I	$V_{CC} =$ min; $I_I = -12$ mA			−1.5	V
HIGH level output voltage	V_{OH}	$V_{CC} =$ min; $I_{OH} =$ max; $V_{IH} =$ min	2.4	3.4		V
LOW level output voltage	V_{OL}	$V_{CC} =$ min; $I_{OL} =$ max; $V_{IL} =$ max		0.2	0.4	V
Input current at max input voltage	I_I	$V_{CC} =$ max; $V_I = 5.5$ V			1	mA
HIGH level input current	I_{IH}	$V_{CC} =$ max; $V_I = 2.4$ V			40	μA
LOW level input current	I_{IL}	$V_{CC} =$ max; $V_I = 0.4$ V			−1.6	mA
Short-circuit output current	I_{OS}	$V_{CC} =$ max (Note 2)	−18		−55	mA
Supply current with outputs HIGH	I_{CCH}	$V_{CC} =$ max		11	21	mA
Supply current with outputs LOW	I_{CCL}	$V_{CC} =$ max		20	33	mA

Note 2: Not more than one output should be shorted at a time.

Figure 11.22b Extract from a 74LS08 IC datasheet (page 2)

Using information from the datasheet, we will be able to connect the 74LS08 IC correctly to achieve the intended purpose.

From the pin connection diagram in the datasheet (see Figure 11.22a), we know that we have to connect pin 14 to the positive power supply and pin 7 to the ground to power up the IC. To perform an AND operation, we can connect pin 1 (1A) to the first input, pin 2 (1B) to the second input and pin 3 (1Y) to the output as shown in Figure 11.23.

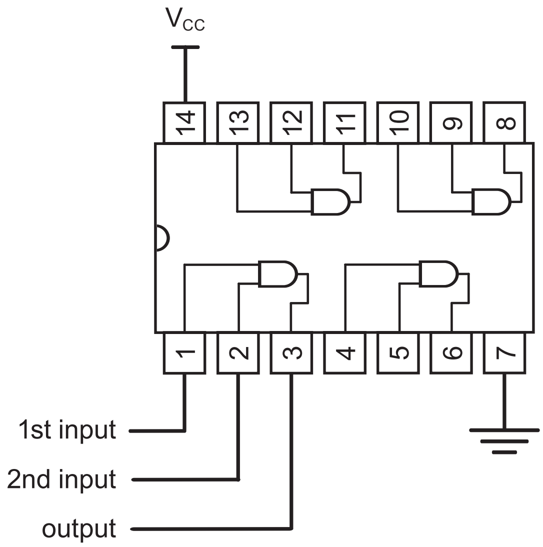


Figure 11.23 74LS08 IC connected to perform the AND operation

Besides the connection diagram, it is also useful to note the following parameters when designing and building circuits: V_{IH} and V_{IL}.

- The datasheet indicates that the minimum value of V_{IH} is 2.0 V. This means that the 74LS08 IC will treat an input voltage of 2.0 V or higher as logic 1.
- The datasheet indicates that the maximum value of V_{IL} is 0.8 V. This means that the 74LS08 IC will treat an input voltage of 0.8 V or lower as logic 0.

These characteristics are common across the 74LS series of ICs. When we use these ICs, we need to make sure that the voltage levels of input signals are at least 2.0 V for logic 1 and at most 0.8 V for logic 0. Signals with a voltage level between 0.8 V and 2.0 V should not be used as they will give an unpredictable result.

Review Questions 11.4

1. ICs come in different types of packaging. How do the types of packaging differ?

2. Draw an 8-pin DIL IC with all of the pins correctly numbered.

3. The pin connection diagram of the 74LS32 quad 2-input OR gates IC is shown in Figure 11.24. Identify three pins that can be used to perform an OR operation.

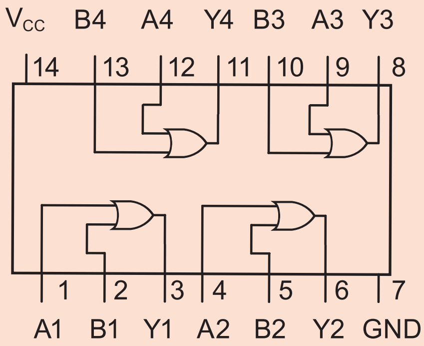


Figure 11.24 74LS32 IC pin connection diagram

First input: Pin ___

Second input: Pin ___

Output: Pin ___

Further Reading

The ICs covered in this chapter, e.g., the 74LS00, are made using technology similar to the BJTs discussed in Chapter 9. These ICs are called transistor-transistor logic (TTL) ICs. The model numbers of these ICs usually start with 54 or 74. TTL ICs are suitable for learning the essential principles and characteristics of ICs (e.g., pin configuration and logic states) as they are generally less complex to use and less prone to damage caused by mishandling.

There is another group of ICs, the complementary metal-oxide semiconductor (CMOS) ICs. These ICs are made using technology similar to MOSFETs (see Further Reading, Chapter 9). Most modern ICs, particularly the more complex ones, use CMOS technology due to the following advantages over TTL ICs:

- MOSFETs are smaller than BJTs. Hence, CMOS ICs can be made using smaller pieces of semiconductor material than TTL ICs, thus reducing the material cost. This becomes significant when there is a large number of transistors (e.g., millions or billions) in each IC.
- In general, CMOS ICs consume less electrical power than TTL ICs. However, the power consumption of CMOS ICs increases at a high frequency of operation.
- CMOS ICs can use a wide range of voltage supplies (3–18 V). TTL ICs, on the other hand, are designed to use only 5 V supplies.
- CMOS ICs are less prone to electrical interference than TTL ICs.

However, CMOS ICs need to be handled more carefully as they are more prone to damage from static electricity.

12 COMBINATIONAL LOGIC CIRCUITS

How do we design and build a decision-making circuit?

In Chapter 11, we learnt that a logic gate can be used to make simple logic decisions. To make complex logic decisions, we need to connect two or more logic gates together to form a combinational logic circuit. In this chapter, we will learn how to design and build combinational logic circuits.

12.1 How do we describe a combinational logic circuit?

Learning Outcomes

- Use a truth table to describe the output of a digital system (up to three inputs).
- Convert a truth table (up to three inputs) into a sum-of-product (SOP) Boolean expression.
- Describe and explain the function of a given combinational logic circuit.

Key Idea

- Truth tables and Boolean expressions are used to describe how a combinational logic circuit operates.

Combinational logic circuits

A **combinational logic circuit** is made up of two or more logic gates connected together. It can perform more useful and complex functions than a single logic gate.

Figure 12.1 shows the block diagram of a combinational logic circuit. It is similar to the block diagram of a logic gate, except there can be more than one output.

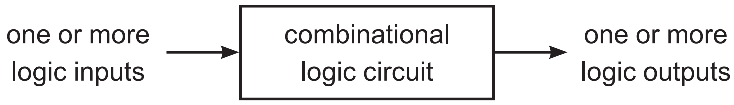


Figure 12.1 Block diagram of a combinational logic circuit

Figure 12.2 shows a combinational logic circuit consisting of an OR gate and an AND gate. The circuit has three inputs (A, B and C) and one output (X). The signal that passes from the OR gate to the AND gate is called an **intermediate signal** as it comes after the inputs but before the output.

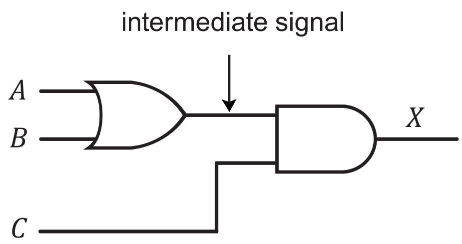


Figure 12.2 A combinational logic circuit

Deriving the truth table of a combinational logic circuit

Similar to the logic gates covered in Chapter 11, the operation of a combinational logic circuit can be described with a truth table. Follow these steps to generate the truth table:

1. Determine the number of rows and columns in the table:

   Number of rows $= 2^N$ where N is the number of inputs
   Number of columns = total number of inputs, intermediate signals and outputs

2. Draw the truth table and fill in all the input combinations.

3. Work out the states of the intermediate signals.

4. Work out the states of the outputs.

Worked Example 12.1

Draw and complete the truth table for the home security logic circuit shown in Figure 12.3. Using the truth table, describe the conditions that will cause the burglar alarm to sound.

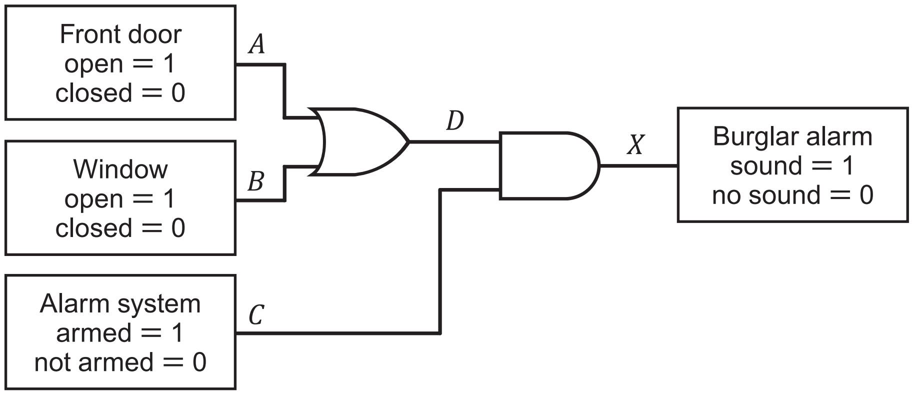


Figure 12.3

Solution

<u>*Step 1*:</u> Since there are three inputs (A, B and C), one output (X) and one intermediate signal (D),

Number of rows = $2^3 = 8$
Number of columns = $3 + 1 + 1 = 5$

<u>*Step 2*:</u> Draw the truth table and fill in all input combinations.

A	B	C	$D = A + B$	$X = D \cdot C$
0	0	0		
0	0	1		
0	1	0		
0	1	1		
1	0	0		
1	0	1		
1	1	0		
1	1	1		

Step 3: Work out the intermediate signal D using A and B. You do not have to refer to C and X at this stage.

A	B	C	$D = A + B$	$X = D \cdot C$
0	0	0	0	
0	0	1	0	
0	1	0	1	
0	1	1	1	
1	0	0	1	
1	0	1	1	
1	1	0	1	
1	1	1	1	

Step 4: Work out the output X using C and D. You do not have to refer to A and B at this stage.

A	B	C	$D = A + B$	$X = D \cdot C$
0	0	0	0	0
0	0	1	0	0
0	1	0	1	0
0	1	1	1	1
1	0	0	1	0
1	0	1	1	1
1	1	0	1	0
1	1	1	1	1

From the truth table, we can see that output X will be 1 when:

- $A = 0$ and $B = 1$ and $C = 1$
- $A = 1$ and $B = 0$ and $C = 1$
- $A = 1$ and $B = 1$ and $C = 1$

In other words, the burglar alarm will sound when:

- the alarm system is armed and the window is open;
- the alarm system is armed and the front door is open; or
- the alarm system is armed and both the window and front door are open.

Boolean expression of a combinational logic circuit

Besides using a truth table, we can also describe a combinational logic circuit using a Boolean expression. The Boolean expression can be derived from the truth table by writing an AND term for each input combination with a resulting output of 1, and then ORing all the AND terms. We will demonstrate this using the truth table in Table 12.1.

Table 12.1 Truth table

A	B	C	X
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	0
1	1	0	1
1	1	1	0

From the truth table, output $X = 1$ when $A = 0$, $B = 1$ and $C = 1$. Since these conditions need to be all present for output $X = 1$, they need to be ANDed together. Recall that the AND operation is represented by '$\cdot$'. Hence, the AND term for this input combination is $\bar{A} \cdot B \cdot C$. Notice that $\bar{A}$ is used to represent $A = 0$. This is because when $A = 0$, its inverse ($\bar{A}$) will be 1.

Also, output $X = 1$ when $A = 1$, $B = 1$ and $C = 0$, thus the corresponding AND term is $A \cdot B \cdot \bar{C}$.

Since either of these two input combinations will result in an output of 1, we should OR their respective AND terms. Recall that the OR operation is represented by '+'. Thus, we obtain the final Boolean expression shown below.

$$X = \bar{A} \cdot B \cdot C + A \cdot B \cdot \bar{C}$$

In mathematics, '+' is the sign for 'sum', and '$\cdot$' is the sign for 'product'. Hence, this form of expression where the AND terms are ORed together is commonly known as a **sum-of-product (SOP)** expression.

Worked Example 12.2

Table 12.2 shows the truth table of a combinational logic circuit with three inputs, A, B and C. Obtain the Boolean expression for output X.

Table 12.2 Truth table

A	B	C	X
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	0
1	1	1	1

Solution

Step 1: Identify the rows of the truth table where output X is 1. In this case, there are three rows as shown.

A	B	C	X	
0	0	0	0	
0	0	1	0	
0	1	0	0	
0	1	1	1	←
1	0	0	0	
1	0	1	1	←
1	1	0	0	
1	1	1	1	←

Step 2: Write the AND term for each input combination with an output of 1.
When $A = 0$, $B = 1$ and $C = 1$, the AND term is $\bar{A} \cdot B \cdot C$.
When $A = 1$, $B = 0$ and $C = 1$, the AND term is $A \cdot \bar{B} \cdot C$.
When $A = 1$, $B = 1$ and $C = 1$, the AND term is $A \cdot B \cdot C$.

Step 3: Form the SOP Boolean expression for output X by ORing the AND terms:

$$X = \bar{A} \cdot B \cdot C + A \cdot \bar{B} \cdot C + A \cdot B \cdot C$$

Review Questions 12.1

1. Draw and complete the truth tables for the circuits shown in Figures 12.4 and 12.5.

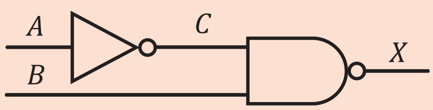


Figure 12.4

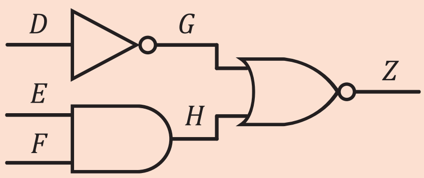


Figure 12.5

2. What is an SOP Boolean expression?

3. Derive the SOP Boolean expressions of the two circuits shown in Figures 12.4 and 12.5 using the truth tables you have drawn.

12.2 How do we obtain a logic circuit from its Boolean expression?

Learning Outcome

- Implement logic circuits using NOT, AND and OR gates given an SOP Boolean expression.

Key Idea

- The circuit diagram of a combinational logic circuit can be obtained from its Boolean expression.

In the previous section, we learnt how to obtain the SOP Boolean expression of a combinational logic circuit from its circuit diagram. In many situations, we also need to do the reverse, i.e., obtain the circuit diagram of a logic circuit from its SOP Boolean expression. To do this, we will need to draw a logic circuit for each AND term, then connect the outputs of these logic circuits to the inputs of an OR gate. We will demonstrate this in Figure 12.6 using the Boolean expression $X = A \cdot B + \bar{A} \cdot C$.

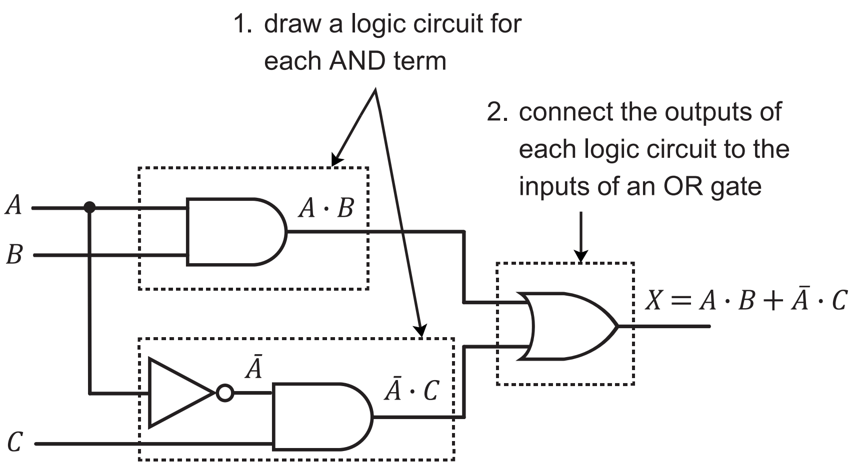


Figure 12.6 Obtaining the circuit diagram from the SOP Boolean expression

- The first AND term, $A \cdot B$, can be drawn as an AND gate with inputs A and B.
- For the second AND term, $\bar{A} \cdot C$, A is put through a NOT gate to obtain $\bar{A}$. $\bar{A}$ and C are the inputs of the second AND gate.
- The outputs of both AND gates are connected to the inputs of an OR gate.

Worked Example 12.3

The output X of a combinational logic circuit with three inputs, A, B and C is given as:

$$X = \bar{A} \cdot C + B + A \cdot \bar{B} \cdot C$$

Draw the circuit diagram of the logic circuit.

Solution

Step 1: Draw a logic circuit for each AND term using NOT and AND gates as shown in Figure 12.7.

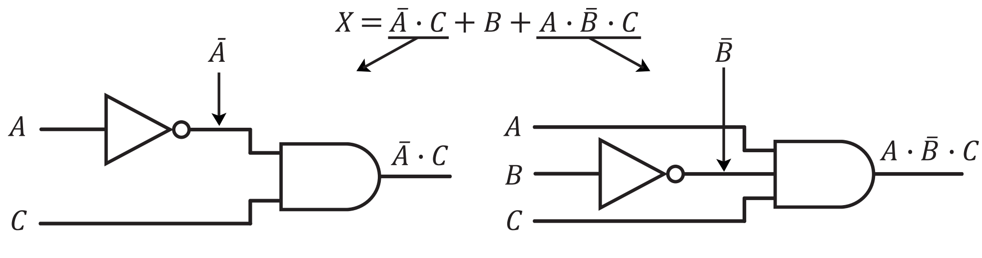


Figure 12.7

Step 2: Connect the outputs of the two logic circuits and input B to an OR gate as shown in Figure 12.8.

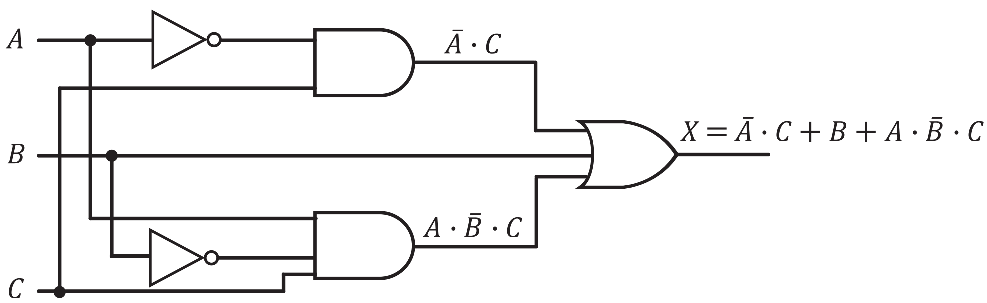


Figure 12.8

From the circuit diagram, the truth table can then be derived using the method introduced in Section 12.1.

Review Question 12.2

1. Construct logic circuits using AND, OR, and NOT gates for the following SOP Boolean expressions:

   (a) $X = \bar{A} \cdot \bar{B} + A \cdot B$

   (b) $Y = \bar{A} \cdot C + A \cdot B \cdot \bar{C} + A \cdot B \cdot C$

12.3 How do we simplify a logic circuit using a Karnaugh map?

Learning Outcome

- Simplify an SOP Boolean expression (up to three variables) using a Karnaugh map.

Key Idea

- An SOP Boolean expression can be simplified using a Karnaugh map. This will result in a logic circuit that uses fewer logic gates.

In the previous section, we learnt how to derive the circuit diagram of a combinational logic circuit from a Boolean expression. The more complex the Boolean expression, the larger the number of logic gates needed. Therefore, it is useful to be able to simplify a Boolean expression and thus reduce the number of logic gates needed. Using fewer gates will also save costs and result in a circuit that is less prone to error.

Consider the SOP Boolean expression for a combinational logic circuit with inputs A, B and C, and output X:

$$X = \bar{A} \cdot B \cdot C + A \cdot \bar{B} \cdot C + A \cdot B \cdot C$$

The logic circuit is shown in Figure 12.9. The circuit consists of two NOT gates, three AND gates and one OR gate. In addition, the AND and OR gates need to have three inputs each.

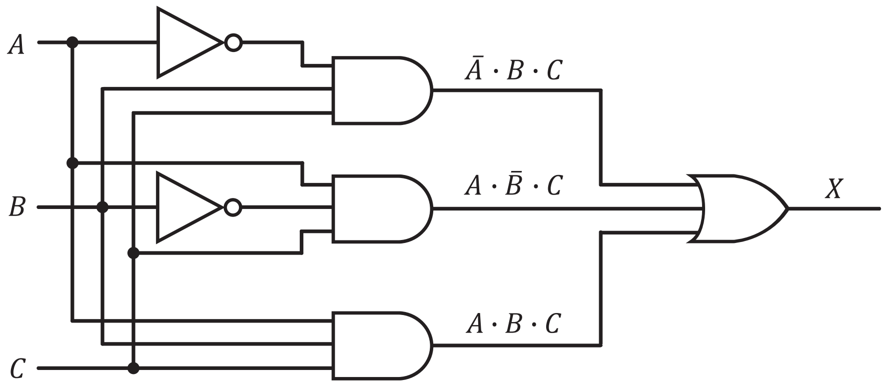


Figure 12.9 Combinational logic circuit before simplification

Using a technique that will be explained later in this section, the Boolean expression can be simplified to:

$$X = A \cdot C + B \cdot C$$

Figure 12.10 shows the logic circuit of the simplified expression. The circuit consists of only two AND gates and one OR gate. The circuit in Figure 12.10 is able to perform the same function as the one in Figure 12.9 using fewer logic gates.

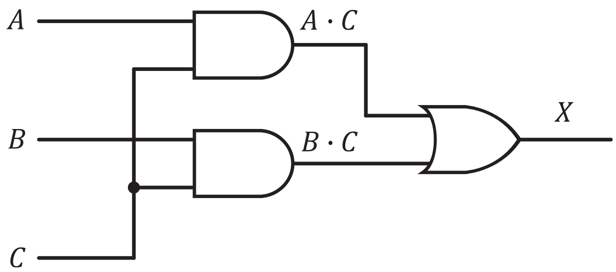


Figure 12.10 Combinational logic circuit after simplification

The first technique that we will learn to simplify Boolean expressions is called the **Karnaugh map** or **K-map** for short. It is a graphical method and involves a number of steps.

Step 1: Set up the K-map

Figure 12.11 shows a K-map that can be used for 2-input logic circuits. It has four cells to store the outputs of all the input combinations. The 0s and 1s outside the cells indicate the states of the inputs. For example, the top left cell will store the output of the input combination $A = 0$ and $B = 0$, while the bottom left cell will store the output of the input combination $A = 1$ and $B = 0$.

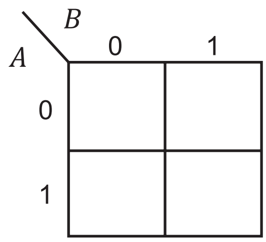


Figure 12.11 K-map for 2-input logic circuits

The K-map for 3-input logic circuits shown in Figure 12.12 has eight cells to store the outputs of all the input combinations. Here, the top left cell will store the output of the input combination $A = 0$, $B = 0$ and $C = 0$, while the bottom left cell will store the output of the input combination $A = 1$, $B = 0$ and $C = 0$.

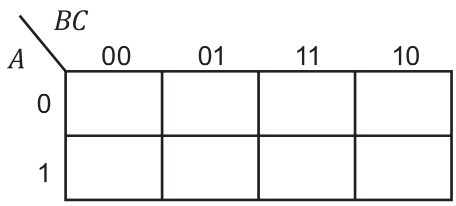


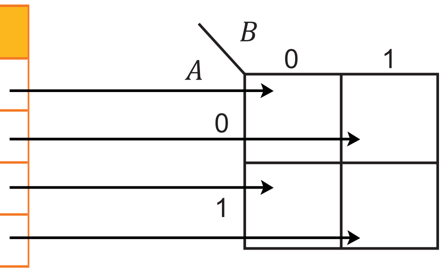
Figure 12.12 K-map for 3-input logic circuits

There are other ways to draw the K-maps, but we need to ensure that only one input changes as we move from one row or column to the next. For example, in Figure 12.12 when we move from the top left cell to the bottom left cell, only input A changes while inputs B and C remain unchanged.

Step 2: Transfer information from the truth table to the K-map

Write the output of each row of a truth table in its corresponding K-map cell as shown in Figure 12.13.

A	*B*	*X*
0	0	
0	1	
1	0	
1	1	



A	*B*	*C*	*X*
0	0	0	
0	0	1	
0	1	0	
0	1	1	
1	0	0	
1	0	1	
1	1	0	
1	1	1	

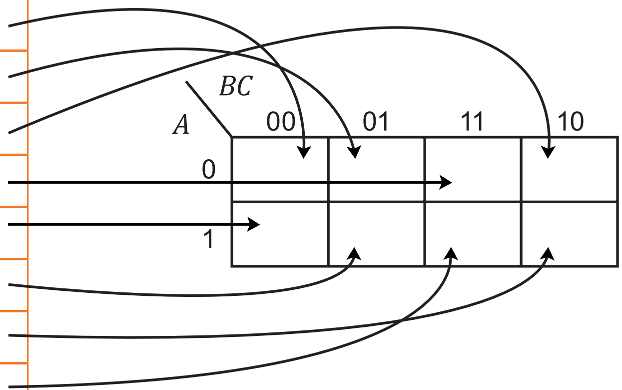


Figure 12.13 Transferring information from the truth table to the K-map

Step 3: Loop the '1's in the K-map

This is the most complicated step. This process is called **looping**:

- Adjacent '1's are looped together in groups of four, two or one (in this order of preference) as shown in Figures 12.14, 12.15 and 12.16, respectively. The first and last column are also considered adjacent to each other, thus we can loop the '1's in these two columns as shown in Figure 12.14c and 12.15c .

- Looping continues until all the '1's have been included inside a loop.

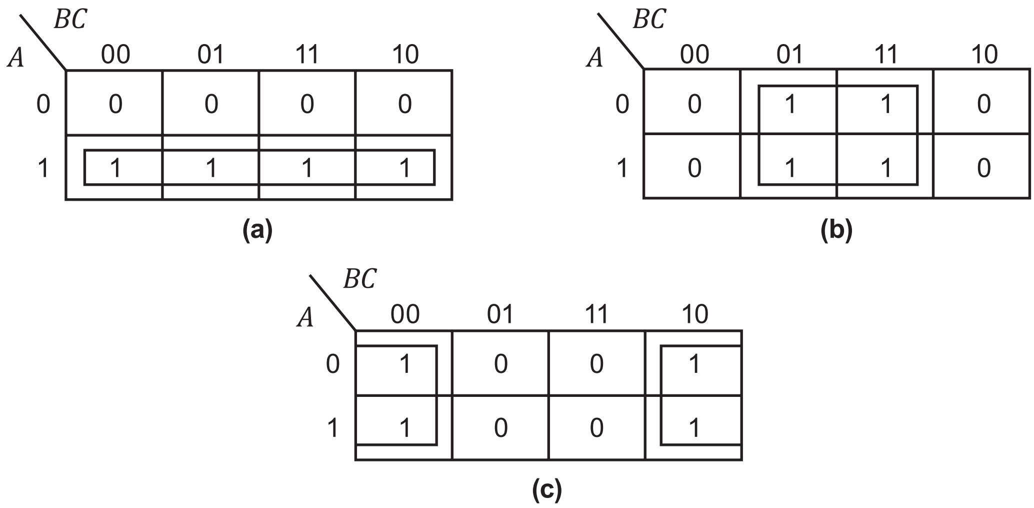


Figure 12.14 Looping in groups of four

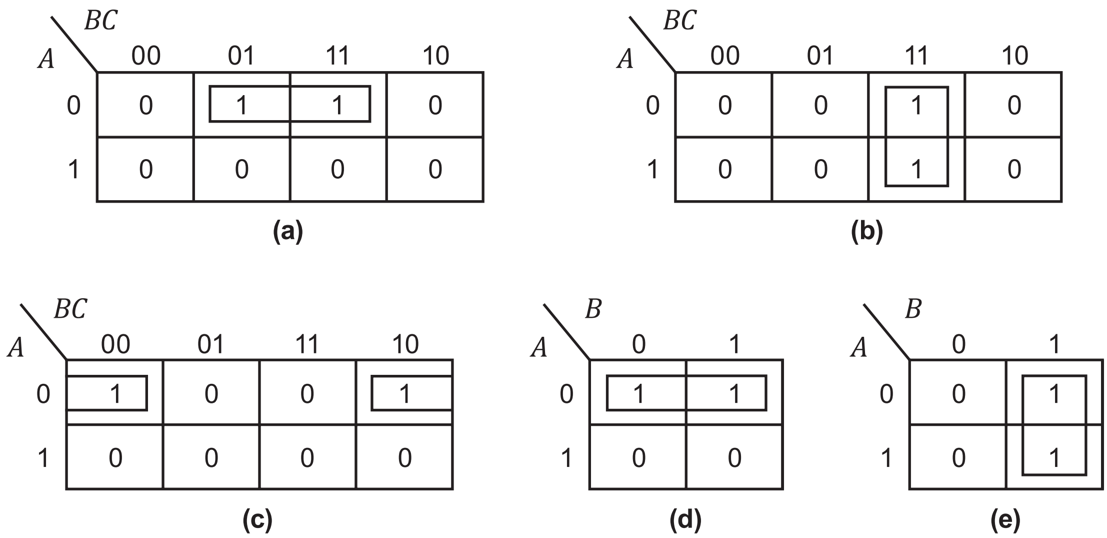


Figure 12.15 Looping in groups of two

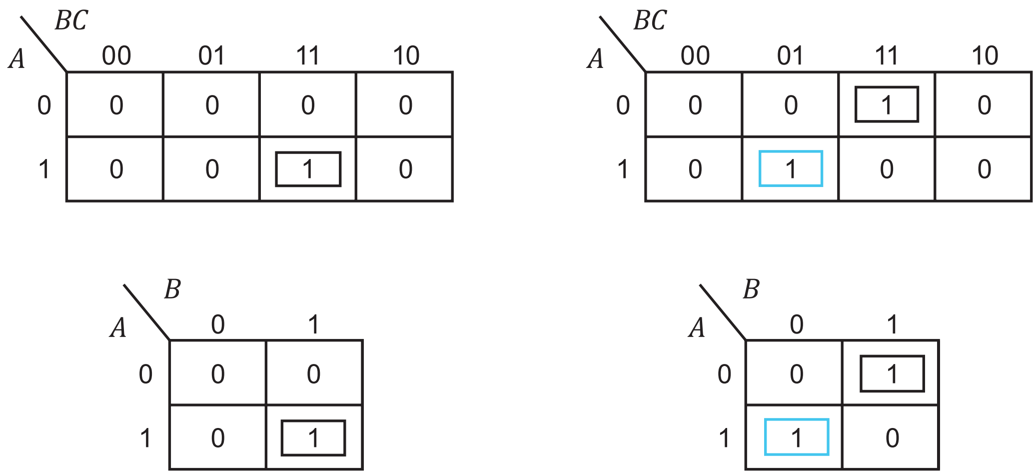
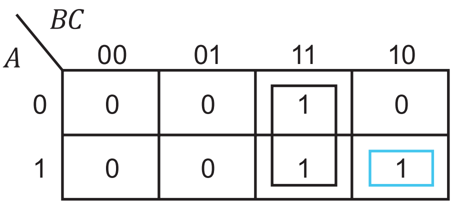
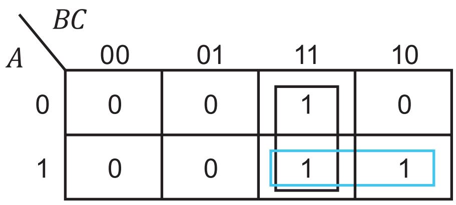


Figure 12.16 Looping in groups of one

To obtain the simplest possible Boolean expression, we should aim to maximise the size of each group and minimise the number of groups. A common strategy is to reuse the ‘1’s where possible to create bigger groups. This will usually result in overlapping groups, which is normal. Figures 12.17b and 12.18c show how the best method of grouping can be achieved.

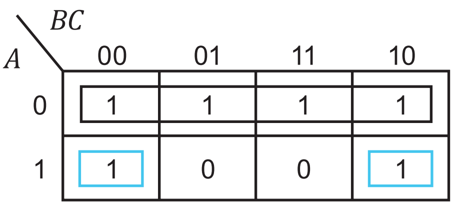


(a) one method of grouping

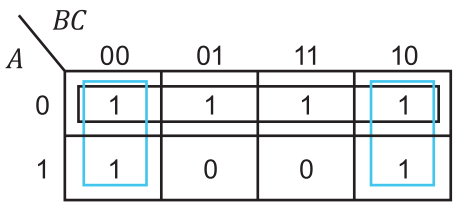


(b) a better method of grouping

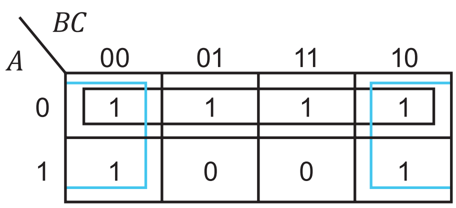
Figure 12.17 Group size should be maximised



(a) one method of grouping



(b) a better method where the size of group is maximised



(c) the best method where the number of groups is further minimised

Figure 12.18 Group size should be maximised and the number of groups minimised

Step 4: Obtain the simplified Boolean expression

Write the AND term for each group based on the common inputs.

Let us consider Figure 12.19. After looping the '1's, we have a group of four and a group of two.

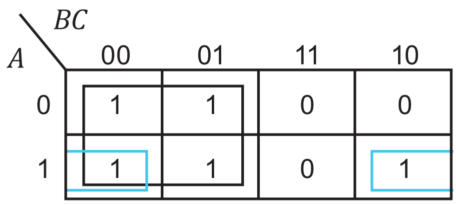


Figure 12.19 A K-map after looping

Let us first examine the group of four as shown in Figure 12.20. The only common input is $B = 0$, so the AND term is $\bar{B}$.

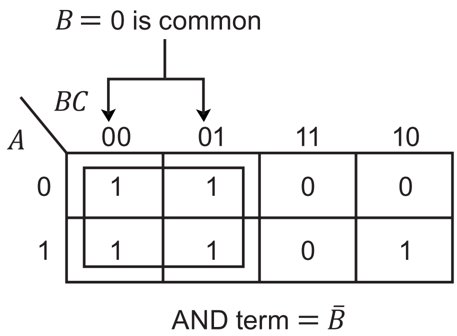


Figure 12.20 Deriving the AND term for the group of four

For the group of two as shown in Figure 12.21, the common inputs are $A = 1$ and $C = 0$, so the AND term is $A \cdot \bar{C}$.

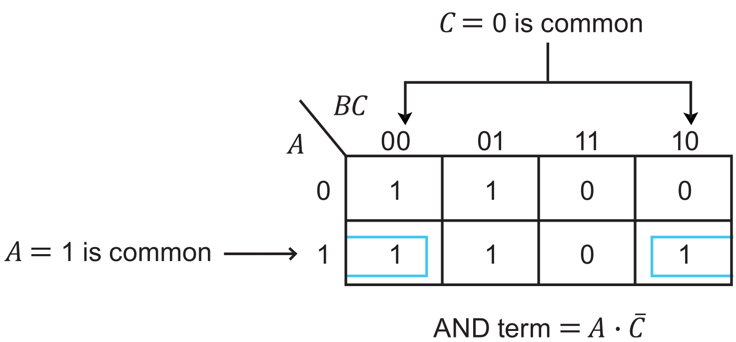
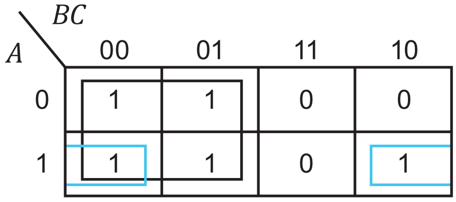


Figure 12.21 Deriving the AND term for the group of two

OR the AND terms to form the final simplified Boolean output expression.

In our example, this would be $X = \bar{B} + A \cdot \bar{C}$.



$$X = \bar{B} + A \cdot \bar{C}$$

Figure 12.22 Combining the terms to form the final simplified Boolean expression

Worked Example 12.4

Table 12.3 shows the truth table of a combinational logic circuit with three inputs A, B and C, and one output X.

Table 12.3 Truth table

A	B	C	X
0	0	0	1
0	0	1	1
0	1	0	0
0	1	1	0
1	0	0	1
1	0	1	0
1	1	0	0
1	1	1	0

(a) Write down the Boolean expression without simplification.

(b) Simplify the Boolean expression from (a) using a K-map.

Solution

(a) Output X is 1 in rows 1, 2 and 5.

A	B	C	X	
0	0	0	1	$\leftarrow \bar{A} \cdot \bar{B} \cdot \bar{C}$
0	0	1	1	$\leftarrow \bar{A} \cdot \bar{B} \cdot C$
0	1	0	0	
0	1	1	0	
1	0	0	1	$\leftarrow A \cdot \bar{B} \cdot \bar{C}$
1	0	1	0	
1	1	0	0	
1	1	1	0	

Based on the states of the input, the Boolean expression is
$X = \bar{A} \cdot \bar{B} \cdot \bar{C} + \bar{A} \cdot \bar{B} \cdot C + A \cdot \bar{B} \cdot \bar{C}$

(b) *Step 1:* Set up the K-map

A \ BC	00	01	11	10
0				
1				

Figure 12.23

Step 2: Transfer information from the truth table into the K-map

A	B	C	X
0	0	0	1
0	0	1	1
0	1	0	0
0	1	1	0
1	0	0	1
1	0	1	0
1	1	0	0
1	1	1	0

A \ BC	00	01	11	10
0	1	1	0	0
1	1	0	0	0

Figure 12.24

Step 3: Loop the '1's in the K-map

A \ BC	00	01	11	10
0	1	1	0	0
1	1	0	0	0

Figure 12.25

Step 4: From the loops, form the AND terms and write down the simplified Boolean expression

$\bar{A}\cdot\bar{B}$

A \ BC	00	01	11	10
0	1	1	0	0
1	1	0	0	0

$\bar{B}\cdot\bar{C}$

Figure 12.26

$$X = \bar{A}\cdot\bar{B} + \bar{B}\cdot\bar{C}$$

Notice that the simplified Boolean expression is much simpler than the original one.

Review Questions 12.3

1. Table 12.4 shows the truth table of a combinational logic circuit. A, B and C are the inputs while X is the output. Obtain a simplified Boolean expression of the circuit using a K-map.

Table 12.4 Truth table

A	B	C	X
0	0	0	0
0	0	1	1
0	1	0	0
0	1	1	1
1	0	0	1
1	0	1	1
1	1	0	0
1	1	1	0

2. Using a K-map, show that the Boolean expression $X = \bar{A} \cdot B \cdot C + A \cdot \bar{B} \cdot C + A \cdot B \cdot C$ can be simplified to $X = A \cdot C + B \cdot C$.

3. Simplify the following Boolean expression using a K-map. $X = \bar{A} \cdot B \cdot \bar{C} + \bar{A} \cdot B \cdot C + A \cdot B \cdot \bar{C} + A \cdot B \cdot C$.

12.4 How do we simplify a logic circuit using Boolean algebra?

Learning Outcome

- Simplify an SOP Boolean expression (up to three variables) using Boolean algebra.

Key Idea

- Besides the K-Map, Boolean algebra can also be used to simplify Boolean expressions.

Boolean algebra is a type of algebra that deals only with two values – 0 and 1. It has three main operations: NOT, OR and AND. Boolean algebra is governed by a number of laws. Table 12.5 shows the Boolean laws involving one variable.

Table 12.5 Boolean laws involving one variable

Boolean law	Explanation
$\bar{\bar{A}} = A$	If $A = 0$, $\bar{\bar{0}} = \bar{1} = 0$ If $A = 1$, $\bar{\bar{1}} = \bar{0} = 1$
$A + 0 = A$	If $A = 0$, then the result will be 0. If $A = 1$, then the result will be 1.
$A + 1 = 1$	Regardless of the value of A, the result will be 1.
$A + A = A$	If $A = 0$, then the result will be 0. If $A = 1$, then the result will be 1.
$A + \bar{A} = 1$	Either A or $\bar{A}$ will be 1, so the result will be 1.
$A \cdot 0 = 0$	Regardless of the value of A, the result will be 0.
$A \cdot 1 = A$	If $A = 0$, then the result will be 0. If $A = 1$, then the result will be 1.
$A \cdot A = A$	If $A = 0$, then the result will be 0. If $A = 1$, then the result will be 1.
$A \cdot \bar{A} = 0$	Either A or $\bar{A}$ will be 0, so the result will be 0.

Table 12.6 shows the Boolean laws for two or more variables. These can be categorised into commutative laws, associative laws, distributive laws and absorption laws.

Table 12.6 Boolean laws for two or more variables

Boolean law	Type
$A + B = B + A$	OR commutative law
$A \cdot B = B \cdot A$	AND commutative law
$A + (B + C) = (A + B) + C$	OR associative law
$A \cdot (B \cdot C) = (A \cdot B) \cdot C$	AND associative law
$A \cdot (B + C) = A \cdot B + A \cdot C$ $(A + B) \cdot (C + D) = A \cdot C + A \cdot D + B \cdot C + B \cdot D$	Distributive laws
$A + A \cdot B = A$ $A \cdot (A + B) = A$ $A + \bar{A} \cdot B = A + B$ $A \cdot (\bar{A} + B) = A \cdot B$	Absorption laws Notice that one or two terms on the left side of the equation are 'absorbed' into the term on the right side.
$\overline{A \cdot B} = \bar{A} + \bar{B}$ $\overline{A + B} = \bar{A} \cdot \bar{B}$	De Morgan's theorem Notice that both equations involve: • removing the NOT operation on the left side of the equation and placing NOT operations over the individual variables on the right side; and • changing the AND operation on the left side to the OR operation on the right side (and vice versa).

Using these Boolean laws, we are able to simplify Boolean expressions. Let us revisit Worked Example 12.4 to simplify the Boolean expression using Boolean algebra instead of a K-map.

Worked Example 12.5

Table 12.7 shows the truth table of a combinational logic with three inputs A, B and C, and one output X.

Table 12.7 Truth table

A	B	C	X
0	0	0	1
0	0	1	1
0	1	0	0
0	1	1	0
1	0	0	1
1	0	1	0
1	1	0	0
1	1	1	0

(a) Write down the Boolean expression without simplification.

(b) Simplify the Boolean expression from (a) using Boolean algebra.

Solution

(a) From Worked Example 12.4, $X = \bar{A} \cdot \bar{B} \cdot \bar{C} + \bar{A} \cdot \bar{B} \cdot C + A \cdot \bar{B} \cdot \bar{C}$

(b) $X = \bar{A} \cdot \bar{B} \cdot \bar{C} + \bar{A} \cdot \bar{B} \cdot C + A \cdot \bar{B} \cdot \bar{C}$

$= \bar{A} \cdot \bar{B} \cdot (\bar{C} + C) + A \cdot \bar{B} \cdot \bar{C}$ — Apply distributive law

$= \bar{A} \cdot \bar{B} \cdot 1 + A \cdot \bar{B} \cdot \bar{C}$ — Apply $C + \bar{C} = 1$

$= \bar{A} \cdot \bar{B} + A \cdot \bar{B} \cdot \bar{C}$ — Apply Boolean law $A \cdot 1 = A$

$= \bar{B} \cdot (\bar{A} + A \cdot \bar{C})$ — Apply distributive law

$= \bar{B} \cdot (\bar{A} + \bar{C})$ — Apply absorption law

$= \bar{A} \cdot \bar{B} + \bar{B} \cdot \bar{C}$ — Apply distributive law

Notice that the result is the same as when using a K-map.

Worked Example 12.6

Simplify the Boolean expression: $X = \overline{\bar{A} \cdot \bar{B}}$

Solution

$$
\begin{aligned}
X &= \overline{\bar{A} \cdot \bar{B}} && \text{Apply De Morgan's theorem} \\
&= \bar{\bar{A}} + \bar{\bar{B}} && \text{Apply } \bar{\bar{A}} = A \\
&= A + B
\end{aligned}
$$

Review Questions 12.4

1. Table 12.8 shows the truth table of a combinational logic circuit. A, B and C are the inputs while X is the output. Obtain the simplified Boolean expression of the circuit using Boolean algebra.

Table 12.8 Truth table

A	B	C	X
0	0	0	0
0	0	1	1
0	1	0	0
0	1	1	1
1	0	0	1
1	0	1	1
1	1	0	0
1	1	1	0

2. Simplify the following Boolean expressions using Boolean algebra.

(a) $X = \bar{A} \cdot B \cdot \bar{C} + \bar{A} \cdot B \cdot C + A \cdot B \cdot \bar{C} + A \cdot B \cdot C$
(b) $X = \overline{\bar{\bar{A}} + \bar{\bar{B}}}$

12.5 How do we use combinational logic to solve real-life problems?

Learning Outcome

- Solve system problems using combinations of logic gates (up to three inputs).

Key Idea

- If a problem can be described using a truth table, a logic circuit can be built to solve it.

Many real-life problems start with a list of conditions that must be fulfilled in order to achieve a particular outcome. Such problems can be described using a truth table and then solved using a combinational logic circuit.

Worked Example 12.7

The organiser of a relay match wants to generate a list of participants that qualify for the semi-finals. Participants will qualify for the semi-finals if they are able to complete any two of the following tasks:

- Jump and touch a hanging object at least 10 times in a minute
- Complete a 100 m dash within 15 seconds
- Complete 10 pull-ups in a minute

Design a logic circuit that is able to decide whether a participant qualifies for the semi-finals.

Solution

<u>Step 1:</u> Set up the truth table

Let A, B and C represent the tasks:

A – Jump and touch the hanging object at least 10 times in a minute
B – Complete a 100 m dash within 15 seconds
C – Complete 10 pull-ups in a minute

Output X should be 1 whenever two or more inputs are 1.

A	B	C	X	
0	0	0	0	
0	0	1	0	
0	1	0	0	
0	1	1	1	$\longleftarrow \bar{A} \cdot B \cdot C$
1	0	0	0	
1	0	1	1	$\longleftarrow A \cdot \bar{B} \cdot C$
1	1	0	1	$\longleftarrow A \cdot B \cdot \bar{C}$
1	1	1	1	$\longleftarrow A \cdot B \cdot C$

<u>Step 2:</u> Simplify the output expression

Method 1: Using a K-map

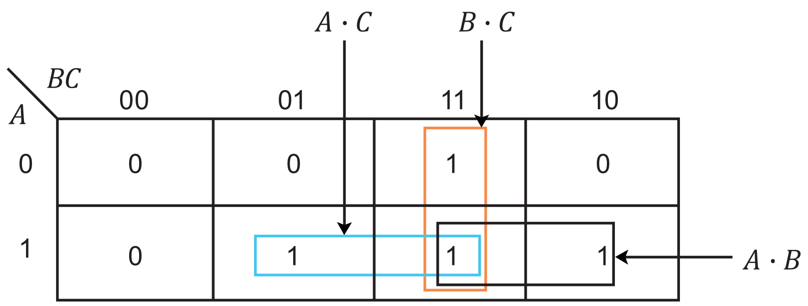


Figure 12.27

$X = A \cdot B + A \cdot C + B \cdot C$

Method 2: Using Boolean algebra

$$
\begin{aligned}
X &= \bar{A}\cdot B\cdot C + A\cdot \bar{B}\cdot C + A\cdot B\cdot \bar{C} + A\cdot B\cdot C && \text{Apply distributive law}\\
&= \bar{A}\cdot B\cdot C + A\cdot \bar{B}\cdot C + A\cdot B\,(\bar{C} + C) && \text{Apply } C+\bar{C}=1 \text{ and } A\cdot 1 = A\\
&= \bar{A}\cdot B\cdot C + A\cdot \bar{B}\cdot C + A\cdot B && \text{Apply distributive law}\\
&= \bar{A}\cdot B\cdot C + A\cdot (\bar{B}\cdot C + B) && \text{Apply absorption law}\\
&= \bar{A}\cdot B\cdot C + A\cdot (B + C) && \text{Apply distributive law}\\
&= \bar{A}\cdot B\cdot C + A\cdot B + A\cdot C && \text{Apply distributive law}\\
&= B\cdot (\bar{A}\cdot C + A) + A\cdot C && \text{Apply absorption law}\\
&= B\cdot (A + C) + A\cdot C && \text{Apply distributive law}\\
&= A\cdot B + B\cdot C + A\cdot C && \text{Rearrange terms}\\
&= A\cdot B + A\cdot C + B\cdot C
\end{aligned}
$$

Step 3: Implement the circuit for the simplified Boolean expression for the output

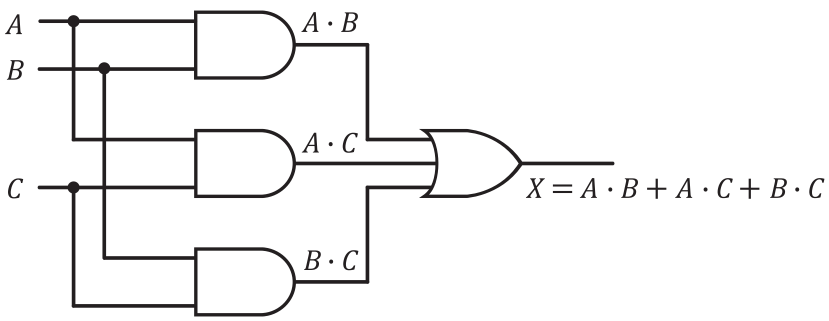


Figure 12.28

Review Questions 12.5

1. Design a logic circuit which gives an output of 1 only when a majority of the inputs A, B, and C are 1.

2. A manufacturing plant sounds an alarm when either or both of the following conditions occur:

   - One or more machines are running after operating hours.
   - One or more machines are running during weekends.

   Design a logic circuit to control the alarm using the following conditions:

   - Input A: $A = 1$ during operating hours; $A = 0$ after operating hours
   - Input B: $B = 1$ during weekdays; $B = 0$ during weekends
   - Input C: $C = 1$ when one or more machines are running; $C = 0$ when all the machines are switched off
   - Output X: the alarm is sounded only when $X = 1$

13 SET-RESET LATCHES

How do we build a basic memory circuit?

When we want to cross a pedestrian crossing, we only need to push the button on the traffic light pole once and the green man will appear after a while. We do not need to push and hold the button because the system 'remembers' that the button has been pushed. This feature is called 'memory'.

Figure 13.1 Push button on the traffic light pole at a pedestrian crossing

In this chapter, we will learn about the Set-Reset (S-R) latch, a type of digital circuit that can store a logic state (1 or 0). We will also learn how to use the S-R latch to build a type of switch called a debounced switch that can provide reliable signals to digital timing circuits.

13.1 How do we build an S-R latch using NOR gates?

Learning Outcomes

- Describe the S-R latch as a digital circuit with memory.
- Draw the symbolic representation of an S-R latch using NOR gates.

Key Ideas

- The S-R latch is a digital circuit that can store a logic state (1 or 0).
- An S-R latch can be built using two NOR gates.

The S-R latch as a system

Figure 13.2 shows a door latch used to hold a door in place.

Figure 13.2 A door latch

In electronics, a latch is a type of digital circuit that can store a logic state (1 or 0). This makes it a single-bit memory system. Figure 13.3 shows the symbol of a **Set-Reset (S-R) latch**. It consists of two inputs (S and R) and two outputs (Q and $\bar{Q}$). We 'set' the S-R latch when we want output Q to become active (i.e., $Q = 1$). Conversely, we 'reset' the S-R latch when we want output Q to become inactive (i.e., $Q = 0$). The output $\bar{Q}$ is always the inverse of Q.

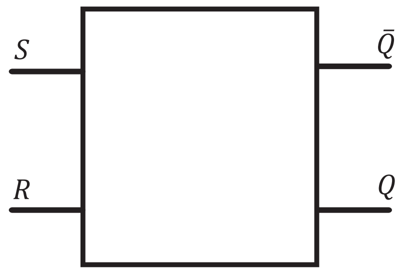
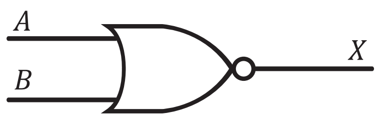


Figure 13.3 Symbol of an S-R latch

We can build an S-R latch using either NOR gates or NAND gates. In this course, we will only focus on NOR gate S-R latches.

Building an S-R latch with NOR gates

We learnt in Chapter 11 that the output of the NOR gate will be 1 only when both inputs are 0. The output will be 0 when one or both of the inputs are 1. Figure 13.4 shows the symbol and truth table of the NOR gate.



A	B	X
0	0	1
0	1	0
1	0	0
1	1	0

Figure 13.4 Symbol (left) and truth table (right) of the NOR gate

We can build an S-R latch with two NOR gates by connecting the output of each NOR gate to one of the inputs of the other NOR gate, as shown in Figure 13.5. The remaining input of each NOR gate will be labelled as S and R, respectively. Output Q is taken from the NOR gate with input R while output $\bar{Q}$ is taken from the NOR gate with input S.

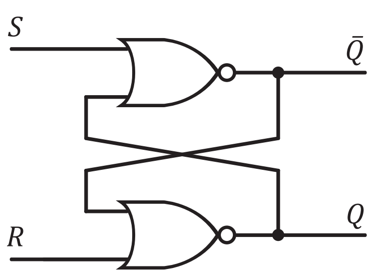


Figure 13.5 NOR gate S-R latch

Review Question 13.1

1. Draw a circuit diagram to show how an S-R latch can be built using two NOR gates.

13.2 How does a NOR gate S-R latch work?

Learning Outcomes

- Construct the truth table of a NOR gate S-R latch and use the table to determine the output of the latch.
- Draw the output timing diagram of a NOR gate S-R latch.

Key Ideas

- A NOR gate S-R latch will be set when $S = 1$ and $R = 0$; it will be reset when $S = 0$ and $R = 1$.
- There is no change to the output (Q) of the NOR gate S-R latch when both inputs (S and R) are 0.

Operation of the S-R latch

Table 13.1 shows the truth table of a NOR gate S-R latch.

Table 13.1 Truth table of a NOR gate S-R latch

Inputs		Outputs		
S	R	Q	$\bar{Q}$	
0	0	no change		
0	1	0	1	← RESET state
1	0	1	0	← SET state
1	1	invalid		

Let us investigate the operation of a NOR gate S-R latch under different input conditions.

Condition 1: $S = 1$ and $R = 0$ (SET)

The latch is 'set'. This causes the latch to become active with output $Q = 1$. Figure 13.6 explains how the latch is set under this condition:

- When $S = 1$, the output of the upper NOR gate will be 0, i.e., $\bar{Q} = 0$.
- When $\bar{Q} = 0$ and $R = 0$, the output of the lower NOR gate will be 1, i.e., $Q = 1$.

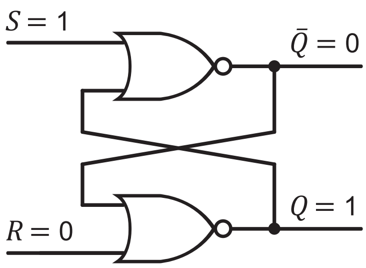


Figure 13.6 S-R latch under condition 1 (SET)

Condition 2: $S = 0$ and $R = 1$ (RESET)

The latch is 'reset'. This causes the latch to become inactive with output $Q = 0$. Figure 13.7 explains how the latch is reset under this condition:

- When $R = 1$, the output of the lower NOR gate will be 0, i.e., $Q = 0$.
- When $Q = 0$ and $S = 0$, the output of the upper NOR gate will be 1, i.e., $\bar{Q} = 1$.

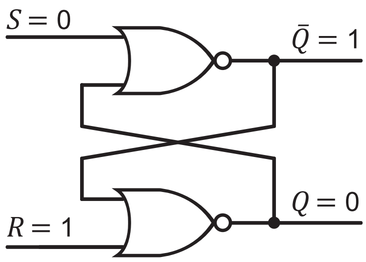


Figure 13.7 S-R latch under condition 2 (RESET)

Condition 3: $S = 0$ and $R = 0$

Q and $\bar{Q}$ will remain in the same logic state that they were before the S-R latch enters this condition. Let us examine two possible cases:

(i) $Q = 1$ and $\bar{Q} = 0$ before entering this condition

Referring to Figure 13.8:

- When $S = 0$ and $Q = 1$, the output of the upper NOR gate will be 0, i.e., $\bar{Q}$ remains at 0.
- When $\bar{Q} = 0$ and $R = 0$, the output of the lower NOR gate will be 1, i.e., Q remains at 1.

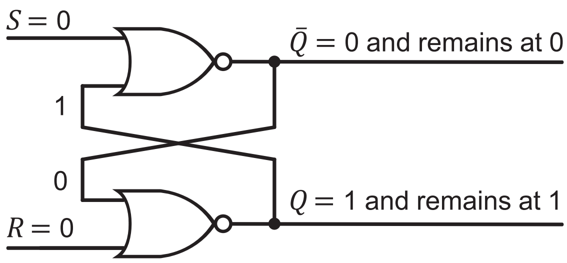


Figure 13.8 S-R latch under condition 3(i)

(ii) $Q = 0$ and $\bar{Q} = 1$ before entering this condition

Referring to Figure 13.9:

- When $R = 0$ and $\bar{Q} = 1$, the output of the lower NOR gate will be 0, i.e., Q remains at 0.
- When $Q = 0$ and $S = 0$, the output of the upper NOR gate will be 1, i.e., $\bar{Q}$ remains at 1.

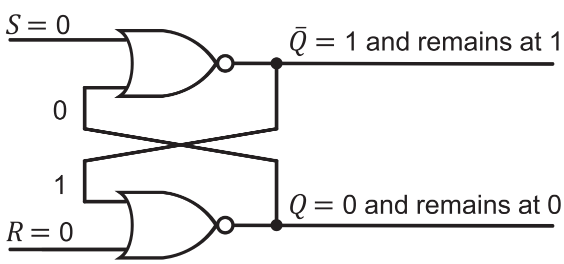


Figure 13.9 S-R latch under condition 3(ii)

Condition 4: S = 1 and R = 1 (invalid)

If one of the inputs of a NOR gate is 1, the output will be 0 regardless of the state of the other input. Hence, under this condition, the output of both NOR gates will be forced to 0. As Q and $\bar{Q}$ should have opposite logic states, this is an invalid condition which should not be used.

Timing diagrams

A **timing diagram** is a useful method to show how the output of a digital system changes with time.

Figure 13.10 shows the timing diagram of an S-R latch.

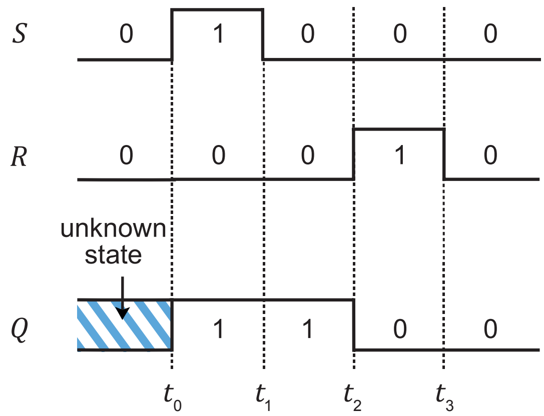


Figure 13.10 Timing diagram of an S-R latch

- At t_0, $S = 1$ and $R = 0$. Q will be 1.
- At t_1, $S = 0$ and $R = 0$. Q will remain at 1.
- At t_2, $S = 0$ and $R = 1$. Q will change to 0.
- At t_3, $S = 0$ and $R = 0$. Q will remain at 0.

Notice that Q is at different states at t_1 and t_3 although the input conditions are the same. This is because when $S = 0$ and $R = 0$, the output of an S-R latch will remain in the same logic state it was in before it entered this condition.

Timing diagrams are also used for timers and counters, which we will learn about in Chapter 14.

Review Questions 13.2

1. Describe the input condition that will cause output Q of a NOR gate S-R latch to change from 1 to 0.

2. Describe the input condition that will cause output Q of a NOR gate S-R latch to remain in the same logic state.

3. Complete the timing diagram in Figure 13.11 for output Q of a NOR gate S-R latch.

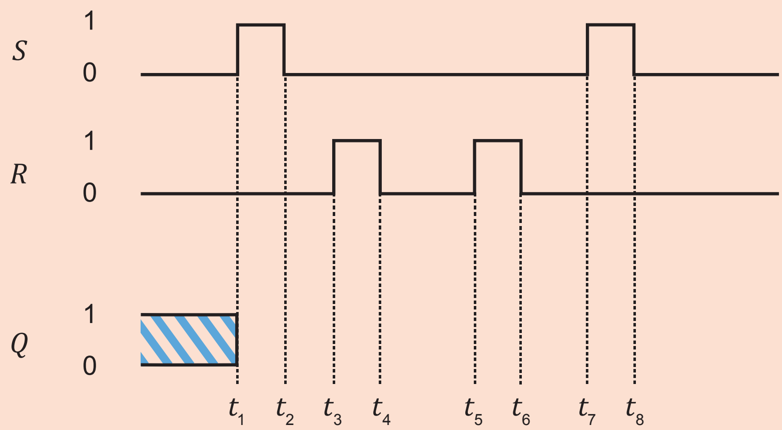


Figure 13.11

13.3 What is an S-R latch used for?

Learning Outcome

- Explain how an S-R latch is used to convert a momentary occurrence into a constant output.

Key Idea

- Because the S-R latch has the ability to store a logic state, it is able to convert a momentary occurrence into a constant output.

The ability of an S-R latch to store a logic state makes it useful for applications that require a momentary occurrence to be converted into a constant output. The button on a traffic light pole at a pedestrian crossing is an example of this. Once the button is pushed (momentary occurrence), the system remembers and maintains this state (constant output).

We will now discuss another example in detail. Figure 13.12 shows an intruder alarm system. When the window is opened, the switch is opened. The BJT will be switched on and the buzzer will sound.

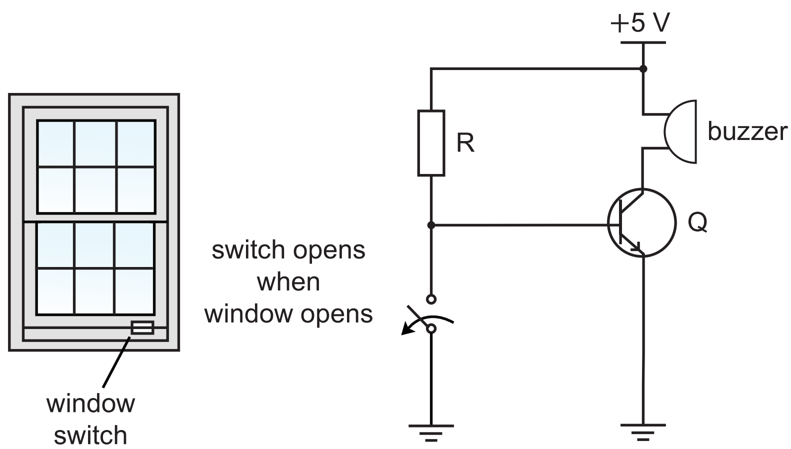


Figure 13.12 Intruder alarm system

A limitation of this system is that once the window is closed, the switch is closed and the buzzer stops. The intruder could close the window after entering the house to turn off the buzzer.

An improvement of the intruder alarm system is shown in Figure 13.13. With this system, the buzzer will sound when the window is first opened and will continue to sound even when the window is closed again. The buzzer can only be deactivated using a hidden switch (S_2).

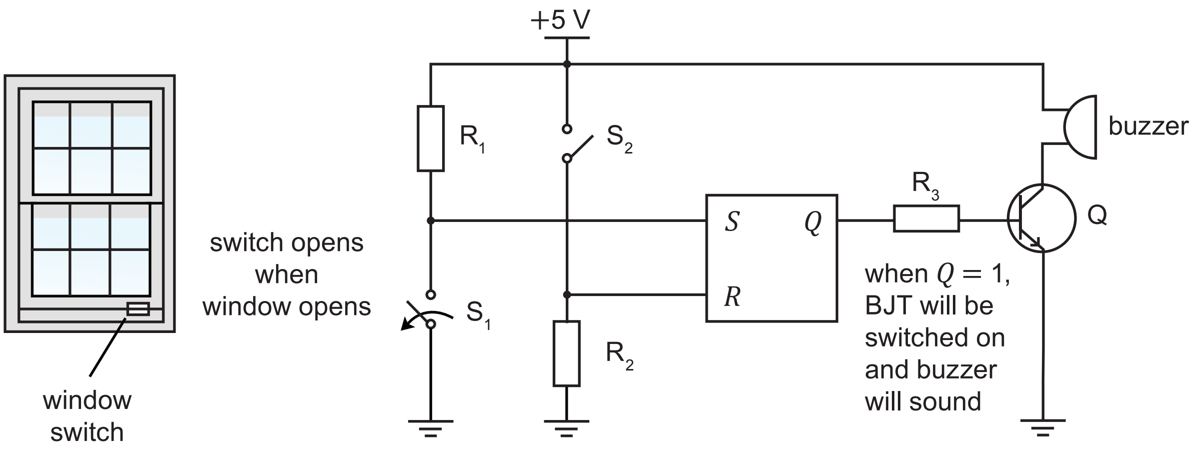


Figure 13.13 Improved intruder alarm system using an S-R latch

Let us examine how the improved intruder alarm system works:

1. To prepare the system for use, the window should first be closed. This closes switch S_1 which causes input S to be pulled down to 0. Next, the hidden switch S_2 is closed to pull up input R to 1. When $S = 0$ and $R = 1$, output Q will be 0. Next, S_2 is opened again so that R becomes 0. The system is now ready to detect intruders.
2. When the window is opened, S_1 is opened. S will be pulled up to 1. When $S = 1$ and $R = 0$, Q will change to 1. This switches on the BJT and the buzzer will sound.
3. The buzzer continues to sound even if the window is closed again. This is because when $S = 0$ and R = 0, Q remains at 1.
4. To deactivate the buzzer, the window should first be closed, which closes S_1 and causes S to be pulled down to 0. Next, S_2 is closed to pull up R to 1. This resets the system, i.e., Q returns back to its original value of 0.

Notice that the intruder alarm system is able to remember that the window was opened. Even if the window is closed again, the buzzer will continue to sound. The S-R latch has converted a momentary occurrence (a window opening temporarily) into a constant output (buzzer sounding) and will maintain this state until the system is reset.

Review Questions 13.3

1. State an electronic system that can be used to convert a momentary occurrence into a constant output.
2. Describe a situation where a momentary occurrence needs to be converted into a constant output.

13.4 How do we build a debounced switch using an S-R latch?

Learning Outcome

- Explain how an S-R latch can be used to build a debounced switch.

Key Ideas

- Contact bounce occurs each time a mechanical switch is opened or closed.
- An S-R latch can be used to build a debounced switch that eliminates the undesired effect of contact bounce.

Purpose of a debounced switch

When a mechanical switch is opened or closed, its contacts will connect and disconnect several times before a firm connection is established. This is known as **contact bounce**. When such a switch is used to build a logic switch, as shown in Figure 13.14, the output voltage will 'bounce' between 0 V (LOW) and 5 V (HIGH) before finally settling at a steady level. This series of rapid multiple voltage changes occurs over a short period of time.

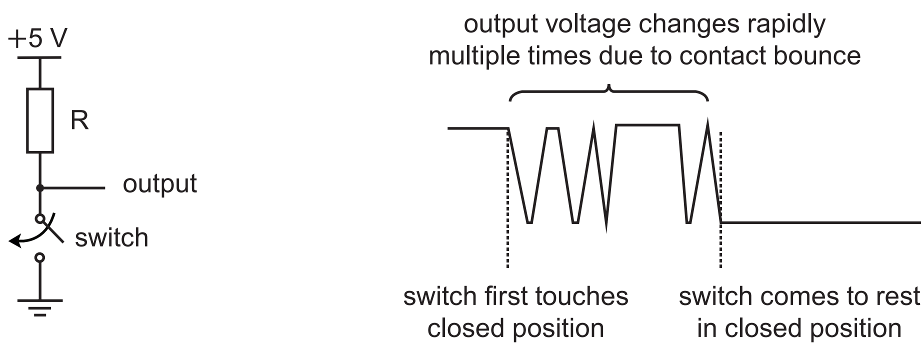


Figure 13.14 Contact bounce in a mechanical switch

The signal in Figure 13.14 has four rising edges (transitions from LOW to HIGH) and five falling edges (transitions from HIGH to LOW). This is unacceptable in digital systems where each rising or falling edge triggers an action. For example, if this signal is used as an input signal for a counter circuit (see Section 14.3), the count value may increase by multiple times when we only want it to increase by one.

For such systems, a **debounced switch**, which produces a single rising or falling edge, needs to be used instead. The output of a debounced switch is shown in Figure 13.15. It has a single transition from LOW to HIGH or HIGH to LOW each time the switch is toggled.

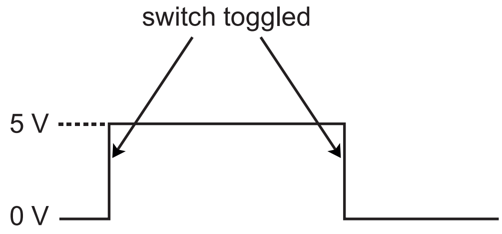


Figure 13.15 Output signal produced by a debounced switch

Building a debounced switch

One method of building a debounced switch is to use an S-R latch as shown in Figure 13.16. The circuit also includes two pull-down resistors and an SPDT switch.

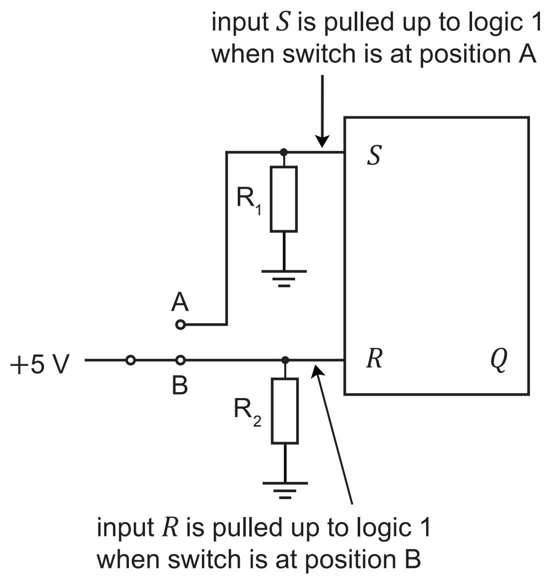


Figure 13.16 A debounced switch built using an S-R latch and SPDT switch

Figure 13.17 explains how this debounced switch works:

1. When the switch is at terminal B, S is pulled down to logic 0 while R is pulled up to logic 1. When $S = 0$ and $R = 1$, Q will be 0.
2. When the switch first leaves terminal B, R will be pulled down to 0. When $S = 0$ and $R = 0$, Q will remain at 0.
3. Due to contact bounce at terminal B, R will alternate multiple times between 0 and 1. However, this does not affect Q, which remains at 0. This is because when $S = 0$, Q will either be reset to 0 (when $R = 1$) or remain at 0 (when $R = 0$).
4. When the switch first touches terminal A, S will be pulled up to 1. When $S = 1$ and $R = 0$, Q will be 1.
5. Due to contact bounce at terminal A, S will alternate multiple times between 0 and 1. However, this does not affect Q, which remains at 1. This is because with $R = 0$, Q will either be set to 1 (when $S = 1$) or remain at 1 (when $S = 0$).

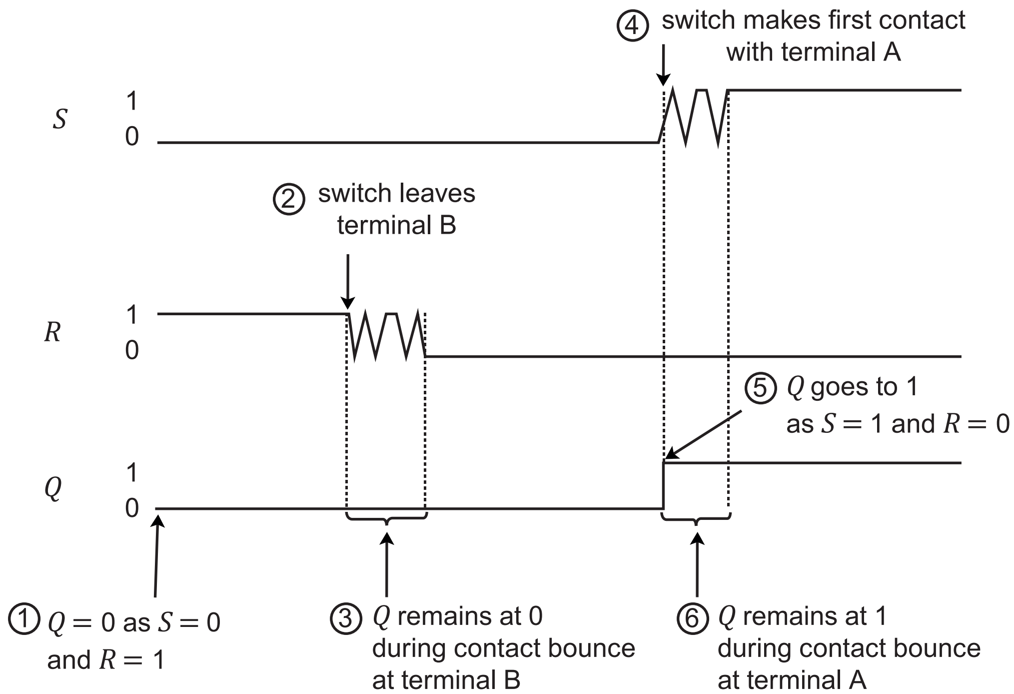


Figure 13.17 Timing diagram of a debounced switch

Notice that Q only has a single transition from LOW to HIGH, i.e., from 0 to 1. When the switch is moved from terminal A back to terminal B, there will be a single transition from HIGH to LOW.

Review Questions 13.4

1. Explain the purpose of using a debounced switch.
2. Draw a circuit diagram to show how a NOR gate S-R latch can be used to build a debounced switch.

14 VOLTAGE COMPARATORS, TIMERS AND COUNTERS

How do we use ICs to perform comparing, timing and counting functions?

In Chapters 11 to 13, we learnt how to use logic gate ICs to build logic circuits and electronic latches. Besides logic gate ICs, there are many other ICs that can be used to perform a wide range of useful functions.

Timer ICs are used for applications that involve timing, such as the traffic light system shown in Figure 14.1, which changes signal according to a preset sequence and timing.

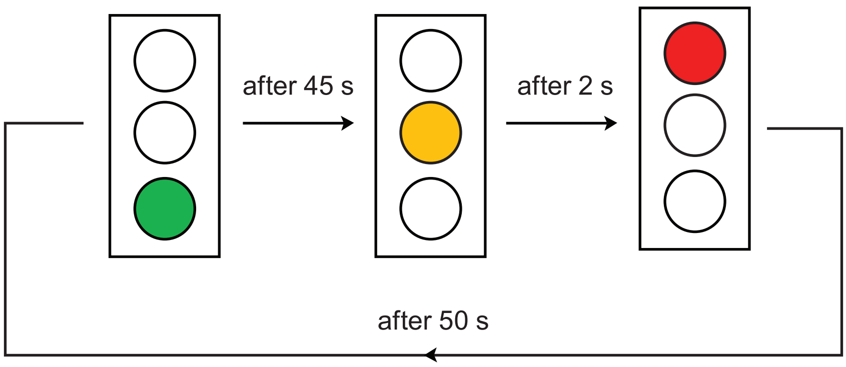


Figure 14.1 Sequence and timing of a traffic light

Figure 14.2 shows an electronic display that informs drivers of the number of parking lots available in a carpark. This system can be built using counter ICs that keep track of and display numbers.

Figure 14.2 Electronic display at the entrance of a carpark

In this chapter, we will learn how to use three types of ICs that can be used to perform voltage comparison, timing and counting functions.

14.1 How do we perform voltage comparison?

Learning Outcomes

- Identify the pins of an LM311 voltage comparator IC from its specification sheet.
- Describe the operation and use of an LM311 voltage comparator IC (with single rail supply only).

Key Idea

- A voltage comparator compares the voltage levels of two analogue signals and produces a digital output signal based on the comparison.

Basic operation of a voltage comparator

In Chapter 8, we learnt that input transducers can be used to convert information in non-electrical form into electrical signals. How are these signals used to determine if a certain event has occurred or if an action needs to be taken? One common way is to use the **voltage comparator**, whose symbol is shown in Figure 14.3.

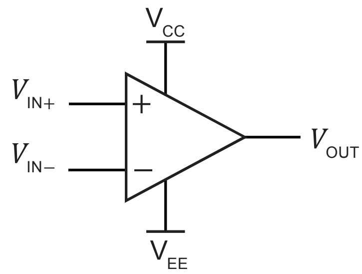


Figure 14.3 Symbol of a voltage comparator

A voltage comparator has two analogue inputs, V_{IN+} and V_{IN-}, and one digital output, V_{OUT}. V_{IN+} is called the **non-inverting input** and is connected to the terminal labelled '+', while V_{IN-} is called the **inverting input** and is connected to the terminal labelled '–'.

The comparator has two voltage supply terminals. The upper terminal is connected to a positive supply voltage, V_{CC} (or V+, which should not be confused with V_{IN+}). The lower terminal is connected to a negative supply voltage, V_{EE} (or V–, which should not be confused with V_{IN-}). In this course, we will only perform voltage comparison involving positive voltages, so the lower terminal will be connected to 0 V (GND).

V_{OUT} is dependent on the two inputs:

- If V_{IN+} is higher than V_{IN-}, V_{OUT} will be HIGH.
- If V_{IN+} is lower than V_{IN-}, V_{OUT} will be LOW.

The voltage level of the HIGH output state is equal to V_{CC}. Depending on the type of voltage comparator used, the LOW output state is equal to either V_{EE} or 0 V. Since we are always using 0 V for V_{EE} in this course, the LOW output state will always be 0 V. Figure 14.4 shows the output of a voltage comparator that uses $V_{CC} = 5$ V and $V_{EE} = 0$ V.

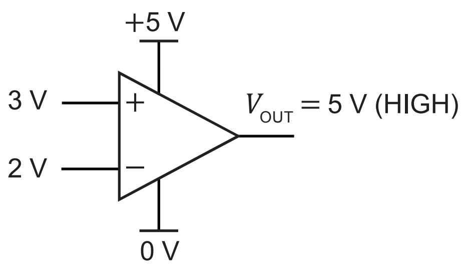


Figure 14.4a Voltage comparator with HIGH output

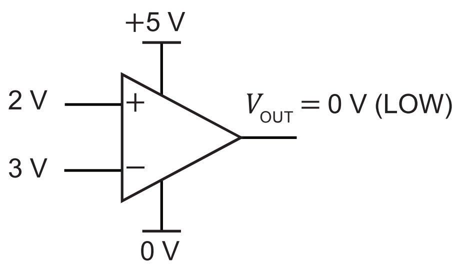


Figure 14.4b Voltage comparator with LOW output

Comparing a varying voltage with a reference voltage

In our daily lives, we often compare a changing or uncertain value with a reference value to decide whether an action needs to be taken. For example, we compare our body temperature (changing value) with 37 °C (reference value) to decide whether we should see a doctor. This idea is also used in electronic systems.

In Figure 14.5, a reference voltage, V_{ref}, is connected to the '−' terminal of a voltage comparator while an input signal from another system is connected to the '+' terminal. In this way, the voltage comparator will produce a HIGH output when the input signal is higher than V_{ref}, and vice versa. To make the system work in opposite manner, we can swap the terminals of V_{ref} and the input signal. We will next examine how this setup can be used to control a lighting system.

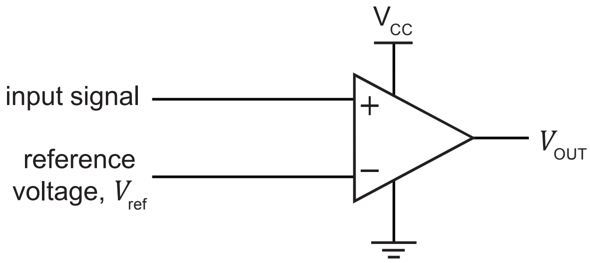


Figure 14.5 Using a reference voltage as one of the inputs of a voltage comparator

Consider the automatic home lighting system shown in Figure 14.6, which will automatically switch on when the surroundings are dark and switch off when they are bright.

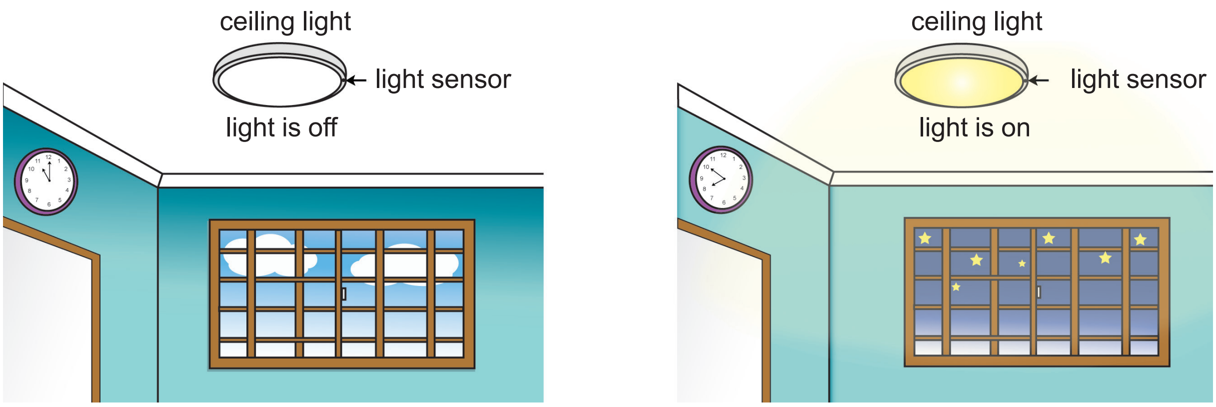


Figure 14.6 An automatic home lighting system

To obtain information about the brightness of the surroundings, we need a light sensor. This can be built using a light-dependent resistor (LDR) connected as a voltage divider as shown in Figure 14.7. V_1, the voltage across R_1, varies according to the amount of light that falls on the LDR as shown in the graph.

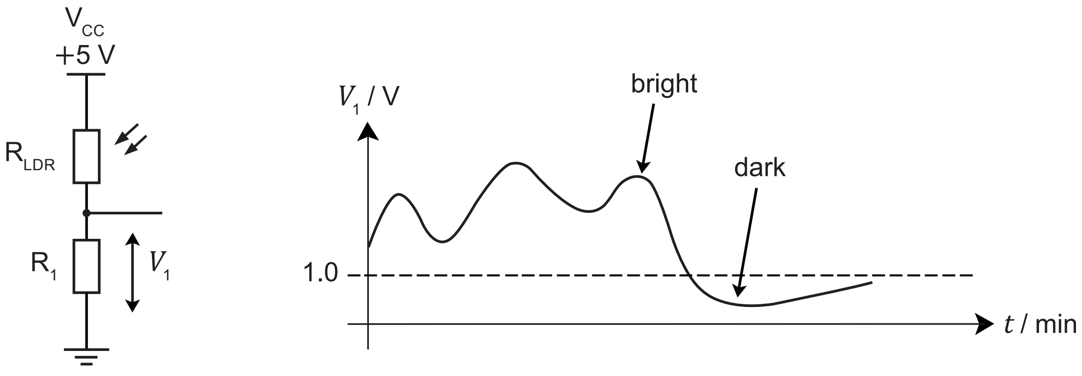


Figure 14.7 A light sensor built using an LDR (left) and the voltage-time graph for R_1 (right)

We want the lights to switch on when the surroundings are dark, i.e., when V_1 is below 1.0 V. To do this, we need to build another voltage-divider circuit, shown in Figure 14.8, to provide a 1.0 V reference voltage. The potentiometer, R, is adjusted until the reference voltage, V_{ref}, is 1.0 V.

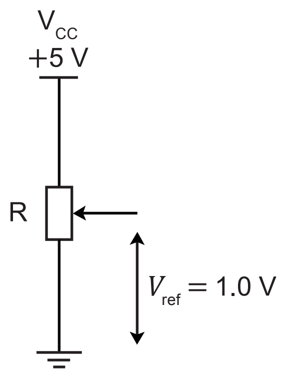


Figure 14.8 Using a potentiometer to provide a reference voltage

V_1 and V_{ref} are then respectively connected as V_{IN-} and V_{IN+} to a voltage comparator as shown in Figure 14.9. When it is dark and V_1 falls below 1.0 V, V_{IN+} will be higher than V_{IN-} and the comparator will produce a HIGH output. Conversely, when it is bright, the comparator will produce a LOW output. V_{OUT} can then be used as an input to another system that switches the lights on and off.

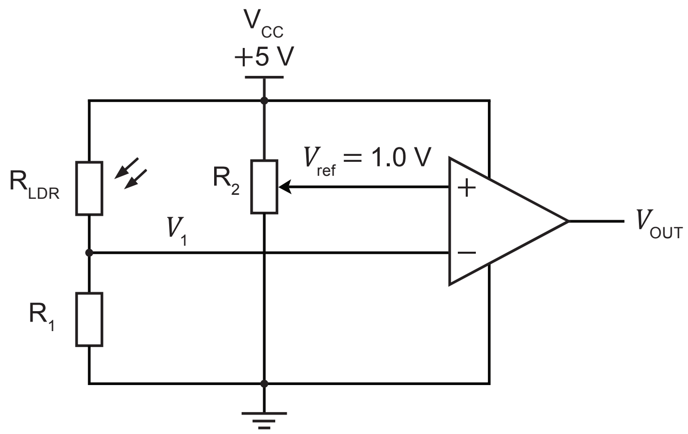


Figure 14.9 A lighting control system consisting of a light sensor and a voltage comparator

LM311 voltage comparator IC

Figure 14.10a shows the **LM311 voltage comparator IC** in an 8-pin dual in-line (DIL) packaging. Figure 14.10b shows the pin connection diagram.

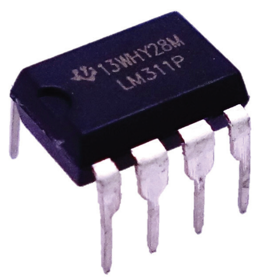


Figure 14.10a An LM311 voltage comparator IC in a DIL package

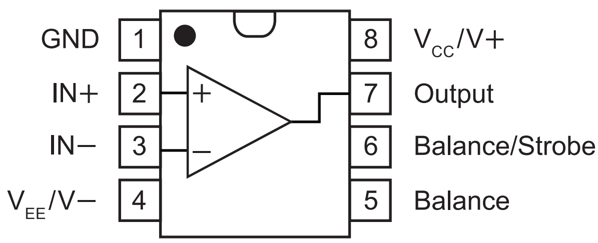


Figure 14.10b Pin connection diagram of an LM311 IC

Figure 14.11 shows how the LM311 IC can be connected to perform voltage comparison. Table 14.1 describes how each pin should be connected.

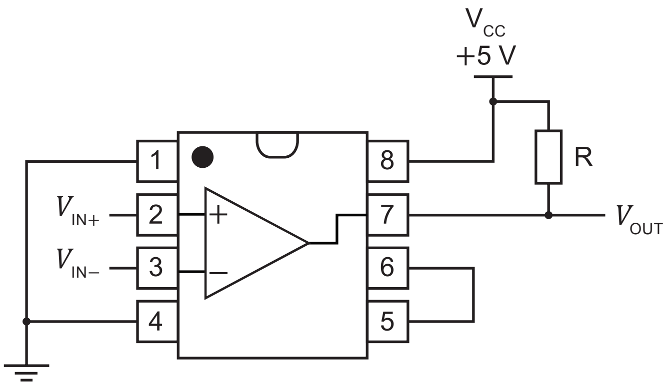


Figure 14.11 Connecting an LM311 IC for voltage comparison

Table 14.1 Pin connections for the LM311 voltage comparator IC

Pin	Name	Connection guide
1	GND	Connects to 0 V (ground)
2	Non-inverting input	Connect to the two input voltages to be compared
3	Inverting input	
4	V_{EE}	Connects to 0 V (ground) in this course as only positive voltages are compared
5	Balance	Will not be used in this course. Both pins should be connected together.
6	Balance/Strobe	
7	Output	Connects to V_{CC} through a pull-up resistor (around 10 kΩ)
8	V_{CC}	Connects to a positive voltage supply (up to 18 V)

The LM311 IC uses an open-collector type of output. When V_{IN+} is lower than V_{IN-}, pin 7 will be connected to the ground, making the output LOW. When V_{IN+} is higher than V_{IN-}, pin 7 will be disconnected from the ground. The pull-up resistor, R, then pulls the voltage of the pin to V_{CC}. Without this pull-up resistor, the comparator will not be able to produce a HIGH output.

Worked Example 14.1

Figure 14.12 shows a circuit with an LM311 voltage comparator IC. Determine whether the output signal is HIGH or LOW.

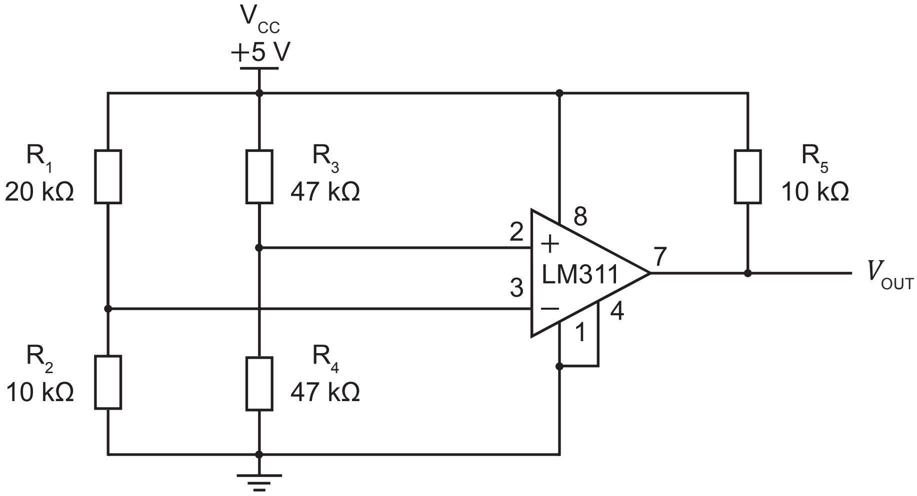


Figure 14.12

Solution

Using the voltage-divider formula,

$$V_{IN+} = \frac{47\text{ k}\Omega}{47\text{ k}\Omega + 47\text{ k}\Omega} \times 5.0\text{ V}$$
$$= 2.5\text{ V}$$

$$V_{IN-} = \frac{10\text{ k}\Omega}{10\text{ k}\Omega + 20\text{ k}\Omega} \times 5.0\text{ V}$$
$$= 1.7\text{ V}$$

Since V_{IN+} is higher than V_{IN-}, the output signal will be HIGH.

In applications which use low-power output transducers such as LEDs or buzzers, the transducers can be connected directly to the output pin (pin 7). Two examples are shown in Figures 14.13 and 14.14.

Worked Example 14.2

Explain the operation of the circuit shown in Figure 14.13.

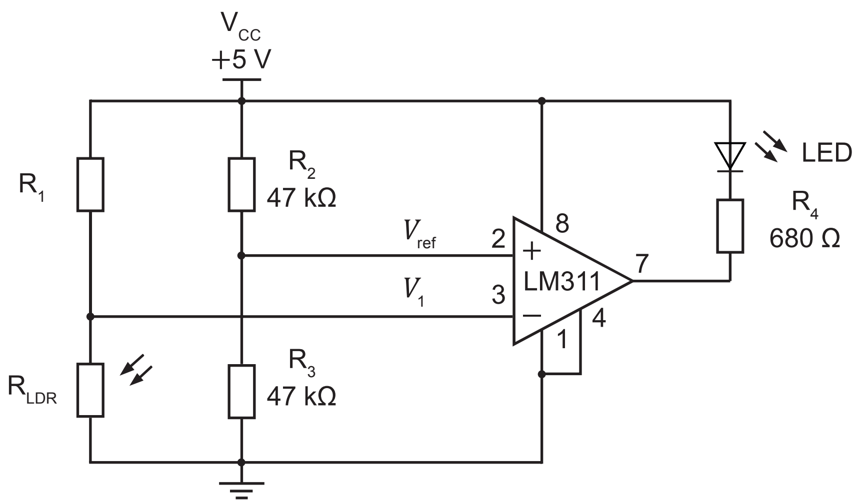


Figure 14.13

Solution

The output voltage of the light sensor, V_1, is connected as V_{IN-}. The reference voltage, V_{ref}, is connected as V_{IN+}.

Using the voltage-divider formula,

$$
\begin{aligned}
V_{IN+} &= V_{ref} \\
&= \frac{47\text{ k}\Omega}{47\text{ k}\Omega + 47\text{ k}\Omega} \times 5.0\text{ V} \\
&= 2.5\text{ V}
\end{aligned}
$$

When the surroundings get darker, R_{LDR} becomes higher than R_1. Hence, V_1 increases. When V_1 exceeds 2.5 V, V_{IN+} will be lower than V_{IN-} and the output pin will be connected to the ground. The LED will light up since its anode is at a higher voltage than its cathode.

When the surroundings get brighter, R_{LDR} becomes lower than R_1. Hence, V_1 decreases. When V_{OUT} falls below 2.5 V, V_{IN+} will be higher than V_{IN-} and the output pin will be disconnected from the ground. The LED will not light up since there is no longer a path to the ground.

Review Questions 14.1

1. Explain how an LM311 voltage comparator IC works by referring to its input and output pins.

2. Explain the operation of the circuit shown in Figure 14.14.

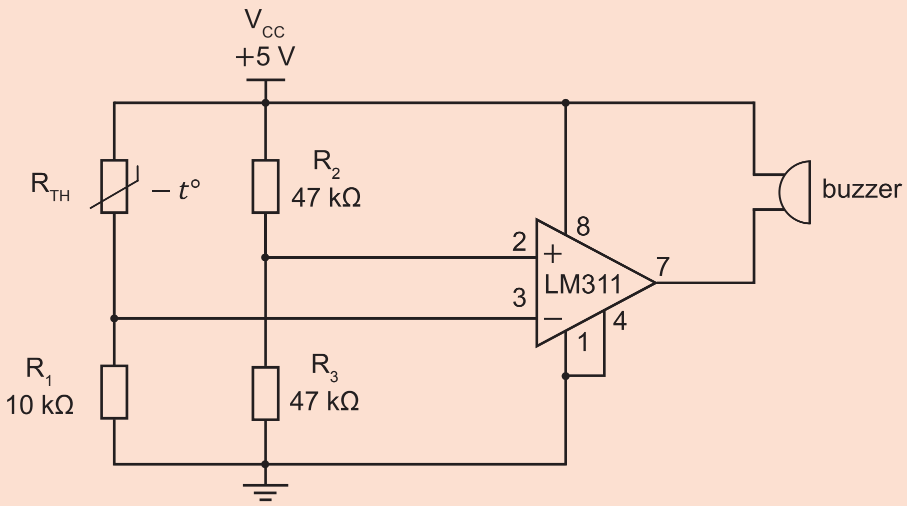


Figure 14.14

14.2 How do we use the 555 timer IC to perform timing functions?

Learning Outcomes

- Distinguish between a monostable and astable multivibrator.
- Identify the pins of a 555 timer IC from its specification sheet.
- Recognise whether a 555 timer IC is set up as a monostable or astable multivibrator from a given circuit.
- Use the formula $T = 1.1RC$ to determine the time period of a 555 timer IC in monostable mode.
- Use the formula $T = \dfrac{(R_1 + 2R_2)C}{1.44}$ to determine the time period of a 555 timer IC in astable mode.
- Draw the output timing diagram of a 555 timer IC.

Key Ideas

- A monostable multivibrator produces a single pulse of a specific width when triggered by an external input.
- An astable multivibrator produces a continuous stream of pulses (rectangular waveform).
- A 555 timer IC can be connected to operate as a monostable or an astable multivibrator.

There are two types of timing activities we often come across in our daily lives:

- One-off events that last for a fixed duration after being activated, e.g., a machine that runs for five minutes after a button is pressed and then stops until the button is pressed again
- Events that continue non-stop in a fixed timing pattern, e.g., traffic light signals

Both of these timing activities can be carried out by using a timer IC such as the 555 timer IC.

555 timer IC

The **555 timer IC** is a widely used device due to its low price and ease of use. Figure 14.15 shows a 555 timer IC in an 8-pin DIL package and its pin connection diagram.

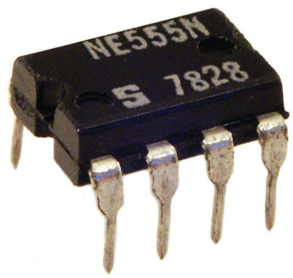


Figure 14.15a A 555 timer IC in a DIL packaging

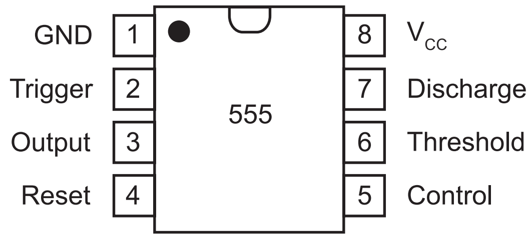


Figure 14.15b Pin connection diagram of a 555 timer IC

Table 14.2 describes the pin functions of the 555 timer IC and how they should be connected.

Table 14.2 Pin functions of the 555 timer IC

Pin	Name	Function
1	GND	Connects to 0 V (ground)
2	Trigger	Causes the output at pin 3 to go HIGH and starts the timing cycle when its voltage drops below $\frac{1}{3}V_{CC}$
3	Output	Produces a digital output: LOW (close to 0 V) or HIGH ($\approx V_{CC} - 1.5$ V)
4	Reset	Resets the timing interval when connected to the ground The timer will not start again until triggered by pin 2. When not in use, this pin is connected to V_{CC}.
5	Control	Controls the trigger and threshold level In most basic applications, this pin is not used and is connected to the ground through a 10 nF capacitor.
6	Threshold	Monitors the voltage across the external capacitor When the voltage at this pin reaches $\frac{2}{3}V_{CC}$, the timing cycle ends and the output on pin 3 goes LOW.
7	Discharge	Connects to the ground and discharges the external capacitor connected to it when the output is LOW and acts like an open circuit when the output is HIGH
8	V_{CC}	Connected to a positive voltage supply between 5 V and 15 V

As the 555 timer IC is always connected to an external circuit, its pin layout is usually drawn in the arrangement shown in Figure 14.16. This makes the overall circuit diagram logical and neat. The supply voltage pin (V_{CC}) is at the top, the ground pin is at the bottom, the input pins are on the left and the output pin is on the right.

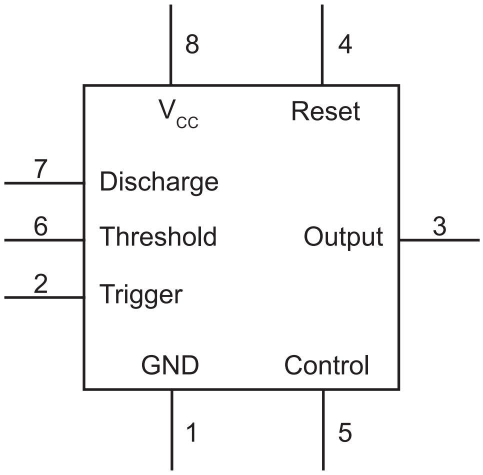


Figure 14.16 Pin layout diagram of 555 timer IC

The operation mode of the 555 timer IC depends on the external circuit that is connected to its input pins. In this course, we will learn how to connect the IC to work as a monostable and an astable multivibrator.

555 timer IC as a monostable multivibrator

A **monostable multivibrator** is a device that produces a single pulse of a specific width (in terms of time, not length) after being activated. The signal used for activating the multivibrator is called a 'trigger'. Figure 14.17 shows an example of such a single pulse, which can be used as a signal to control another device.

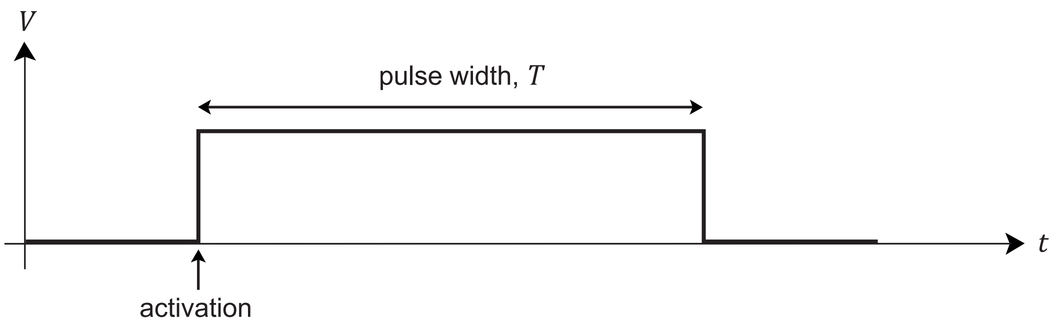


Figure 14.17 A monostable multivibrator produces a single pulse

Figure 14.18 shows how the 555 timer IC can be connected to work as a monostable multivibrator. Note the following:

- Pin 2 (trigger) is connected to a pull-up resistor and a pushbutton switch. When switch S is open, pin 2 is pulled up to V_{CC}. When switch S is closed by pushing it, pin 2 will become 0 V.
- Pins 6 and 7 are connected together. Both pins are then connected to an RC circuit formed by R_1 and C_1. The voltage across C_1 is equal to the voltage at both pins.

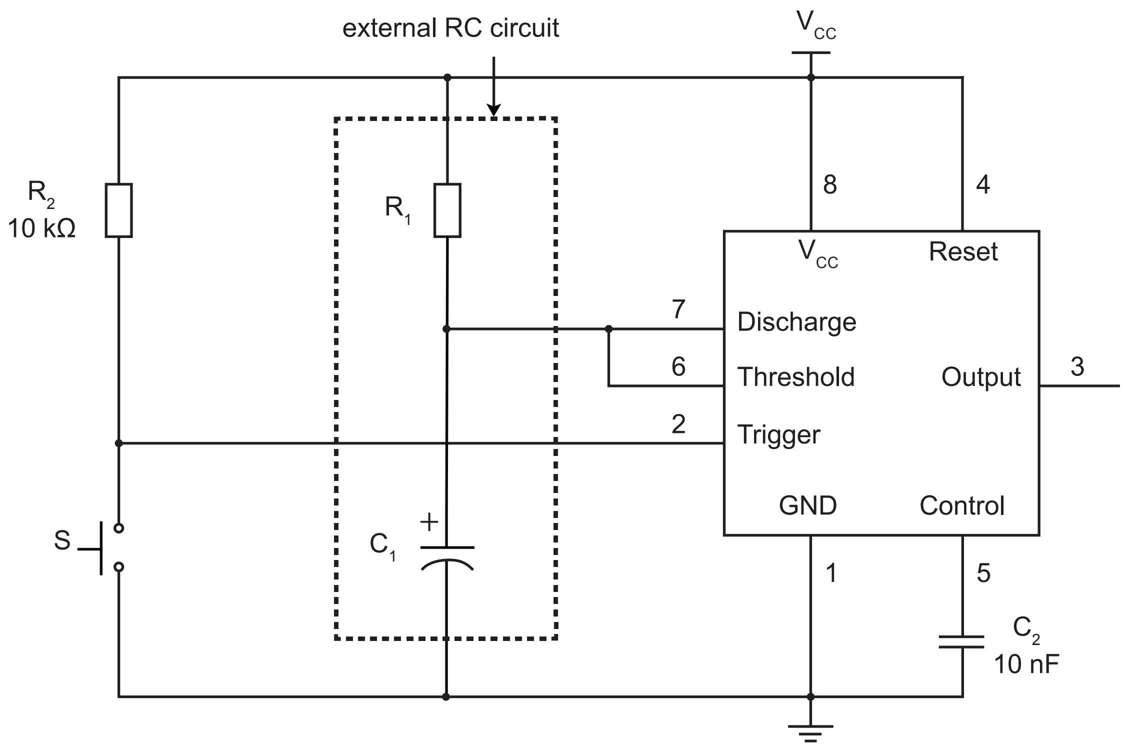


Figure 14.18 555 timer IC connected to operate as a monostable multivibrator

When a 555 timer IC is connected as a monostable multivibrator, the following occurs:

1. At the start, switch S is open, causing the voltage at pin 2 (trigger) to be pulled up to 5 V.
2. As pin 2 (trigger) is higher than $\frac{1}{3}V_{CC}$, the output is LOW. The IC connects pin 7 (discharge) to the ground, which completely discharges capacitor C_1.
3. When switch S is closed, the voltage at pin 2 (trigger) is pulled down to 0 V.
4. Since pin 2 (trigger) is lower than $\frac{1}{3}V_{CC}$, the output goes HIGH and the timing cycle starts. At the same time, the IC causes pin 7 (discharge) to act as an open circuit.
5. C_1 starts charging through R_1 towards V_{CC}.
6. When the voltage across C_1 reaches $\frac{2}{3}V_{CC}$, it will be detected by pin 6 (threshold).
7. The output goes LOW and the timing cycle stops.

Refer to Figure 14.19 for the timing diagram which shows how the voltages at pins 2, 3 and 6 change over time.

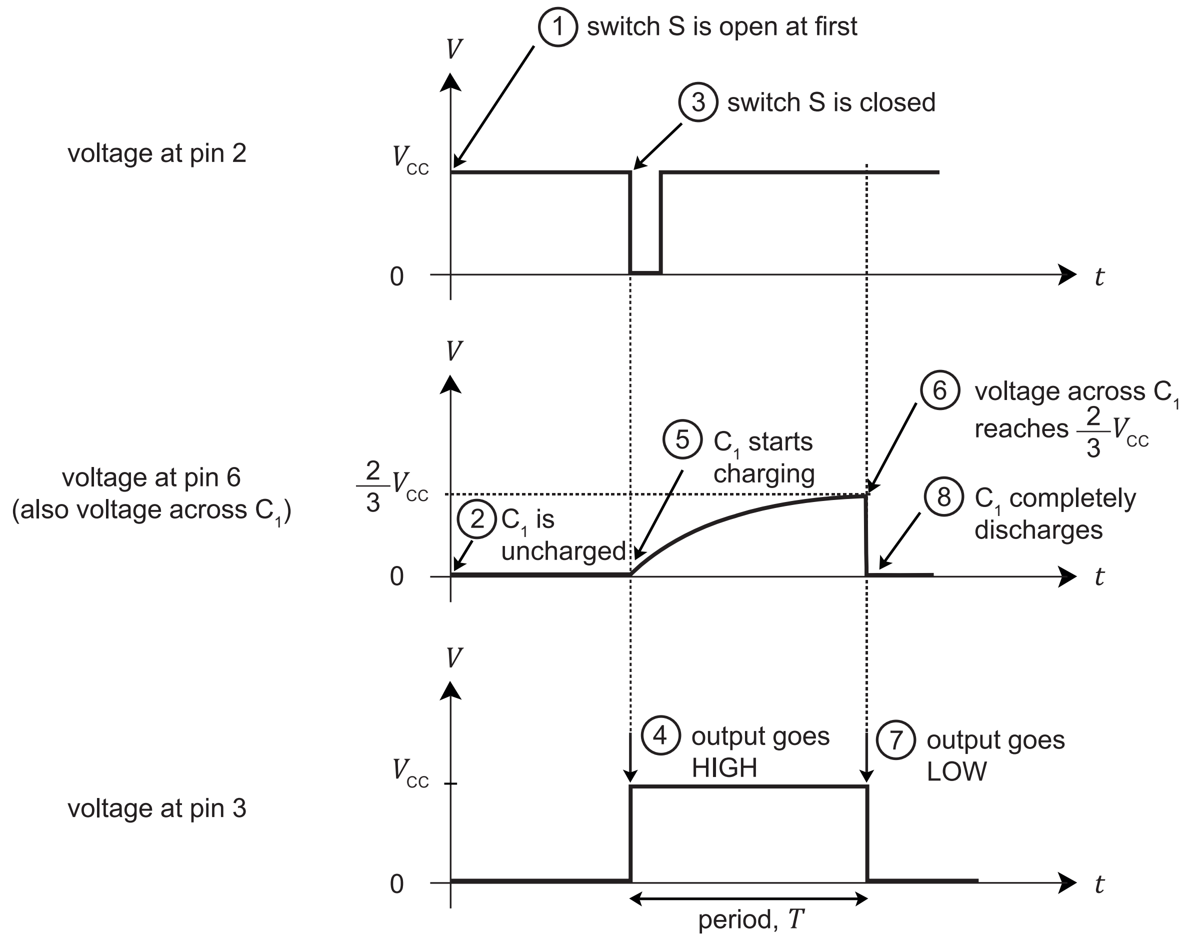


Figure 14.19 Timing diagram of a 555 timer IC operating as a monostable multivibrator

The pulse width of the output, T, is determined by the value of R_1 and C_1. It can be calculated using the following equation.

$$T = 1.1RC$$

where T = pulse width (in s),
R = resistance (in Ω),
C = capacitance (in F)

Note that R_2 is not part of the equation as it is simply acting as a pull-up resistor for switch S and is not involved in the charging process.

Worked Example 14.3

Refer to Figure 14.18. Given that R_1 = 5.6 kΩ, R_2 = 10 kΩ and C_1 = 47 μF, calculate the pulse width of the output when switch S is pushed.

Solution

Substitute R = 5.6 kΩ and C = 47 μF into the equation $T = 1.1RC$:

$$
\begin{aligned}
T &= 1.1 \times (5.6 \times 10^3\ \Omega) \times (47 \times 10^{-6}\ \text{F}) \\
&= 0.290\ \text{s} \\
&= 290\ \text{ms}
\end{aligned}
$$

Worked Example 14.4

A student plans to use the monostable multivibrator circuit in Figure 14.18 to provide a single pulse of 45 s. Determine the values of R_1 and C_1 that should be used.

Solution

From Figure 14.19, we can see that the pulse width is approximately equal to the time taken for C_1 to charge to $\frac{2}{3}$ of the applied voltage. This corresponds to the time constant of an RC circuit. Refer to the circuit in Worked Example 6.4, which had a time constant of 22 ms with R = 2.2 kΩ and C = 10 μF.

Since 45 s is nearly 2000 times longer than 22 ms, we should choose a capacitor with much larger capacitance, e.g., 1000 μF.

Substituting T = 45 s and C = 1000 μF into $T = 1.1RC$,

$$
\begin{aligned}
45\ \text{s} &= 1.1 \times R \times (1000 \times 10^{-6}\ \text{F}) \\
R &= 41\ \text{k}\Omega
\end{aligned}
$$

We can use a 33 kΩ fixed resistor in series with a 0–10 kΩ variable resistor and adjust the variable resistor until their combined resistance is 41 kΩ.

Review Questions 14.2A

1. Complete Figure 14.20 to show how a 555 timer IC can be connected as a monostable multivibrator.

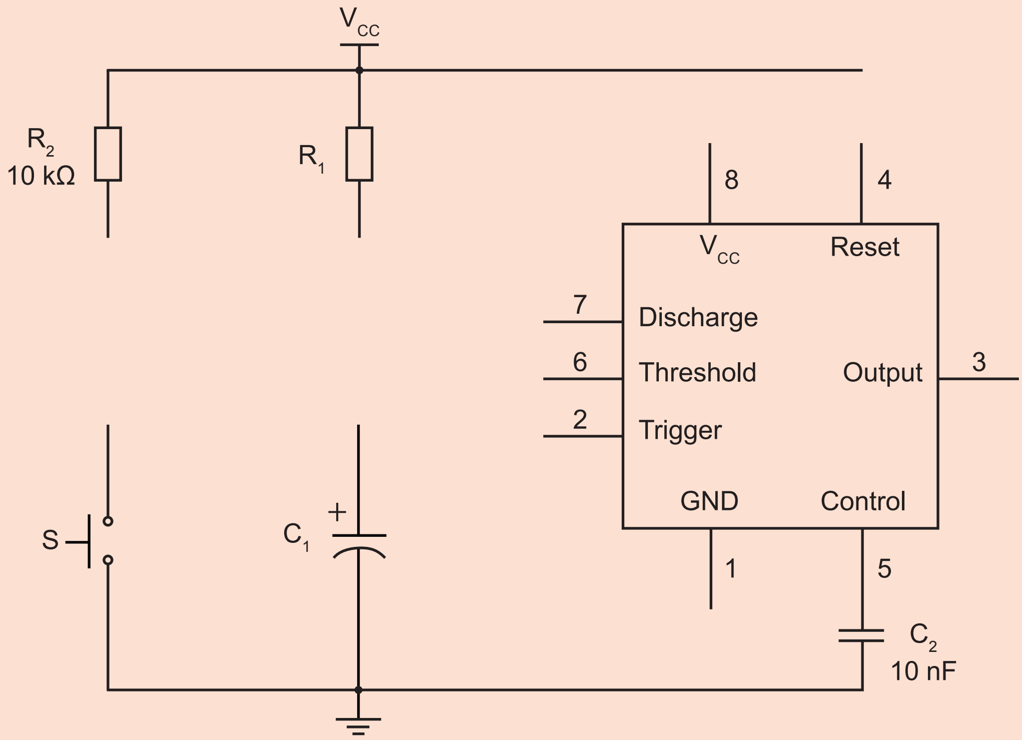


Figure 14.20

2. A student plans to use the monostable multivibrator circuit in Figure 14.18 to provide a single pulse with a width of 3.0 s. Determine the values of R_1 and C_1 that should be used.

555 timer IC as an astable multivibrator

An **astable multivibrator** is a device that produces a continuous stream of pulses (rectangular waveforms). Unlike the monostable multivibrator, there is no trigger. Figure 14.21 shows an example of pulses produced by an astable multivibrator. Such pulses are useful for producing flashing lights and as a clock signal for a counter IC (see Section 14.3).

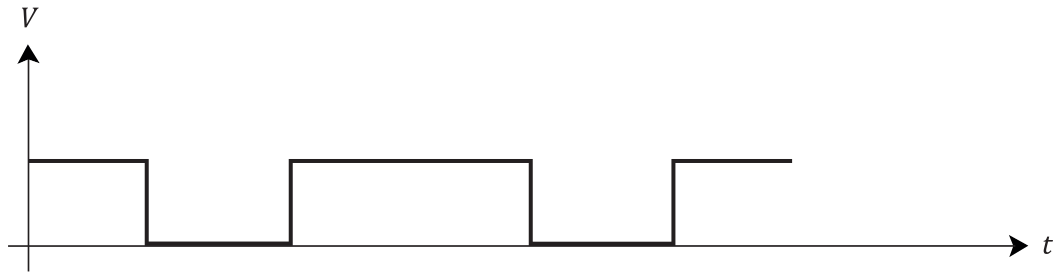


Figure 14.21 An astable multivibrator produces a continuous stream of pulses

Figure 14.22 shows how the 555 timer IC can be connected to work as an astable multivibrator. Like the monostable multivibrator, the external circuit is an RC circuit. However, notice that it is pin 2 (trigger) and pin 6 (threshold) that are connected together. Both pins are connected to capacitor C_1 such that the voltage across C_1 is equal to the voltage at pins 2 and 6.

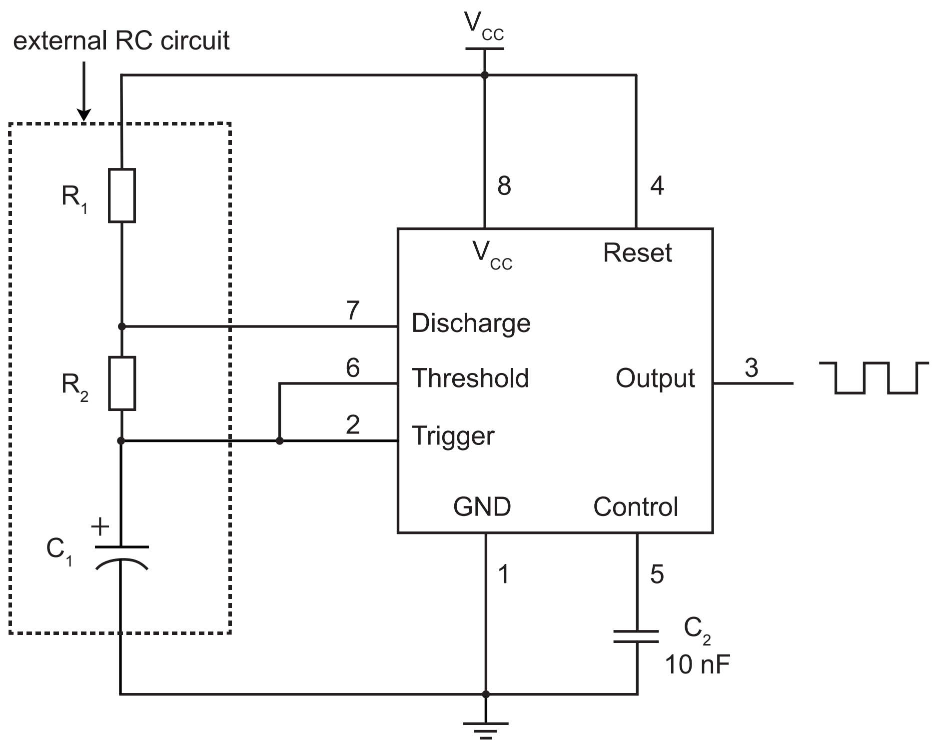


Figure 14.22 Connecting a 555 timer IC as an astable multivibrator

When a 555 timer IC is used as an astable multivibrator, the following occurs:

1. At the start, assume that C_1 is not charged. Hence, the voltage at pin 2 (trigger) is 0 V.
2. As pin 2 is lower than $\frac{1}{3}V_{CC}$, the output will be HIGH, which causes pin 7 (discharge) to act as an open circuit. C_1 then starts charging through R_1 and R_2 towards V_{CC}.
3. C_1 continues to charge until the voltage across it, which is also the voltage at pin 6 (threshold), reaches $\frac{2}{3}V_{CC}$.
4. The output goes LOW. The IC then connects pin 7 to the ground, causing C_1 to start discharging through R_2.
5. C_1 continues to discharge until the voltage across it decreases to $\frac{1}{3}V_{CC}$.
6. The output at pin 3 goes HIGH again and the process repeats itself.

Refer to Figure 14.23 for the timing diagram which shows how the voltages at pins 2, 3 and 6 change over time.

The first output cycle should be ignored as it is dependent on how much charge C_1 holds at the start. Figure 14.23 assumes that C_1 is uncharged. If C_1 holds some charge at the start, then the cycle will either start in the same manner (if the voltage across C_1 is less than $\frac{1}{3}V_{CC}$) or after step 4 (if the voltage across C_1 is more than $\frac{1}{3}V_{CC}$).

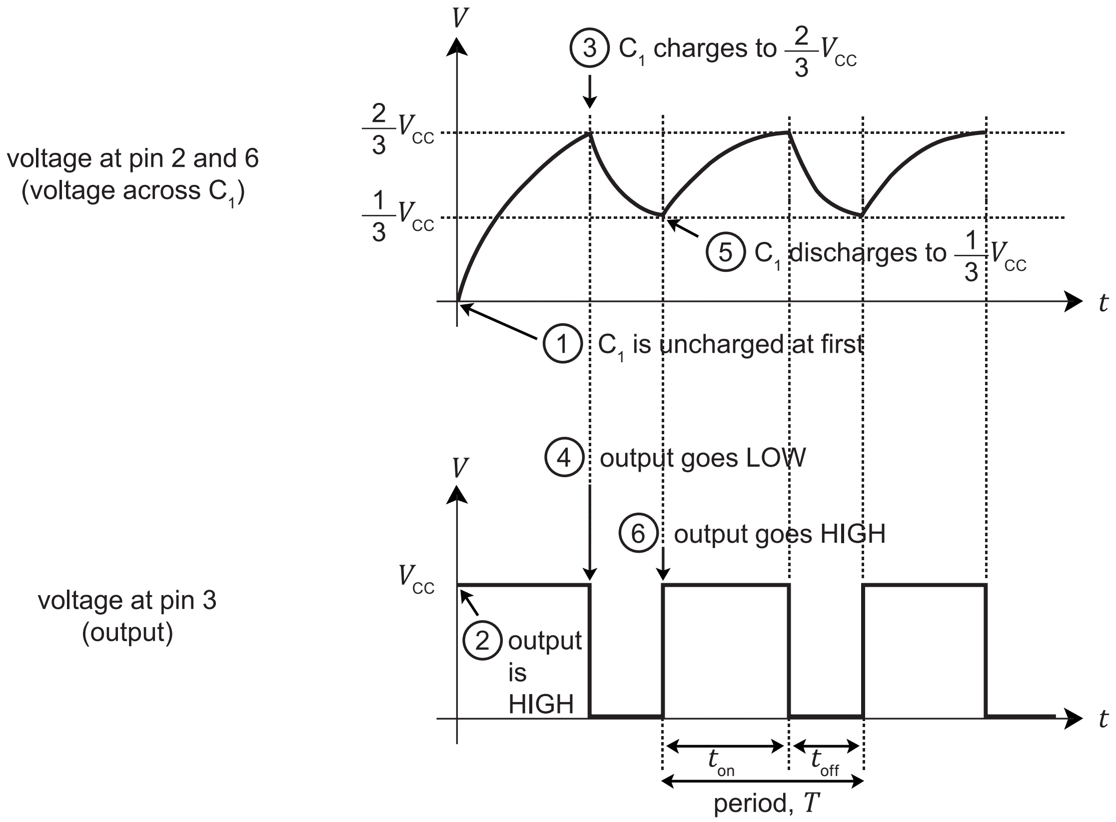


Figure 14.23 Timing diagram of a 555 timer IC operating as an astable multivibrator

Notice that the output signal alternates between the HIGH and LOW states in a fixed timing pattern. The duration of the signal at the HIGH state is labelled as t_{on} since the HIGH state is commonly associated with a device being switched on. Conversely, the duration of the signal at the LOW state is called t_{off}. The period of a complete cycle is labelled as T, where $T = t_{on} + t_{off}$.

The duration of t_{on}, t_{off} and T are determined by the values of R_1, R_2 and C_1. They can be calculated using the following equations:

$$T = \frac{(R_1 + 2R_2)C}{1.44}$$

$$t_{on} = 0.7(R_1 + R_2)C$$

$$t_{off} = 0.7R_2C$$

where T = period (in s),
R = resistance (in Ω),
C = capacitance (in F)
t_{on} = duration in which output is HIGH (in s),
t_{off} = duration in which output is LOW (in s).

Recall that both R_1 and R_2 are involved during the charging of C_1, but only R_2 is involved in the discharging process. This explains why the equation for t_{on} involves both resistors while the equation for t_{off} only involves R_2.

The duty cycle and frequency of the pulses can be calculated using the following equations:

$$\text{Duty cycle} = \frac{t_{on}}{T} \times 100\%$$

$$f = \frac{1}{T}$$

where T = period (in s),
f = frequency (in Hz),
t_{on} = duration in which output is HIGH (in s).

Worked Example 14.5

Refer to the circuit shown in Figure 14.22. Given R_1 = 1.0 kΩ, R_2 = 10 kΩ and C_1 = 47 μF, calculate:

(a) the period of the output signal;

(b) the duty cycle of the output signal; and

(c) the frequency of the output signal.

Solution

(a) $T = \dfrac{(R_1 + 2R_2)C}{1.44}$

$= \dfrac{[(1.0 \text{ x } 10^3\,\Omega) + 2 \times (10 \times 10^3\,\Omega)] \times 47 \times 10^{-6}\text{ F}}{1.44}$

$= 685\text{ ms}$

(b) $t_{on} = 0.7(R_1 + R_2)C$

$= 0.7 \times (1.0 \text{ x } 10^3\,\Omega + 2 \times 10 \times 10^3\,\Omega) \times 47 \times 10^{-6}\text{ F}$

$= 362\text{ ms}$

Duty cycle $= \dfrac{t_{on}}{T} \times 100\%$

$= \dfrac{362\text{ ms}}{685\text{ ms}} \times 100\%$

$= 52.8\%$

(c) Frequency, $t_{on} = \dfrac{1}{T}$

$= \dfrac{1}{685 \times 10^{-3}\text{ s}}$

$= 1.46\text{ Hz}$

Extension

From the calculated values, we can draw the waveform of the output signal:

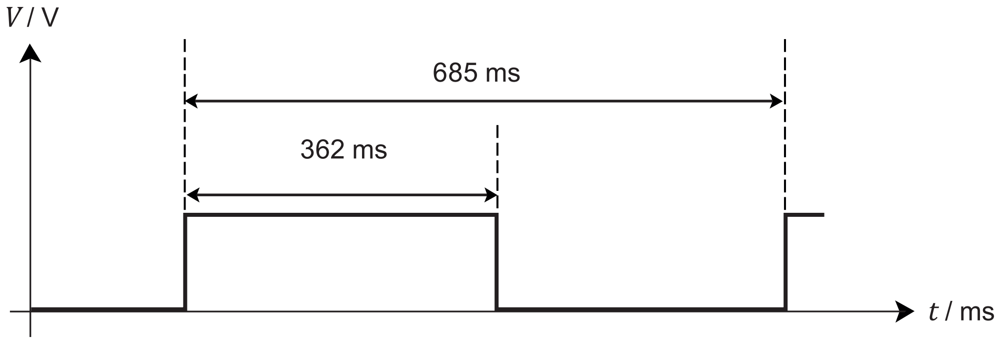
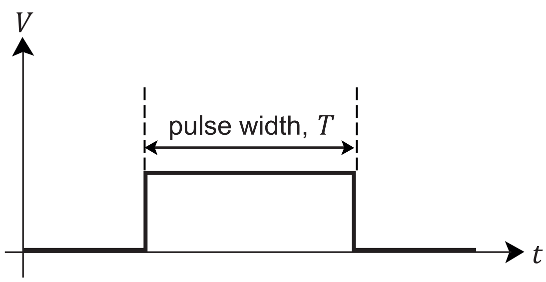
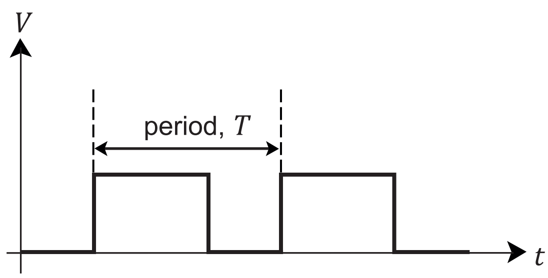


Figure 14.24

Table 14.3 summarises the differences between a monostable and an astable multivibrator built using a 555 timer IC.

Table 14.3 Comparing the monostable and astable multivibrator

Monostable multivibrator	Astable multivibrator
When triggered, a single rectangular pulse of a predetermined pulse width is produced. The pulse width is determined by a resistor and a capacitor that are externally connected to the 555 timer IC.	It produces a rectangular wave whose period is determined by two resistors and a capacitor that are externally connected to the 555 timer IC. This rectangular wave will be generated the moment the IC is powered up without the need for a trigger.
Output waveform: 	Output waveform: 
Commonly used in timers and debounced switches	Commonly used in LED flashers, logic clocks and tone generators

Review Questions 14.2B

1. Complete Figure 14.25 to show how a 555 timer IC can be connected to work as an astable multivibrator. Your answer should include all necessary components and connections. All inputs and outputs should be clearly labelled.

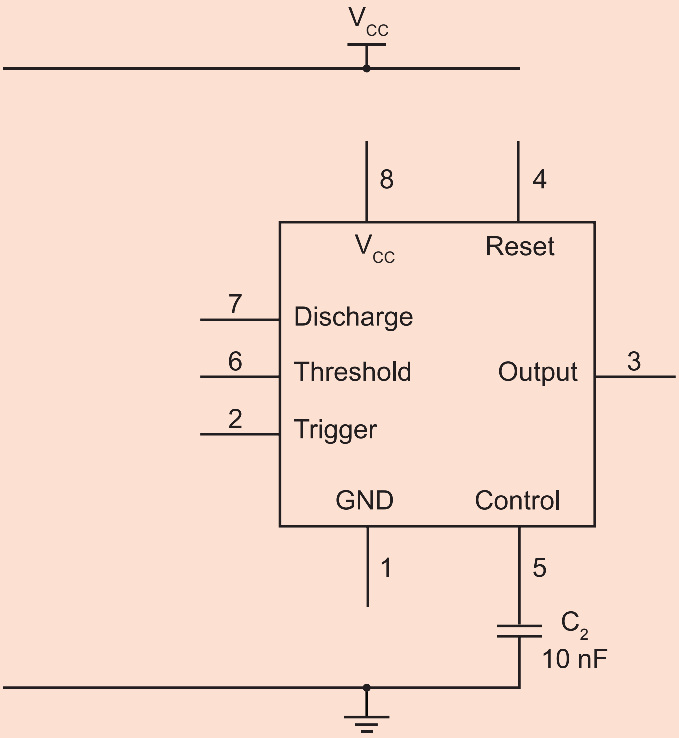


Figure 14.25

2. The 555 timer IC is connected to operate as an astable multivibrator as shown in Figure 14.26. Calculate the period of the output signal.

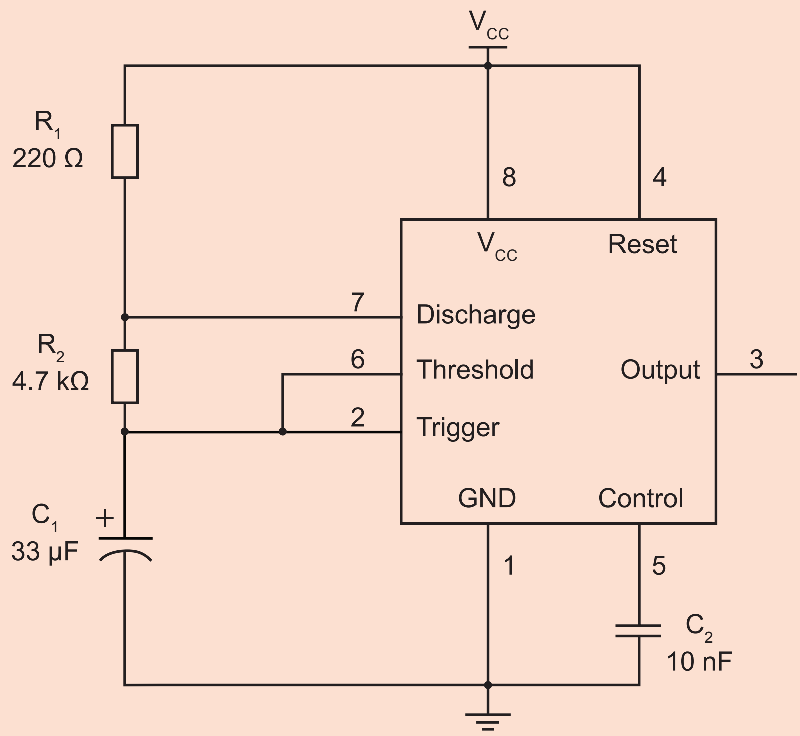


Figure 14.26

14.3 How do we use the 74LS390 decade counter IC to perform counting functions?

Learning Outcomes

- Identify the pins of a 74LS390 4-bit decade counter IC from its specification sheet.
- Describe the operation and use of a 74LS390 IC.
- Show understanding of how the output of a 74LS390 IC can be shown on a 7-segment display.
- Show understanding of how two 4-bit decade counters in a 74LS390 IC can be connected to count to 99.

Key Ideas

- A decade counter is a counter that counts from 0 to 9 and then returns to 0 again.
- The 74LS390 4-bit decade counter IC has two decade counters that can be used together to count up to 99.

Counting is an important application of electronics. In the introduction of this chapter, we saw how the electronic display at a carpark entrance informs drivers about the number of available parking lots. Another example is the banknote counting machines used by banks and money changers as shown in Figure 14.27. Digital clocks and stopwatches also use counters to count the seconds, minutes and hours that have passed.

Figure 14.27 Banknote counting machine

Figure 14.28 shows the block diagram of a basic counter with two inputs and one output. The first input (reset) resets the count value to zero while the second input (clock) tells the counter to increase the count value by one. The output is the count value.

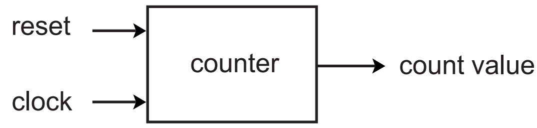


Figure 14.28 Block diagram of a basic counter

74LS390 dual 4-bit decade counter IC

The **74LS390 IC** is a dual 4-bit **decade counter** IC. Figures 7.29a and 7.29b show a 74LS390 IC in 16-pin DIL packaging and its pin connection diagram, respectively. The IC consists of two counters – counter 1 and counter 2. Each counter has three input pins (CKA, CLR, CKB) and four output pins (Q_A , Q_B, Q_C and Q_D).

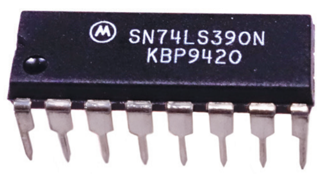


Figure 14.29a A 74LS390 IC in DIL packaging

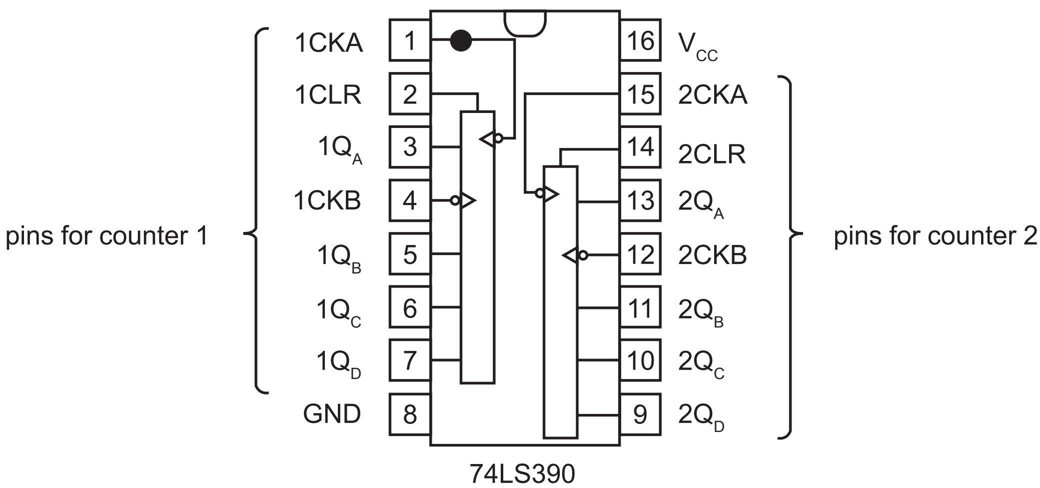


Figure 14.29b Pin connection diagram of a 74LS390 IC

Table 14.4 describes the pin functions of the 74LS390 IC and how they should be connected.

Table 14.4 Pin functions of the 74LS390 IC

Pin	Name	Function
16	V_{CC}	Connects to a 5 V positive supply
8	GND	Connects to the ground (0 V)
1, 15	1CKA, 2CKA	Clock A input pins for counters 1 and 2, respectively – connect to a signal called 'clock', which increases the count value by one for each falling edge (as indicated by the symbol ○▷)
2, 14	1CLR, 2CLR	Clear input pins for counters 1 and 2, respectively – connect to a signal called 'reset', which resets the count value to zero when it is HIGH
4, 12	1CKB, 2CKB	Clock B input pins for counters 1 and 2, respectively – connect to the Q_A pins of the respective counters, which cause the counter to function as a decade counter
7, 6, 5, 3	$1Q_D$, $1Q_C$, $1Q_B$, $1Q_A$	Output pins for counter 1 – combined together to represent the count value as a binary coded decimal (BCD) with $1Q_D$ as the most significant bit (MSB) and $1Q_A$ as the least significant bit (LSB)
9, 10, 11, 13	$2Q_D$, $2Q_C$, $2Q_B$, $2Q_A$	Output pins for counter 2 – combined together to represent the count value as a BCD with $2Q_D$ as the MSB and $2Q_A$ as the LSB.

Table 14.5 shows the BCD count sequence of the 74LS390 counter IC. The count sequence is triggered by the falling edge of the clock signal, i.e., when the signal to the CKA pin goes from HIGH to LOW. Each time a falling edge occurs, the count value will increase by one. When the count value reaches 1001, it will be reset to 0000 the next time the count sequence is triggered.

Table 14.5 Count sequence of the 74LS390 IC (decade counter mode)

4-bit BCD				Decimal equivalent
Q_D	Q_C	Q_B	Q_A	
0	0	0	0	0
0	0	0	1	1
0	0	1	0	2
0	0	1	1	3
0	1	0	0	4
0	1	0	1	5
0	1	1	0	6
0	1	1	1	7
1	0	0	0	8
1	0	0	1	9

We will now learn how to use the 74LS390 counter IC using the circuit shown in Figure 14.30.

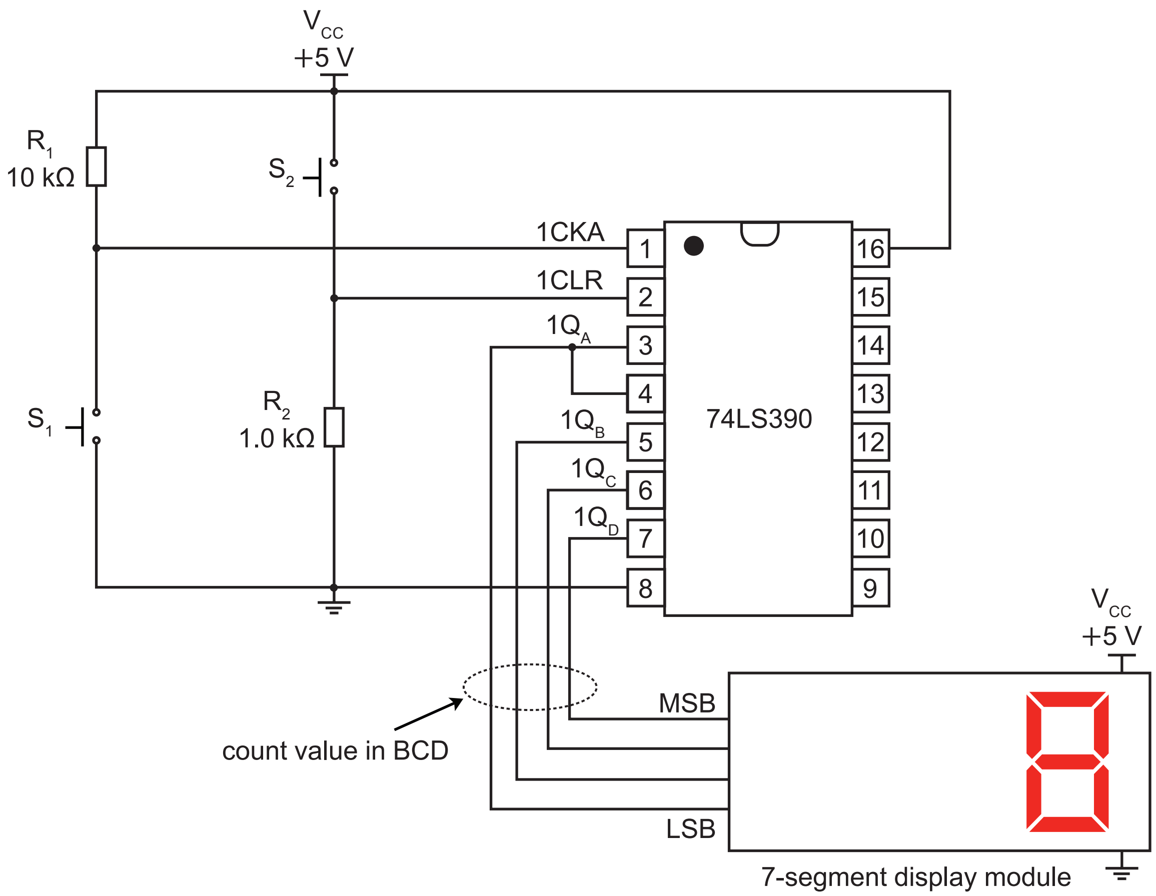


Figure 14.30 Using counter 1 of the 74LS390 IC

Note the following points about the connections:

- Pins 3 ($1Q_A$) and 4 (1CKB) are connected together so that counter 1 functions as a decade counter;
- Pins 7 ($1Q_D$), 6 ($1Q_C$), 5 ($1Q_B$) and 4 ($1Q_A$) are connected to a 7-segment display module that takes in the BCD represented and displays the decimal equivalent.

Carry out the following steps:

1. Close S_2 momentarily by pushing and releasing it. When S_2 is closed, the signal at pin 2 (1CLR) goes from LOW to HIGH. This resets the count value:

   $$Q_D = 0 \qquad Q_C = 0 \qquad Q_B = 0 \qquad Q_A = 0$$

   The 7-segment display module will display '0'. When S_2 is opened again, pin 2 returns from HIGH to LOW and the counter is ready to start counting.

2. Close S_1 momentarily by pushing and releasing it. When S_1 is closed, the signal at pin 1 (1CKA) goes from HIGH to LOW, creating a falling edge. This increases the count value by one:

   $$Q_D = 0 \qquad Q_C = 0 \qquad Q_B = 0 \qquad Q_A = 1$$

   The 7-segment display module will display '1'.

3. Close S_1 momentarily again by pushing and releasing it. This increases the count value by one:

   $$Q_D = 0 \qquad Q_C = 0 \qquad Q_B = 1 \qquad Q_A = 0$$

   The 7-segment display module will display '2'.

4. Continue to push S_1 and observe how the number displayed on the 7-segment display increases by one each time S_1 is pressed.

5. When the count value reaches '9', close S_1 momentarily again by pushing and releasing it. The IC will automatically reset the count value to 0.

   $$Q_D = 0 \qquad Q_C = 0 \qquad Q_B = 0 \qquad Q_A = 0$$

In practice, S_1 needs to be a debounced switch. Otherwise, each time S_1 is closed or opened, there will be multiple rising and falling edges, which also causes the count value to increase multiple times.

Figure 14.31 shows the timing diagram for steps 1–3.

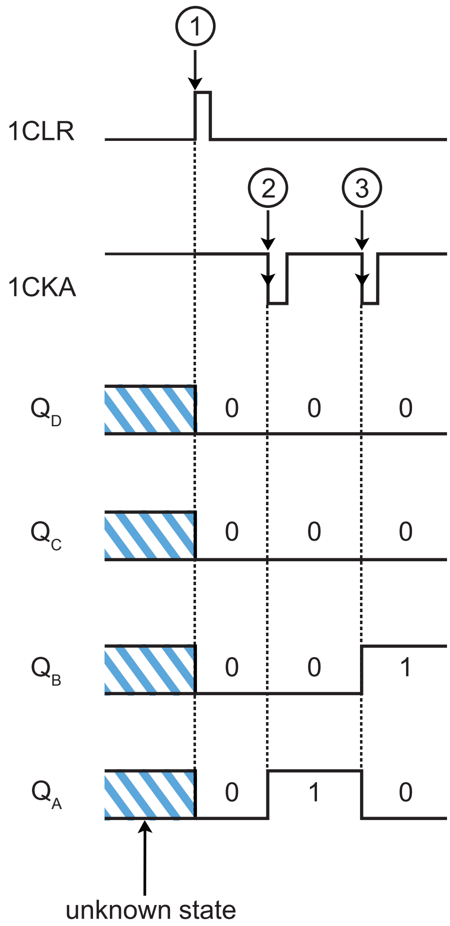


Figure 14.31 74LS390 counter timing diagram

The circuit in Figure 14.30 only uses counter 1 of the 74LS390 IC, and thus can only count up to 9. We can increase the count range to 99 by using both counters as shown in Figure 14.32. The following additional connections (highlighted in yellow) are required:

- Pin 13 ($2Q_A$) to pin 12 (2CKB) so that counter 2 functions as a decade counter
- Pin 7 ($1Q_D$) to pin 15 (2CKA) so that $1Q_D$ acts as the clock for counter 2
- Pin 2 (1CLR) to pin 14 (2CLR) so that both counters are cleared when S_2 is pushed
- Pins 9 ($2Q_D$), 10 ($2Q_C$), 11 ($2Q_B$) and 13 ($2Q_A$) to a second 7-segment display module

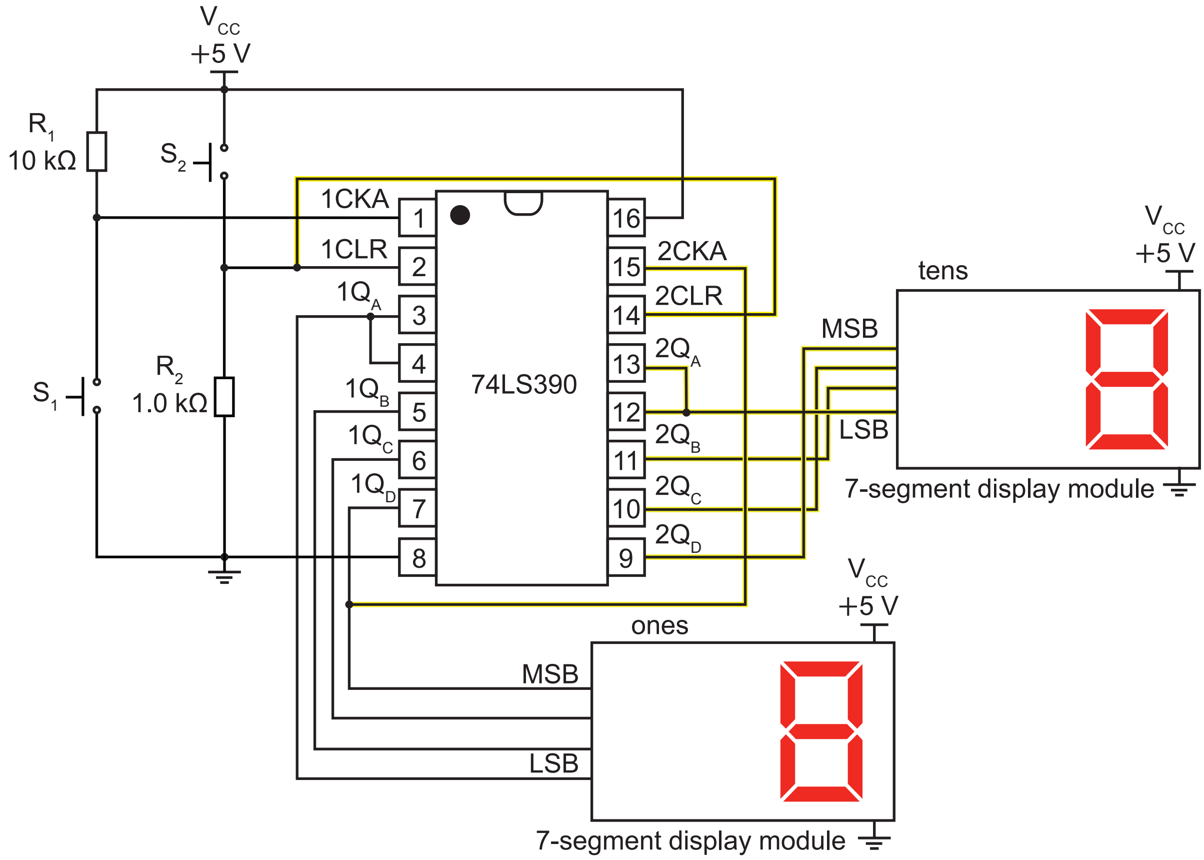


Figure 14.32 Using both counters in a 74LS390 IC to count to 99

The clock signals for the circuits in Figures 14.30 and 14.32 are generated by using a mechanical switch. In some applications, the clock signal is provided by another IC.

In Figure 14.33, the output of a voltage comparator IC is used as the clock signal for a 74LS390 IC. An infrared sensor similar to the one in Figure 8.24 is used. When an object (e.g., a car) passes by the infrared sensor, the output voltage of the sensor becomes nearly zero. Hence, V_{IN+} becomes lower than V_{IN-} and the output of the comparator goes from HIGH to LOW. The 74LS390 IC then counts the number of times this situation occurs. This is the basic idea behind the electronic carpark display which we discussed in the introduction.

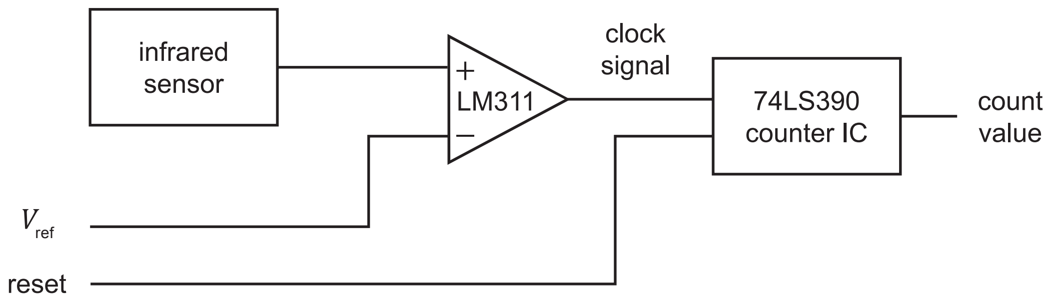


Figure 14.33 Using the output of a voltage comparator as the input of a 74LS390 IC

Figure 14.34 shows the output of a 555 timer IC (set up as a 1 Hz astable multivibrator) being used as the clock signal for a 74LS390 IC through an AND gate. When input A is LOW, the clock signal will be LOW and the count value will stay the same. When input A is HIGH, the clock signal will become a 1 Hz rectangular signal. The count value will increase by one every second. This circuit can be used as a simple stopwatch.

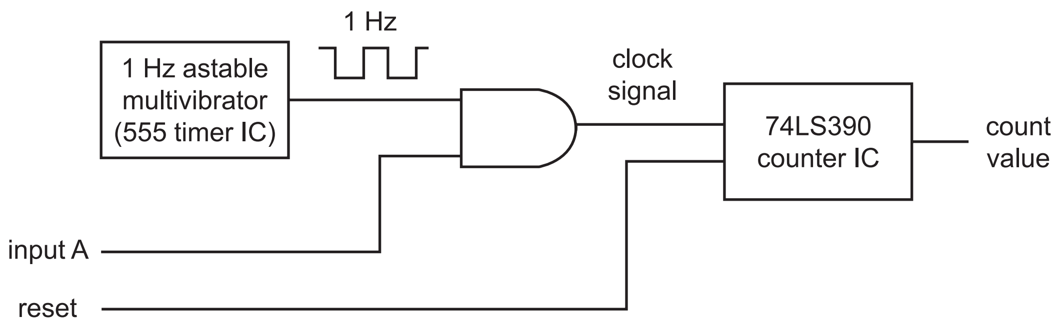


Figure 14.34 Using the output of an astable multivibrator as the input of a 74LS390 IC

Review Question 14.3

1. Complete the timing diagram of the 74LS390 counter IC in Figure 14.35.

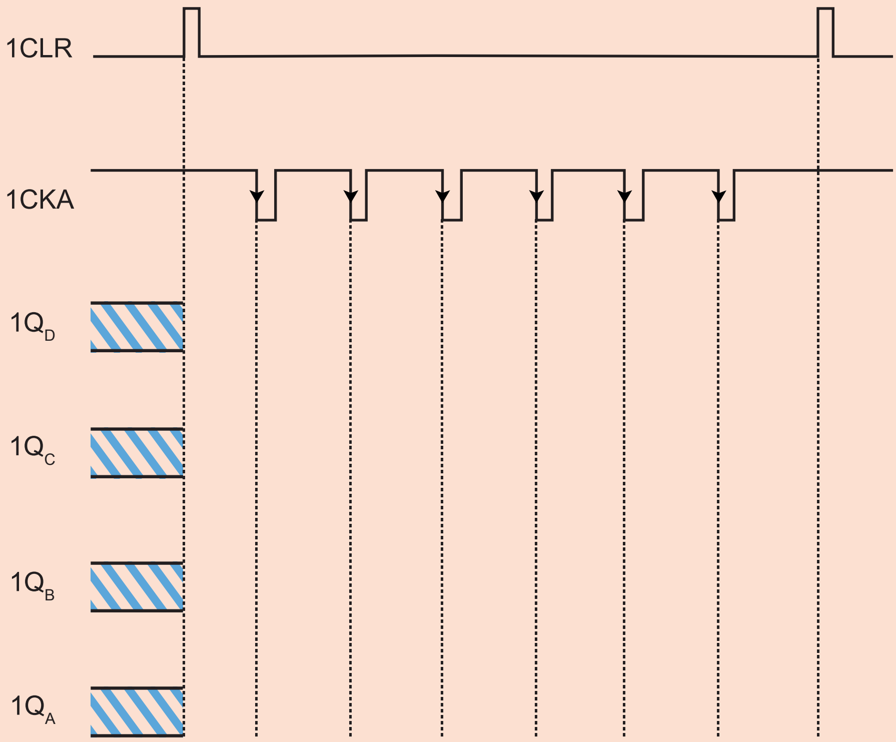


Figure 14.35

Further Reading

The logic gates ICs discussed in chapter 11 and the three ICs in this chapter are known as non-programmable ICs because:

- they perform a fixed specific function, e.g., the LM311 IC only performs voltage comparison while the 555 timer IC only performs timing; and
- their pins have fixed functions, e.g., pin 1 of the 74LS390 IC is always the clock input.

In comparison, a programmable IC can be made to perform different functions by giving it different sets of instructions called programs. An example of a programmable IC is the microcontroller IC shown in Figure 14.36. This particular model comes mounted on a printed circuit board (PCB), which allows it to connect to external circuits easily. Notice that there is a set of analogue input pins and a set of digital input/output (I/O) pins.

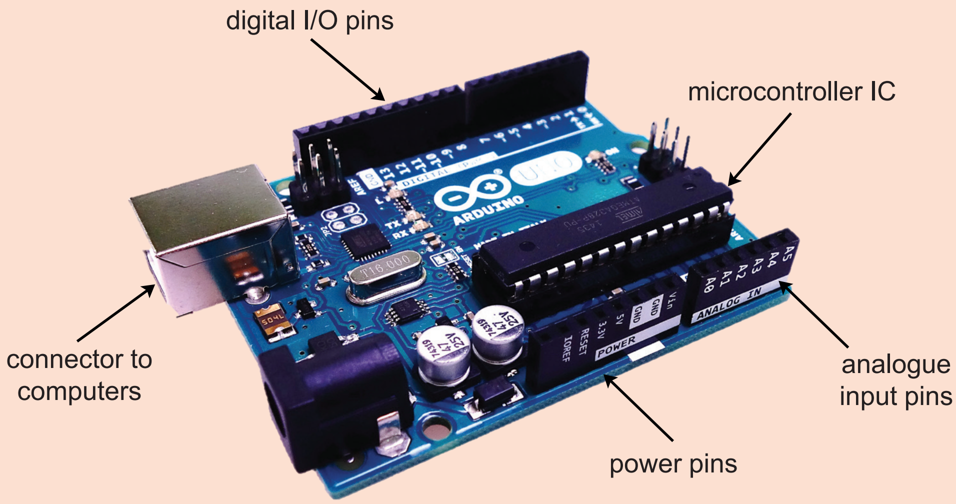


Figure 14.36 A microcontroller IC mounted on a PCB

The following set of instructions will turn the microcontroller into a voltage comparator:

1. Make digital I/O pin 1 an output pin.
2. Compare the voltages at analogue input pins 1 and 2.
3. If the voltage at analogue input pin 1 is higher than analogue input pin 2, send out a HIGH output at digital I/O pin 1; otherwise, send out a LOW output.
4. Go back to step 2.

The following set of instructions will turn the microcontroller into a monostable vibrator:

1. Make digital I/O pin 1 an input pin.
2. Make digital I/O pin 2 an output pin.
3. Set the voltage at digital I/O pin 2 to LOW.
4. Keep checking the voltage of digital I/O pin 1. When it goes from HIGH to LOW, set the voltage at digital I/O pin 2 to HIGH.
5. After 0.5 s (or any predetermined time period), set the voltage at digital I/O pin 2 back to LOW.
6. Go back to step 4.

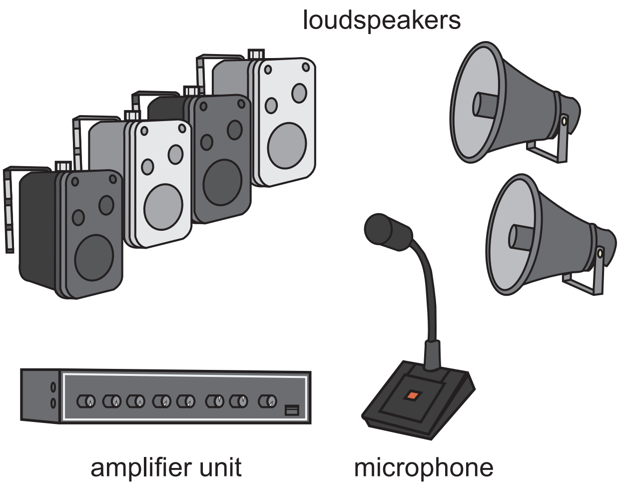
These two examples provide a brief glimpse into the vast range of functions (some of which are very complex) that a programmable IC can be made to perform.

In this course, we only covered non-programmable devices. However, the ideas introduced here (e.g., pin configuration, timing diagrams, connection to external circuits, etc.) are important ideas that are common to both types of devices and hence are also needed to use programmable devices correctly.

15 ENGINEERING DESIGN PROCESS

How do we design, build and test an electronic system?

Electronic engineering is the application of the science of electronics to make useful systems that can solve real-life problems. Two examples of such systems are shown in Figure 15.1. The public address system uses a microphone, an amplifier and several loudspeakers to broadcast messages to groups of people located at different places. The electronic payment system allows for the quick cashless payment of transport fares using a stored value card with an embedded IC.



Public address system

Electronic payment system

Figure 15.1 Products of electronic engineering

These electronic systems were developed through a set of steps known as the **engineering design process**. In this chapter, we will study this process and the engineering skills involved in it.

15.1 What are the key steps in the engineering design process?

Learning Outcomes

- Create new processes, products or projects through the synthesis of ideas from a wide range of sources by:
  - using research methods including web search, textbooks, library resources, literature reviews, etc.;
  - specifying the requirements of an electronic product based on the problem definition; and
  - building a prototype circuit using a prototype board.
- Maintain and organise records of project work development.
- Write a project report using information collated from project work.

Key Idea

- The engineering design process consists of a set of steps which engineers take to design, build and test a working system.

Overview of the engineering design process

There are a few different models for the engineering design process which differ slightly from each other. Figure 15.2 shows the flowchart of the engineering design process adopted for this course. The process consists of a set of steps which engineers take to design, build and test a working system.

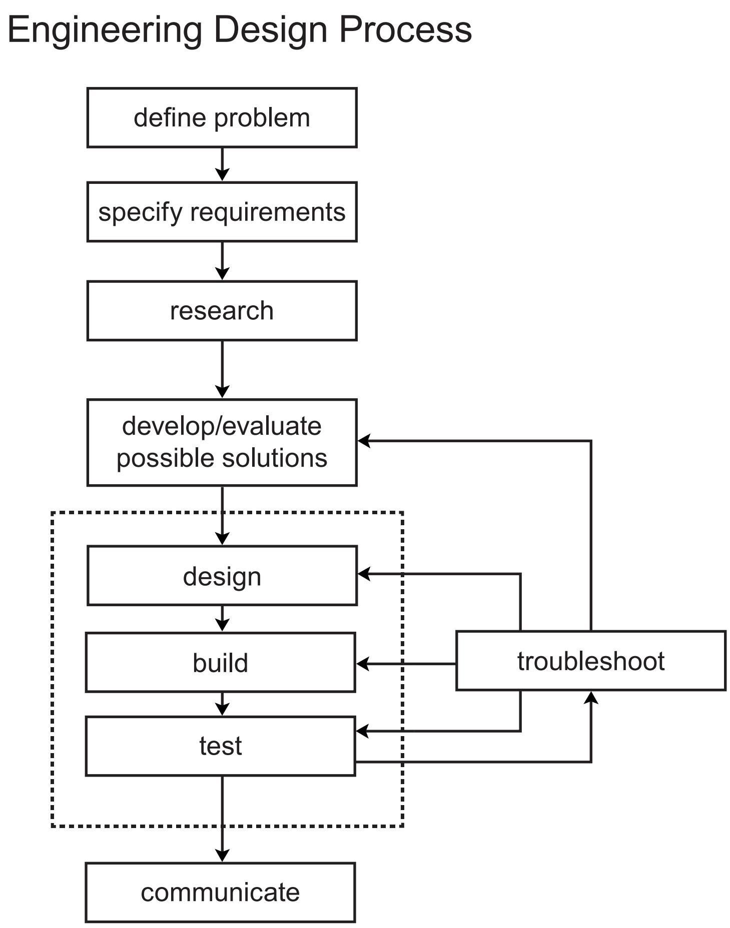


Figure 15.2 The engineering design process

It is important to understand that this is an iterative process. By iterative we mean that some or all of the steps are repeated over and over as needed before arriving at the final design. Also, the actual steps may not follow the order shown in Figure 15.2. For example:

- After some research, a student finds a way to produce a timing circuit using a capacitor and a resistor. He then evaluates whether the method is suitable for the project at hand. After evaluation, he goes back to do research on other areas of the project. Thus, he iterates the research and evaluation steps.
- After building and testing a prototype circuit, another student finds that the design cannot meet the specified requirements. She then goes back to do further research to find alternative solutions. Thus, she iterates the steps of building, testing and research.

Defining a problem

To solve a problem effectively, we need to know exactly what it is. Without an accurate definition and description of the problem, the requirements of the electronic systems to be built cannot be properly specified.

One way of describing a problem is to write out a statement using the following template: '[Who] need(s) [what] because [why]'. For example:

> At a popular eatery, the counter staff has to shout out their orders so the kitchen staff can hear them. This has a negative impact on the ambience of the place and the voices of the counter staff. The counter staff needs a communication system because orders need to reach the kitchen staff clearly.

Specifying requirements

After defining the problem, the next step is to specify a set of requirements that the electronic system should meet in order to solve the problem.

> Minimum requirements of the communication system:
>
> - a microphone that can pick up the voices of the counter staff over the chatter of the customers
> - a cable that carries the signal from the microphone at the counter to the kitchen
> - an audio amplifier that amplifies the signals from the microphone
> - a loudspeaker to broadcast the orders clearly
> - a volume knob to adjust the volume of the loudspeaker
> - the entire system should use only a single 9 V DC source and the current drawn should not exceed 100 mA
>
> Enhanced features (if time and cost permit):
>
> - an indicator light that alerts the kitchen staff of an incoming order
> - another set of a microphone and loudspeaker to allow two-way communication between the kitchen and counter staff

There may be conflicting requirements which would require trade-offs to be made. For example, to make the amplifier more powerful, a larger current would be needed, which may exceed the current limit.

After the requirements are specified, we should draw the block diagram of a system that can meet the requirements. The inputs, processes and outputs of the system should be clearly marked out. Figure 15.3 shows the block diagram of the communication system.

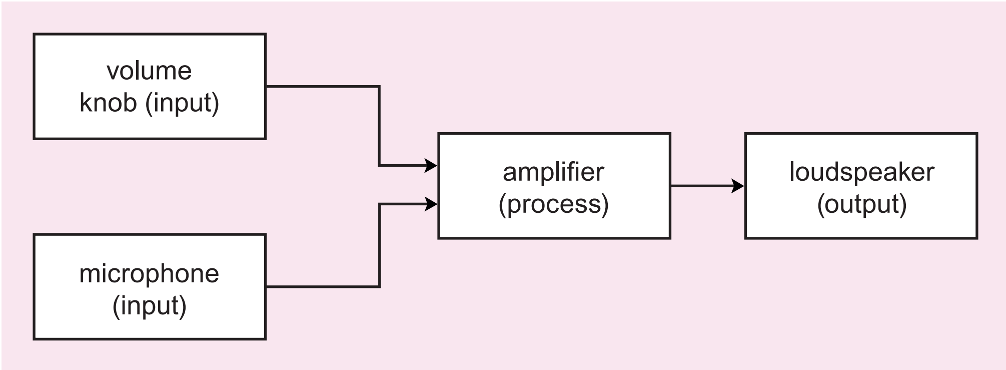


Figure 15.3 Block diagram of an electronic communication system

Research

Good research starts with specific research questions which help us to locate the information needed and determine if that information is relevant.

Possible research questions for the communication system:

- What are the different types of audio amplifiers? What are their advantages and disadvantages?
- How much gain is enough for the audio amplifier?
- How should the volume knob be incorporated into the system?

The research should be drawn from different sources of information, such as websites, books and subject experts. The information obtained should also be evaluated for its credibility. Table 15.1 shows some examples of credible and less-credible sources of information. Nonetheless, we should not totally disregard the less-credible sources. For instance, there are many homemade online videos that allow us to learn how different circuits behave without having to connect them. However, once a potential idea has been identified, we should always verify it by connecting our own circuit (see the next section on evaluation).

Table 15.1 Examples of information sources

Credible sources of information	• published textbooks • established websites with a wide range of well-organised information on electronics • subject experts such as school teachers, lecturers from established institutions, or practicing engineers • online videos posted by established institutions
Less-credible sources of information	• homemade online videos • personal blogs that mention electronics among many other topics

In research, it is ethical to acknowledge and give due credit to the originators of the information we use. Table 15.2 shows the details that should be included in our acknowledgement.

Table 15.2 Acknowledgement of information used

Type	Details	Use of information
Book	Title: Electronic Devices Author: A.B. Lim Edition: 2nd edition Year: 2010 Publisher: JJ Publication	Used the audio amplifier circuit on page 16 as a reference
Website	Web address: http://www.circuits.com Date of access: 20 Aug 2016	Used the circuit diagram of the audio amplifier with volume control as a reference
Experts	Mr. Sunil (project supervisor)	Adopted Mr. Sunil's suggestion on how to increase the maximum volume of the amplifier

Developing and evaluating possible solutions

Our research should lead to possible ideas that can be used to build the system. However, it is also possible that we come up with novel ideas that are not the result of research. Whichever the case, these ideas need to be developed and evaluated to see if they are feasible. In electronics, most of these ideas are related to the design of circuits.

Possible ideas for the communication system:

- There are three main classes of transistor amplifiers. Each has its own advantages and disadvantages, e.g., using class A amplifiers would result in a system that is easier to build; however, the power consumption would be high.
- Audio amplifier ICs can also be used instead of BJTs.
- The signal from a microphone is in the magnitude of tens of mV. This is too small to drive a loudspeaker, which requires a voltage level of at least 0.2 V. Hence, the voltage gain of the amplifier should be around 20.
- A common way of incorporating a volume knob is by using a voltage-divider circuit at the input stage.

An effective and fast way to evaluate the workability of a circuit design is to use circuit simulation software (see the next section) to generate the expected output of the circuit. The software helps to identify potential circuit design issues without having to actually build the circuit.

We can also physically build a circuit and use test instruments to study its characteristics and performance. This is usually more time-consuming than using circuit simulation software but it provides more realistic results.

Designing

Although this is shown as a separate step in Figure 15.2, the preliminary design work actually starts when we develop and evaluate possible solutions. In this step, all the evaluated circuits are put together to form a complete system.

Circuit simulation software can also be used at this stage to draw the circuit diagram and generate the expected output of the entire system. Using this software has the added advantages of producing a neatly drawn diagram and ensuring that only standard symbols are used.

Building

We build prototypes so we can test and verify our designs before going on to build the final product. This avoids the unnecessary wastage of materials, time and money if the design is not workable. The prototype should be able to perform all essential functions.

There are a number of prototype boards that can be used to build electronic circuits, such as the breadboard, strip board and donut board shown in Figure 15.4.

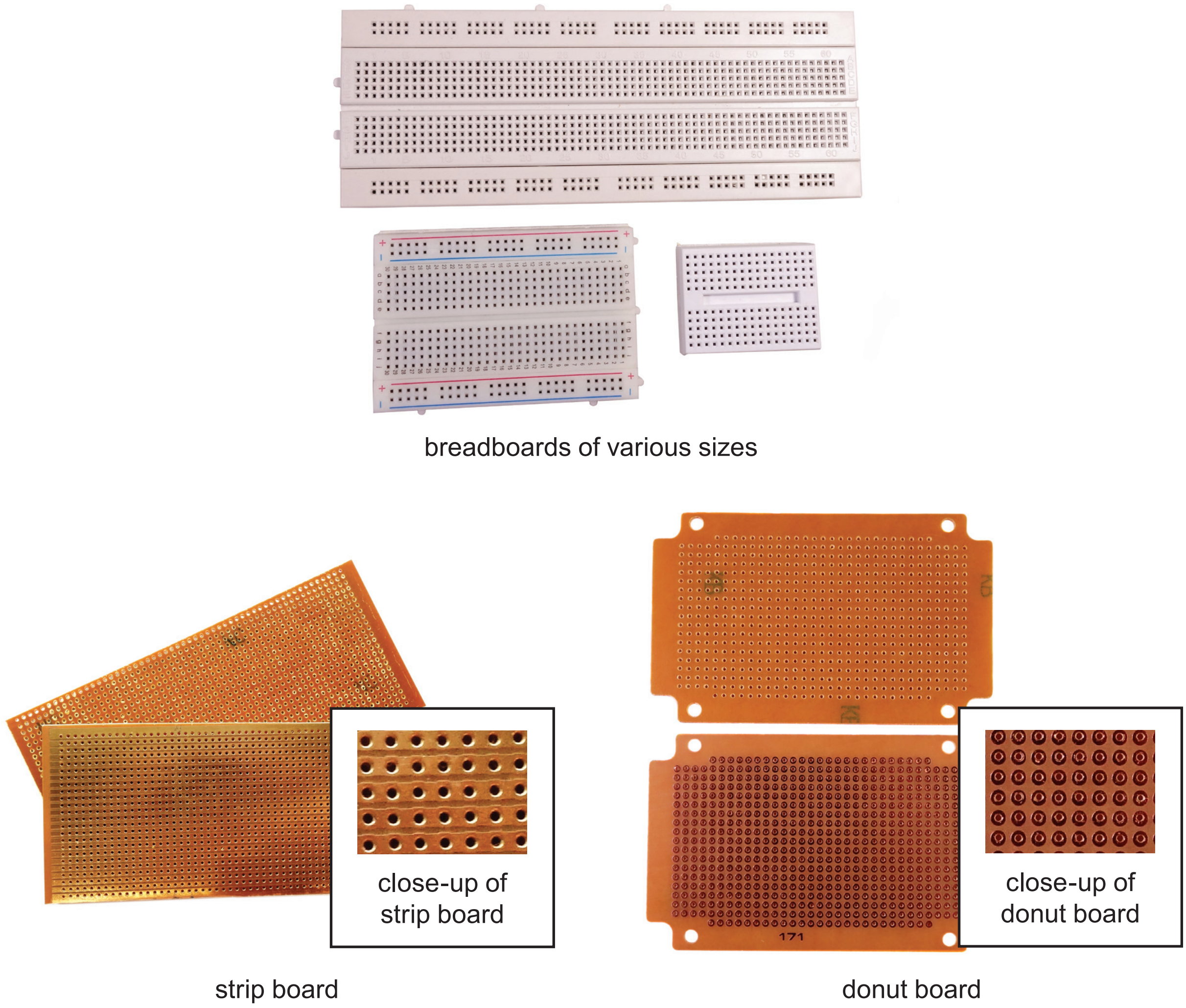


Figure 15.4 Common prototype boards

In this course, we will only use the breadboard. It is a plastic board with holes to insert components. Figure 15.5 shows a circuit connected on a breadboard.

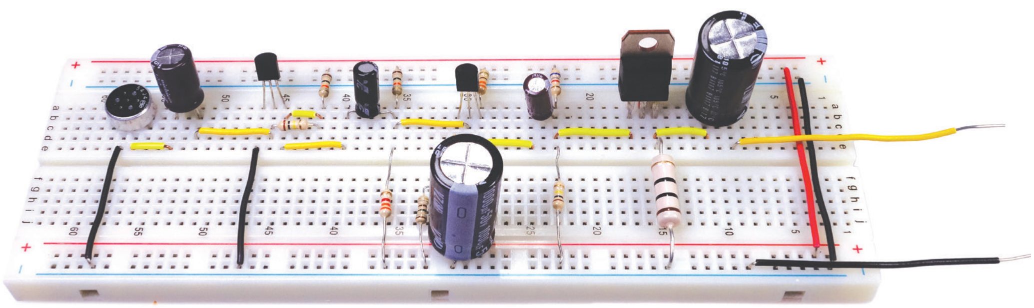


Figure 15.5 A circuit connected on breadboard

An important advantage of the breadboard is that it allows components to be placed, connected and removed easily. This means we can build and amend circuits easily.

Inside the board, the holes are electrically connected as shown in Figure 15.6. The rows of 25 holes at the top and bottom sections of the board are connected together and the columns of five holes at the middle sections are connected together.

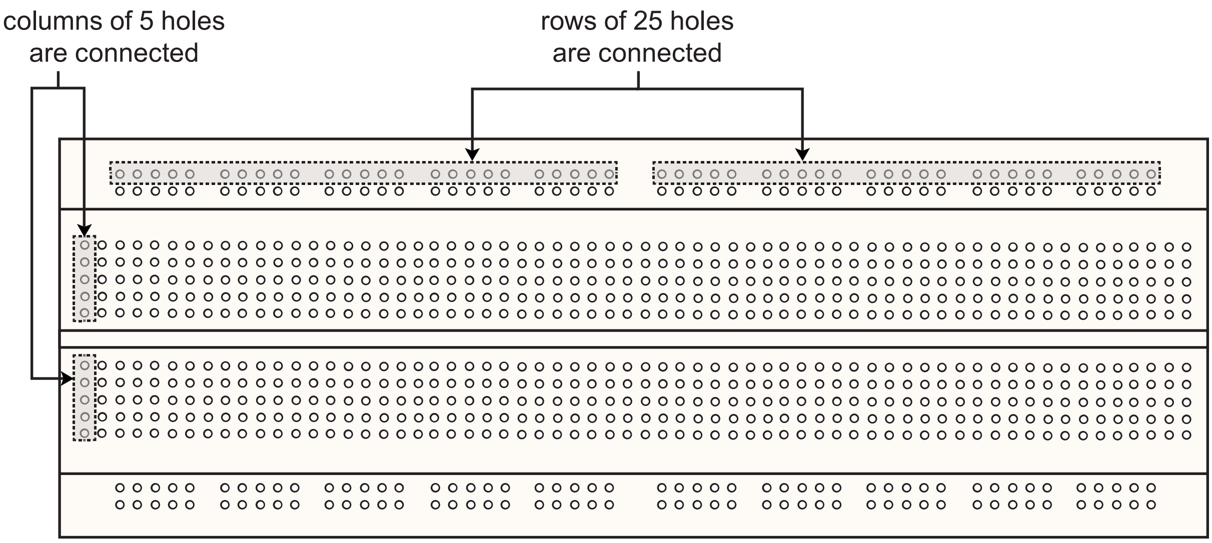


Figure 15.6 Internal connections of a breadboard

Using good techniques to build circuits on breadboard will make your circuits neat and easy to understand. This in turn helps to prevent and identify faults. Figure 15.7 shows two circuits built on a breadboard. The circuit on the left is poorly built but the one on the right is well built.

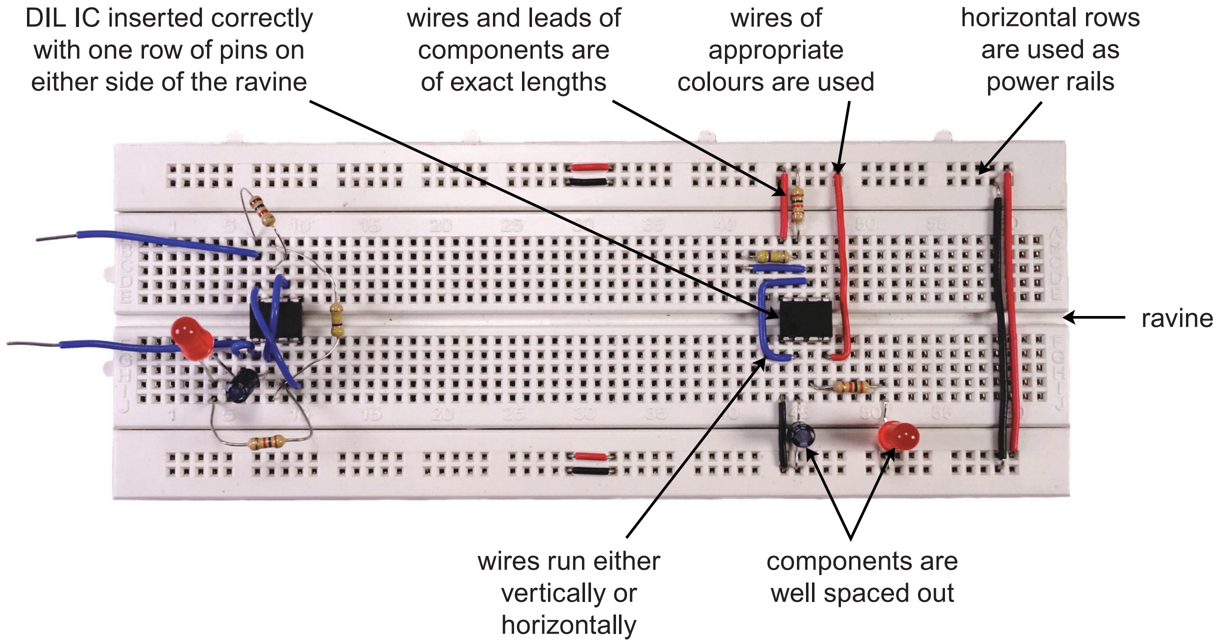


Figure 15.7 A poorly built circuit (left) and a well-built circuit (right)

Table 15.3 compares the two circuits in Figure 15.7. You should adopt the good breadboard techniques used to build the circuit on the right as described in Table 15.3.

Table 15.3 Comparison of poorly and well-built circuits on breadboard

Poorly built circuit (left)	Well-built circuit (right)
The circuit does not use the horizontal rows as power rails; instead, each component uses a pair of wires that run across the board for power connection. This makes the circuit unnecessarily complex.	The upper and lower horizontal rows are used as power rails. This is a systematic and neat method of connecting components to the power supply.
The wires and component leads are excessively long. This makes the circuit messy and prone to accidental short circuits.	The wires and component leads are trimmed to the exact lengths. This makes the circuit neat and minimises the likelihood of an accidental short circuit.
The wires criss-cross each other in a haphazard manner.	The wires run either vertically or horizontally with no unnecessary criss-crossing. This makes the circuit neat and easy to understand.
All the wires are of the same colour, which makes it difficult to identify the connections.	Wires of different colours are used to identify the connections: • red – positive voltage supply • black – ground • blue – signal
The components are slanted and may not be fully pushed in. This may result in poor connections.	All components are fully pushed in vertically into the holes of the breadboard to ensure firm connections.
The components are crammed into a small area. This makes the circuit messy and prone to accidental short circuits.	The components are well spaced out. This makes the circuit neat and minimises accidental short circuits.
The IC is correctly inserted with one row of pins on either side of the ravine. However, the top surface of the IC is obstructed by wires, making it hard to identify the IC.	The IC is correctly inserted with one row of pins on either side of the ravine. The top surface of the IC is not obstructed, making it easy to identify the IC.

Components placed on strip boards and donut boards need to be soldered to secure them onto the boards and connect them together. **Soldering** is the process of melting a metallic alloy (known as a solder) and allowing it to solidify to form an electrical connection. The advantage is that the physical strength of the connections created by soldering is much stronger than that of the components placed on the breadboard. However, it is time-consuming to build and amend the circuit as solder needs to be removed and re-applied each time a change is to be made.

Figure 15.8a Soldering kit

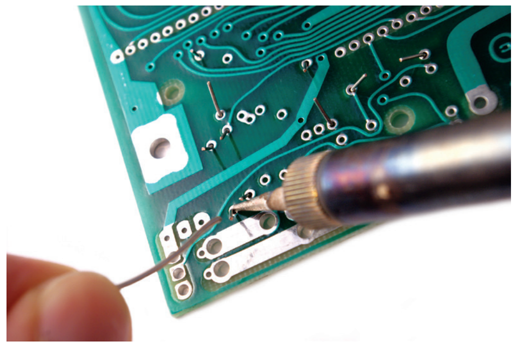


Figure 15.8b Melting solder with a soldering iron

Testing

After the prototype circuit has been built on a prototype board, we need to conduct tests to check if the system meets the specified requirements. Most of these tests require the use of test equipment (see Section 15.4).

The conditions and results of the tests should be clearly documented for future reference and reporting. Table 15.4 shows some examples of how we can document the tests we conduct.

Table 15.4 Table detailing tests and results

Description and objective of test	Test conditions and procedures	Observations and measurements
1. To test if the system enables kitchen staff to hear orders from the counter staff	a. Conduct the test in a quiet environment b. Conduct the test in a noisy environment	a. Orders can be heard clearly in a quiet environment b. Orders become slightly unclear in a noisy environment even at maximum volume
2. To test if the volume knob allows the volume to be adjusted	a. In a quiet environment, listen to the sound level from the loudspeaker as the volume knob is adjusted	a. The volume knob works
3. To determine the current drawn by the circuit and ensure it is below the maximum level allowed	a. Connect a multimeter along the power supply line b. Measure the current when there is no active amplification c. Measure the current during amplification d. Compare the measurements against the maximum current allowed	b. Standby current = 20 mA c. Operating current = 24 mA d. The current drawn by the circuit falls within the maximum limit of 100 mA
4. To determine the voltage gain of the amplifier	a. Use a function generator to provide a 10 mV peak 300 Hz input sine signal b. Adjust the volume knob to the maximum volume c. Display the output signal on an oscilloscope and measure the peak output voltage d. Divide the peak output voltage by the peak input voltage to obtain the voltage gain	c. Peak output voltage = 500 mV d. Voltage gain, $\lvert A_V \rvert = \frac{500 \text{ mV}}{10 \text{ mV}} = 50$

Troubleshooting

When electronic systems do not perform as expected, electronic engineers need to find the cause of the problem. The process of finding and correcting the faults in an electronic system is called **troubleshooting**. Like testing, troubleshooting usually requires the use of test equipment.

There is no fixed way to perform troubleshooting. In general, troubleshooting involves the elimination and confirmation of possible causes of faults. Some examples:

- Circuits without the correct voltage supply will not work. Check if the power supply is connected properly to the circuit by using a multimeter to measure the voltage across the positive supply and the ground.
- A system may not work properly due to an incorrect input signal, e.g., a sine signal is used instead of a square wave. Check if the input signal is correct by viewing the signal on an oscilloscope or double-checking the setting of the function generator.
- Replace a component you suspect to be faulty with a new one. If the problem disappears, then the fault is likely caused by the component. If the problem persists, then the component is probably not faulty.
- Break down the system into subsystems and test each subsystem individually. This should help to narrow the fault down to the specific subsystem in which it lies.

Troubleshooting can also involve making inferences from the observations. Some examples:

- If the problem is inconsistent and only occurs occasionally, the system could be operating near the threshold value at one or more parts of the circuit. Threshold values are borderline values. For example, if a BJT switch requires a signal with a minimum voltage of 3.0 V to be switched on and the circuit provides a signal of exactly 3.0 V, then this part of the circuit is operating near the threshold value.
- If the problem is not a total failure but a partial one, it could be caused by incorrect component values. For example, if the resistance of the current-limiting resistor for an LED is too high, the LED will light up but it will not be as bright as it should.

Experience counts a lot in troubleshooting as engineers often troubleshoot based on similar problems they have previously encountered. Troubleshooting can be challenging at first but you will build up experience and confidence with practice.

Communicating

Due to the complexity of their projects, engineers frequently work in teams. The ability to communicate ideas and results clearly and accurately, both verbally and in writing, is an important skill.

Because of the large amount of information involved, it is good practice for us to record our ideas and the activities we have conducted in an engineering notebook. Relying on memory will inevitably lead to the loss of information. Figure 15.9 shows an example of how we can record the results of a test in an engineering notebook. The notes in your engineering notebook will be valuable in helping you report the work done at each step of the engineering design process.

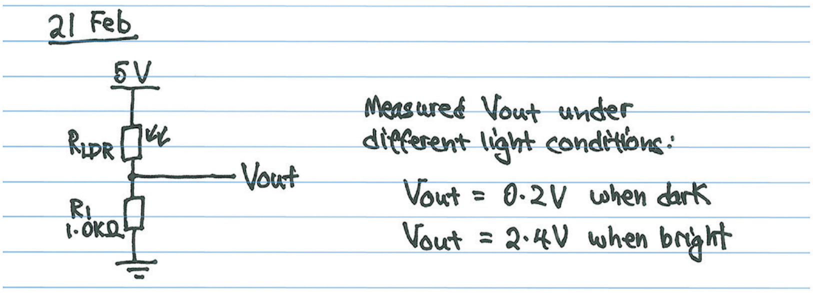


Figure 15.9 Extract from an engineering notebook

In this course, you will be required to produce a report of an electronic system which you have designed, built and tested. Below are some guidelines on how you should write your report:

- Describe in detail the work you have done at each step of the engineering design process.
- Use clear and concise language in the passive voice (e.g., 'The 100 Ω resistor was replaced with a 1 kΩ resistor') rather than the active voice (e.g., 'I changed the 100 Ω resistor to a 1 kΩ resistor').
- Include all block diagrams and circuit diagrams.
- Support your explanations with appropriate diagrams, charts and tables.
- Acknowledge the sources of information used in your design.

Review Question 15.1

1. State the main steps of the engineering design process. Briefly describe what each step entails.

15.2 How do we manage project timelines?

Learning Outcomes

- Recognise the characteristics of a successful project plan.
- Draw a Gantt chart for a project with known tasks, precedence and duration.

Key Idea

- Successful projects should be able to meet the requirements and be completed on time.

Time management

Good time management is needed to ensure a project gets completed on time.

A **Gantt chart** is a horizontal bar chart commonly used to manage the timeline of a project. It provides a graphical representation of the tasks in a project for easy monitoring and communication.

Consider a building project that involves the following tasks:

- Laying the foundation – this takes three months (90 days)
- Building the house – this takes 10 months (300 days) and can only start after the foundation is laid
- Painting the house – this takes one month (30 days) and can only start after the house is built
- Installing the electrical supply – this takes two months (60 days) and can only start after the house is built

The information is represented by the Gantt chart shown in Figure 15.10. At a glance, we can easily see the tasks involved, the duration of each task and the estimated completion date.

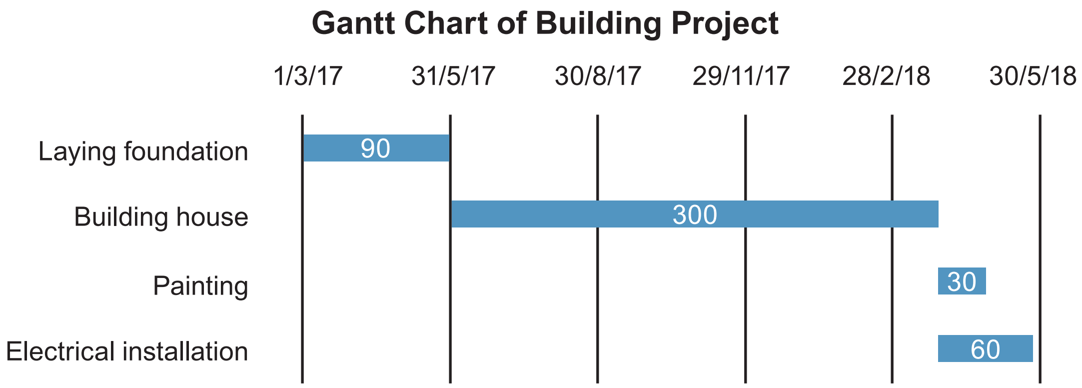


Figure 15.10 Gantt chart of a building project

When drawing a Gantt chart, it is important to pay attention to the **precedence** of tasks, which is the order in which the tasks are scheduled. In the example of the building project, the building of the house should be scheduled after the laying of the foundation. However, painting and electrical installation can be carried out concurrently after the building is completed.

We can use a spreadsheet software such as Microsoft Excel to create a basic Gantt chart using the following steps:

Step 1: Enter all the tasks that need to be completed, together with their start dates and durations as shown in Figure 15.11.

	A	B	C	D
1	**Task**	**Start date**	**Duration (in days)**	**End date**
2	Task 1	1/3/2017	20	21/3/2017
3	Task 2	22/3/2017	20	11/4/2017
4	Task 3	22/3/2017	10	1/4/2017
5	Task 4	12/4/2017	5	17/4/2017

Figure 15.11 Entering the tasks, start dates and durations into the spreadsheet software

Step 2: Use the chart function in the software to generate a horizontal bar chart as shown in Figure 15.12 from the information you have keyed in. You can refer to the manual or online help function of the software to find out how to convert your values into a chart.

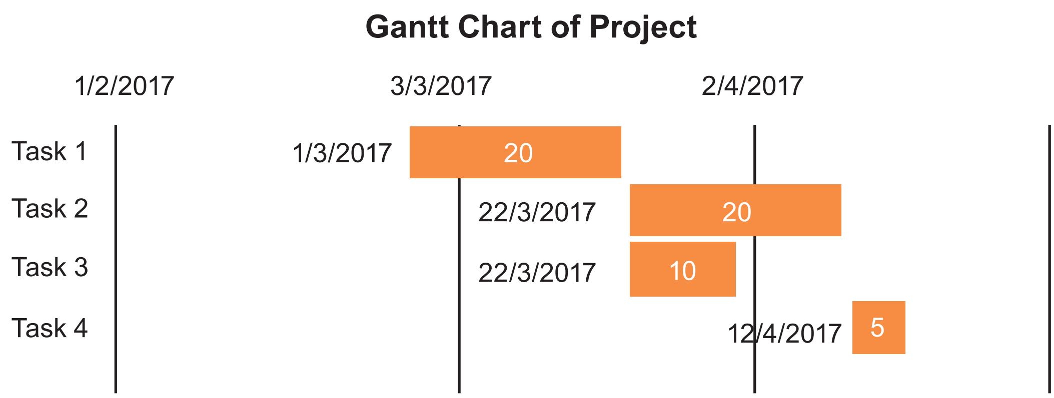


Figure 15.12 Generating a basic Gantt chart

An advantage of using a spreadsheet software is that any changes made to the titles, number, start dates or durations of the tasks will be automatically updated in the chart.

Review Question 15.2

1. Use the information below to draw a Gantt chart for the project described below. There are four tasks in total.
    - Task 1 should start on 1 March and be completed by 31 March.
    - Task 2 can start after Task 1 has been completed, and is expected to take one month to complete.
    - Task 3 can start after Task 1 has been completed, and is expected to take two months to complete.
    - Task 4 can only start after Tasks 2 and 3 have been completed, and is expected to take three months to complete.

15.3 How do we use circuit simulation software to analyse circuit designs?

Learning Outcomes

- Appraise the role of computer simulation in circuit design (advantages and limitations).
- Use circuit simulation software to verify a circuit design.

Key Idea

- Circuit simulation software allows us to verify the functionality of circuit designs in a fast and cost-effective manner.

Circuit simulation software uses the computational and processing ability of computers to model the behaviour of electrical and electronic circuits. Modern circuit simulation software can achieve this to a high level of accuracy, making it an invaluable tool in the analysis of circuits.

The main advantages of using circuit simulation software are:

- Saves cost – no components need to be purchased
- Saves time – no need to build a physical circuit or set up test equipment

There is a range of circuit simulation software developed by different companies. The common features and functions include:

- A workspace to place components and virtual instruments
- A library from which components can be selected
- A range of virtual instruments such as the multimeter, oscilloscope and function generator
- Wiring of components and virtual instruments to form a circuit
- Simulation of circuits and display of output

In this course, we will be using National Instrument's Multisim software. Figure 15.13a shows the screen capture of a half-wave rectifier circuit drawn using the software. Figure 15.13b shows the input waveform (in blue) and output waveform (in red) displayed on the virtual oscilloscope.

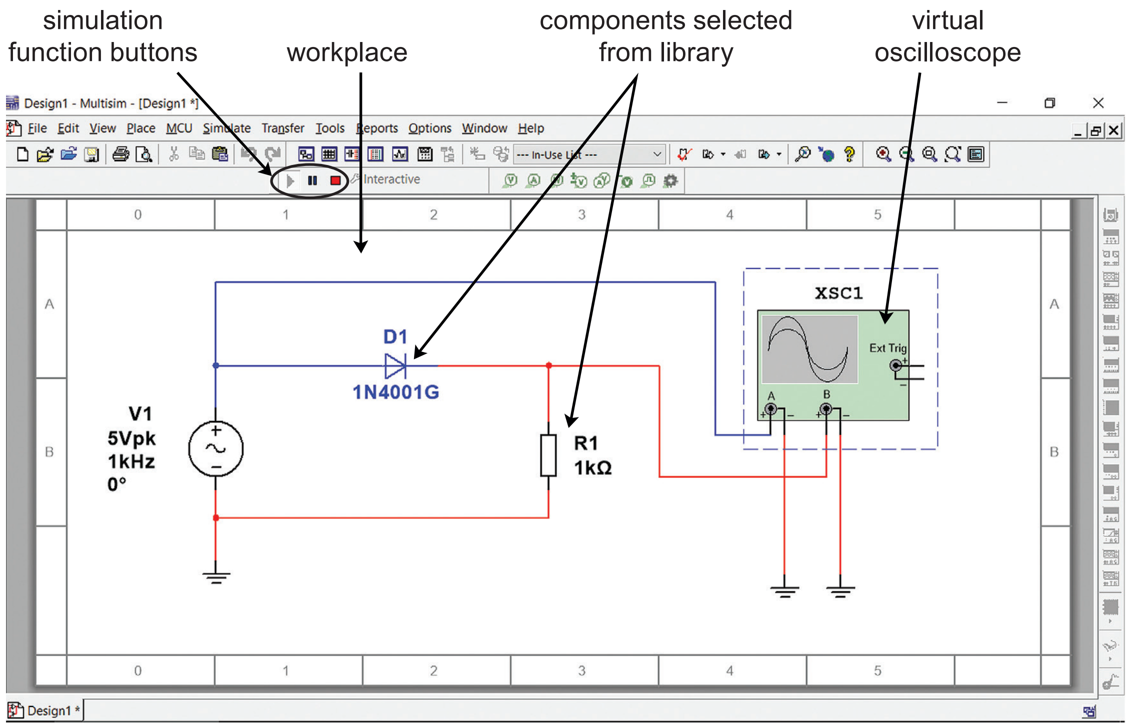


Figure 15.13a Screen capture of a circuit drawn using Multisim

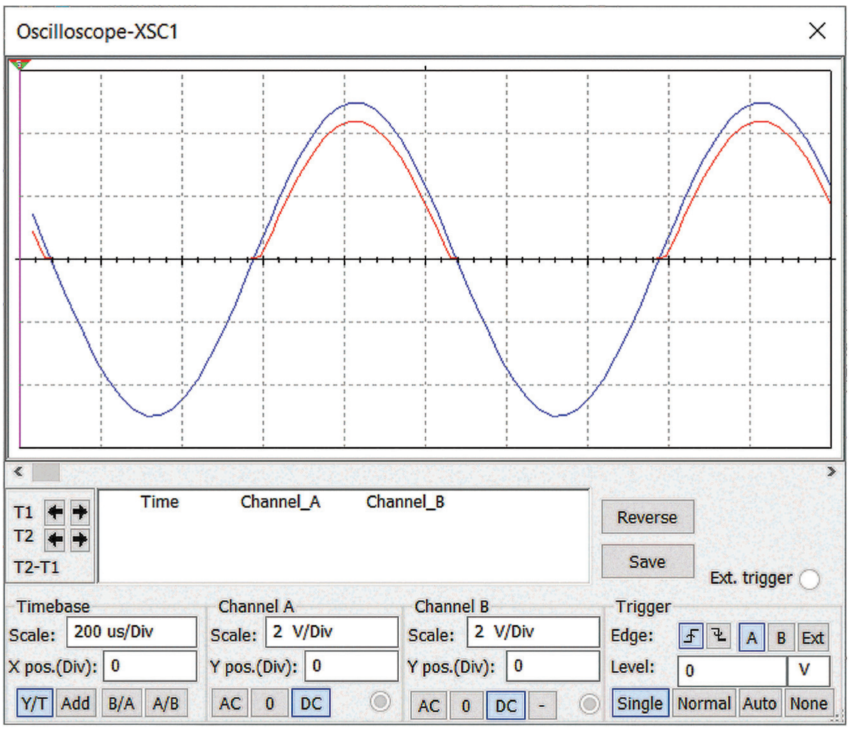


Figure 15.13b Virtual oscilloscope display

By studying the outputs of the indicators and virtual instruments, we can obtain information on the workings of the circuit. We can also make modifications to the circuit, such as changing the values of the components, and observe the effects on the outputs.

Despite the advantages of using computer simulation, there is still a need to build the physical circuit after the computer-based analysis is completed. This is because the computer simulation assumes certain working conditions which may differ from the actual working conditions. This software is also unable to simulate certain conditions such as temperature changes.

Review Question 15.3

1. State the advantages and limitations of using circuit simulation software.

15.4 When and why do we use electronic test equipment?

Learning Outcome

- Use relevant test and measuring equipment (digital multimeter, function generator and oscilloscope) to test and troubleshoot prototype circuits.

Key Ideas

- Electronic test equipment is a set of essential tools needed to test and troubleshoot electronic circuits.
- It is important to know the functions of different types of electronic test equipment and how to use them correctly.

Electronic test equipment

We use **electronic test equipment** to test whether an electronic system is working as designed and to measure the performance of the system. In this course, we will use a set of electronic test equipment that consists of the following four instruments:

1. DC power supply unit
2. Digital multimeter
3. Function generator
4. Digital storage oscilloscope

DC power supply unit

All electronic circuits need one or more voltage sources to work. Two common voltage sources are batteries and the DC power supply unit (PSU) shown in Figure 15.14.

PSUs come in two types – fixed or variable voltage. The fixed type supplies a fixed voltage, e.g., 5 V, which cannot be adjusted. The variable type offers greater flexibility as it can be adjusted to supply a range of voltage, e.g., 0–20 V.

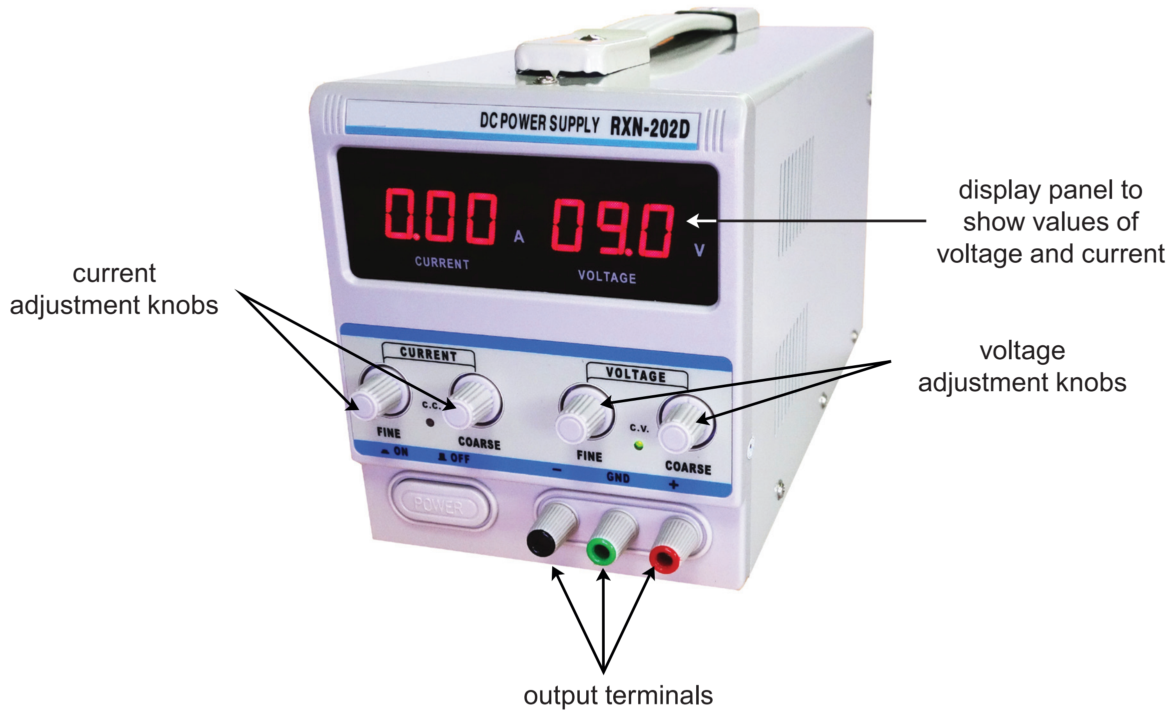


Figure 15.14 A PSU

Table 15.4 Advantages of using PSUs vs batteries

Advantages of using PSUs	Advantages of using batteries
• The voltage supplied by PSUs can usually be adjusted in small steps while batteries can only provide voltages of fixed increments, e.g., 1.5 V, 3.0 V, 4.5 V, etc. • PSUs can supply a higher current than most batteries and thus are able to support high-power applications. • Unlike batteries that need to be replaced when they become flat, PSUs can continuously supply power as long as they are connected to the mains.	• Batteries do not need a mains supply. • Batteries are very light and are hence more portable than PSUs, which often weigh a few kilograms.

Digital multimeter

Digital multimeters are versatile instruments that can be used to measure different electrical quantities such as voltage, current and resistance. Figure 15.15 shows a basic digital multimeter. It has three sockets for inserting test leads, a centre knob to select its functions and a display panel to show the readings.

Figure 15.15 A digital multimeter

More sophisticated models may have additional functions such as:

- checking whether two points in a circuit are electrically connected (a buzzer will sound if so) – this function is known as a continuity check;
- checking the polarity of a diode;
- measuring the current gain of a BJT; and
- measuring the capacitance of capacitors.

The measurements taken with a multimeter provide information about the circuit. For example:

- By measuring the resistance between two points in a circuit, we can tell whether they have been accidentally short-circuited – the multimeter will give a resistance reading of zero if so.
- By measuring the current through a bulb that does not light up, we can tell if the current is too small or if there is a break in the path leading to the bulb.
- By measuring the DC voltage at the base, collector and emitter of a BJT amplifier, we can tell if the amplifier is properly biased.

Function generator

Some electronic circuits, e.g., audio amplifiers, receive AC signals as inputs. To test these circuits, we need to feed AC test signals into the circuit and observe the output. Function generators, like the one shown in Figure 15.16, can provide a range of AC test signals of different types (e.g., sine, rectangular or triangle), frequency and peak voltage.

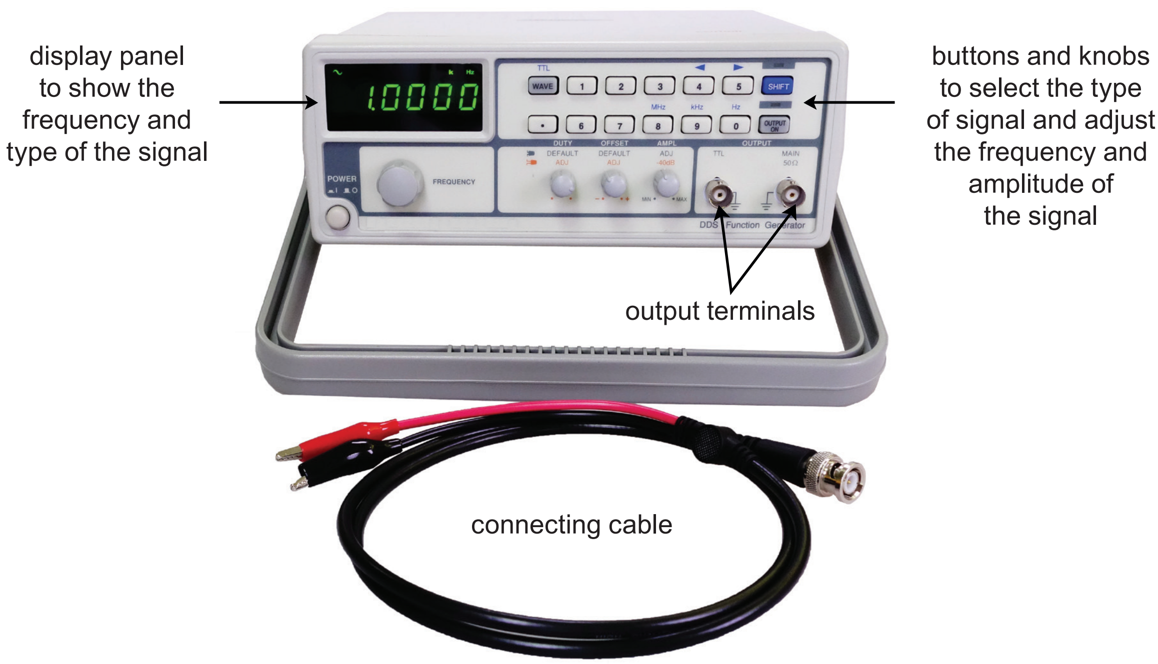


Figure 15.16 A function generator

Digital storage oscilloscope

In electronics, we often need to observe how the voltages at different points of a circuit change with time. This provides us with important information on the behaviour and performance of the circuit. We frequently use the digital storage oscilloscope for this purpose.

Figure 15.17 shows a typical digital storage oscilloscope. It consists of a prominent liquid-crystal display (LCD) screen, input connectors, and buttons and knobs for adjustments.

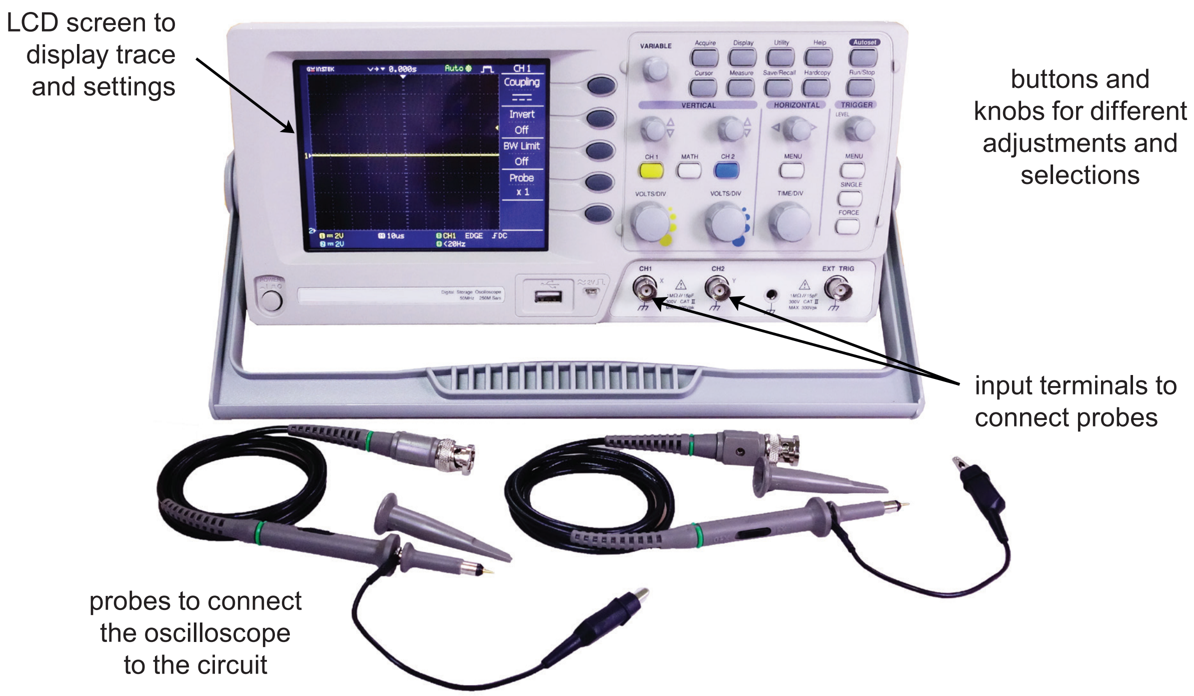


Figure 15.17 Digital storage oscilloscope

Figure 15.18 shows the display of a digital storage oscilloscope. The display is a trace that represents a voltage-time graph. The scales of the vertical and horizontal axes are 2.0 V per division and 250 μs per division, respectively. Since the peak of the waveform is two vertical divisions above the DC level, it has a peak voltage of 4.0 V. Also, one cycle of the waveform takes up four horizontal divisions, thus it has a period of 1.0 ms (1000 μs).

Most oscilloscopes come with cursor and measurement functions. In Figure 15.18, the two cursors are placed at two successive peaks. This enables the period (shown as 990.0 μs) and the frequency (shown as 1.010 kHz) to be displayed automatically.

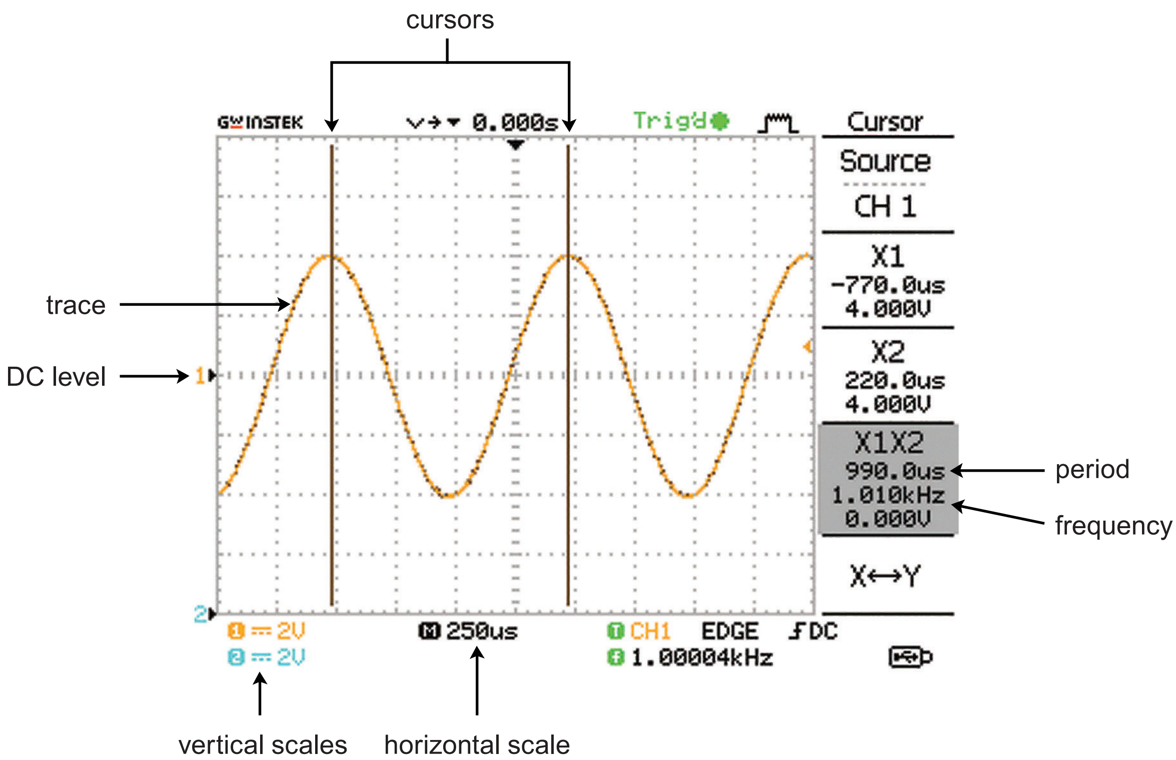


Figure 15.18 Display of a digital storage oscilloscope

Review Question 15.4

1. Describe the specific functions of a PSU, digital multimeter, function generator and digital storage oscilloscope.

GLOSSARY

555 timer IC	An 8-pin IC that can be used as a monostable or an astable multivibrator
74LS390 (decade counter) IC	A 16-pin IC with two decade counters
7-segment LED display	A device for displaying decimal digits; it consists of seven segments and a decimal point which are each illuminated by an LED
active region	The BJT operating region where the collector current changes linearly with the base current
AC voltage	A voltage that changes polarity periodically
alternating current (AC)	A current that changes direction periodically
ampere	The SI unit of current
amplification	The process of increasing the magnitude of an electronic signal
analogue signal	An electrical signal that varies continuously over time
AND gate	A logic gate that performs the AND operation, which gives an output of 1 only when both inputs are 1
anode	The positive terminal of a semiconductor diode which is connected to the p-type semiconductor
astable multivibrator	A timing device that produces a continuous stream of pulses (rectangular waveforms)
avalanche current	The large reverse current that flows through a practical diode when the reverse voltage exceeds its breakdown voltage
base	One of three terminals of a BJT; the current flowing in or out of the base determines the size of the current that flows between the collector and emitter terminals
base activation voltage	The minimum forward voltage needed for a current to flow from the base of a BJT to its emitter
base-collector junction	The PN junction between the base and the collector of a BJT

base-emitter junction	The PN junction between the base and the emitter of a BJT
base quantity	One of the seven physical quantities from which other physical quantities are derived
base unit	The unit of a base quantity
BCD to 7-segment decoder	A device which converts a BCD into a 7-segment code
biasing	The process of setting up a BJT to work at a particular operating point
binary-coded decimal (BCD)	A coding system which uses groups of 4-bit binary code to represent the digits of a decimal number
binary system	A number system which is made up of two distinct digits: 0 (smallest) and 1 (biggest)
bipolar junction transistor (BJT)	A three-terminal device that consists of three layers of semiconductors arranged either in the order NPN or PNP
bit	A digit in the binary system
block diagram	A diagram that provides an overview of a system by showing the subsystems that form the overall system and how information or energy flows through them
Boolean expression	A type of mathematical expression that can be used to describe logic operations
branch	One of the possible paths in a parallel circuit that current can flow
breakdown region	The region in which a practical diode will operate when the reverse voltage exceeds its breakdown voltage
breakdown voltage	The reverse voltage that will cause current to flow freely through a practical diode in the reverse direction; in general, this should be avoided as it will damage the diode
bridge configuration	An arrangement of diodes that forms a full-wave rectifier
buzzer	An output transducer that converts an electrical signal into a beeping or buzzing sound
bypassed capacitor	A capacitor that is connected in parallel with another component to allow AC signals to bypass the component
capacitance	The ability of a capacitor to store electric charges

capacitor	A component used to store electric charges
carbon resistor	A type of resistor in which the resistance is provided by a thin layer of carbon film
cathode	The negative terminal of a semiconductor diode which is connected to the n-type semiconductor
charging	The process of increasing the amount of electric charge stored on the plates of a capacitor
charging graph	A graph that shows how the voltage across a capacitor increases with time
circuit	An electrical path consisting of electrical components connected with wires
circuit diagram	A diagram drawn using standard symbols that shows how the components in a circuit are connected together
circuit simulation software	A computer application which models the behaviour of electrical and electronic circuits
closed circuit	A continuous electrical path
closed loop	An electrical path that starts and ends at the same point
collector	One of three terminals of a BJT (in NPN BJTs, current will flow from this terminal to the emitter terminal)
combinational logic circuit	A logic circuit made up of two or more logic gates connected together
common-anode 7-segment display	A type of 7-segment display with all the anodes of its LEDs connected together
common base (CB) configuration	A configuration in which the input of a BJT amplifier is connected to its emitter and the output is taken from its collector
common-cathode 7-segment display	A type of 7-segment display with all the cathodes of its LEDs connected together
common collector (CC) configuration	A configuration in which the input of a BJT amplifier is connected to its base and the output is taken from its emitter
common emitter (CE) configuration	A configuration in which the input of a BJT amplifier is connected to its and the output is taken from its collector
contact bounce	A phenomenon where the contacts of a mechanical switch connect and disconnect several times before a firm connection is established; it occurs each time the switch is opened or closed

conventional current	The current that flows from the positive terminal of a source to its negative terminal
coupling capacitor	A capacitor used to pass AC signals but block DC voltages
current	The rate of flow of electrical charge
current-divider formula	A formula that is used to calculate the currents through resistors connected in parallel
current-limiting resistor	A resistor that is connected in series with a component to limit the current flowing through it
current rating	The maximum current that a wire or component can carry without getting overheated or damaged
cutoff region	The BJT operating region where the collector current is nearly zero and the collector-emitter voltage is close to the supply voltage
Darlington pair	A setup in which two BJTs are connected together to increase the overall current gain
datasheet	A document that contains important information on how a component or device can be used correctly and safely
DC current gain	The ratio of the collector current to the base current
DC level	The voltage level which a waveform oscillates about
DC load line	The line that reflects the conditions which the supply voltage and the resistors in a BJT circuit impose on the BJT
DC voltage	A voltage that does not change polarity
debounced switch	A switch that eliminates the effect of contact bounce, producing a digital signal with a single rising or falling edge
decade counter	A counter that counts from 0 to 9 and then returns to 0 again
decimal system	A number system which is made up of ten distinct digits: 0 (smallest), 1, 2, 3, 4, 5, 6, 7, 8 and 9 (biggest)
derived quantity	A quantity obtained by multiplying or dividing two or more base quantities
derived unit	The unit of a derived quantity
dielectric	A thin layer of insulating material separating the two metal plates of a capacitor

digital signal	An electrical signal that can only vary in steps
direct current (DC)	A current that flows in one direction only
direct current (DC) voltage source	A source that supplies a constant voltage
discharging	The process of decreasing the amount of electric charge stored on the plates of a capacitor
discharging graph	A graph that shows how the voltage across a capacitor decreases with time
doping	The process of adding impurities to a semiconductor to increase its electrical conductivity
driver	An application of BJT which allows a small current to drive a load that needs a larger current
dual in-line (DIL)	A type of IC packaging which consists of two parallel rows of pins extending perpendicularly from a black rectangular plastic housing
duty cycle	The percentage of the period of a rectangular waveform during which the waveform is at the higher voltage level
electrical signal	A voltage or current that carries information
electromagnetic waves	A group of energy waves which includes visible light and infrared
electromechanical relay	A mechanical switch that is opened and closed by a current
electromotive force (e.m.f.)	The work done by a source in driving a unit charge around a circuit
electronic test equipment	A set of equipment used to test and troubleshoot electronic circuits
emitter	One of three terminals of a BJT (in NPN BJTs, current will flow from the collector terminal to this terminal)
emitter follower	*See* **common collector (CC) configuration**
energy efficiency	The percentage of input energy which is converted into useful energy
engineering design process	A set of steps which engineers take to design, build and test a working system

farad	The SI unit of capacitance
fixed resistor	A resistor with fixed resistance
floating output	An undesirable condition where the output terminal of a logic switch is left unconnected
'flyback' or 'flywheel' diode	A reverse-biased diode connected in parallel with an inductive device (e.g., a motor or relay) to prevent a voltage spike from damaging the transistors in a circuit
forward-biased	The mode of a diode when its anode is connected to the positive terminal of a source and its cathode is connected to the negative terminal
forward voltage	The voltage drop across a diode when it is forward-biased
frequency	The number of complete waveforms produced in one second
full-wave rectifier	A rectifier that converts the negative half of an AC input voltage into a positive voltage
Gantt chart	A horizontal bar chart commonly used to manage the timeline of a project
ground	A reference voltage which represents 0 V
half-wave rectifier	A rectifier that removes the negative half of an input AC voltage
heating effect of current	The production of heat when a current flows through a conductor
hertz	The SI unit of frequency
ideal diode	A model that treats a forward-biased diode as a perfect conductor and a reverse-biased diode as a perfect insulator
infrared (IR) diode	An LED that emits infrared rays
input	The information or energy that goes into a system
input transducer	A device that converts non-electrical information or quantities into electrical signals or quantities
integrated circuit (IC)	A miniature electronic circuit formed on a very small piece of semiconductor material
intermediate signal	A signal that comes after the inputs but before the output
inverting input	One of two analogue inputs of a voltage comparator; the output of the

	comparator will be LOW if the voltage of this input is higher than that of the non-inverting input
Karnaugh map (K-map)	A graphical method used to simplify a Boolean expression
Kirchhoff's current law (KCL)	A law stating that the algebraic sum of all the currents entering and leaving a node is equal to zero
Kirchhoff's voltage law (KVL)	A law stating that the algebraic sum of all the voltages within a closed loop is zero
knee voltage	The minimum forward voltage needed for a current to flow freely through a practical diode
least significant bit (LSB)	The bit in a binary number with the lowest place value
light-dependent resistor (LDR)	A resistor whose resistance changes with the intensity of light that falls on it
light-emitting diode (LED)	A special type of diode that gives off light
LM311 voltage comparator IC	An 8-pin IC with a single voltage comparator
load	A component that converts the electrical energy supplied by a source into other forms of energy
logic gate	A digital system with one logic output and at least one logic input
logic operation	The decision-making process performed by a logic gate or combinational logic circuit
looping	One of the steps in the Karnaugh map where the '1's in the map are grouped into sets of 1, 2, 4 and 8
loudspeaker	An output transducer that converts electrical signals into sound energy
maximum average forward current	The maximum average current that can flow through a diode without damaging it
maximum working voltage (of a capacitor)	The maximum voltage that should be applied across a capacitor to avoid damaging it
microphone	An input transducer that converts sound energy into electrical signals

monostable multivibrator	A timing device that produces a single pulse of a specific duration after being activated
most significant bit (MSB)	The bit in a binary number with the highest place value
motor	An output transducer that converts electrical energy into mechanical energy
NAND gate	A logic gate that performs the NAND operation, which gives an output of 0 only when both inputs are 1
negative temperature coefficient (NTC) thermistor	A thermistor whose resistance decreases with temperature
node	A junction in a circuit where currents meet
non-inverting input	One of two analogue inputs of a voltage comparator; the output of the comparator will be HIGH if the voltage of this input is higher than that of the inverting input
non-ohmic conductor	A conductor that does not obey Ohm's law
non-periodic	A term used to describe a waveform which does not repeat itself at regular intervals
non-polarised capacitor	A type of capacitor with no fixed polarity
NOR gate	A logic gate that performs the NOR operation, which gives an output of 0 when one or both of the inputs are 1
NOT gate	A logic gate that performs the NOT operation, which inverts an input to the opposite state
NPN BJT	A BJT that consists of a thin layer of p-type semiconductor sandwiched between two thicker layers of n-type semiconductor
n-type semiconductor	A semiconductor that relies primarily on negative charges to conduct electricity
ohm	The SI unit for resistance
Ohm's law	A law stating that the current flowing through a metallic conductor is directly proportional to the potential difference across the conductor, provided the physical conditions remain constant

ohmic conductor	A conductor that obeys Ohm's law
open circuit	A broken electrical path
OR gate	A logic gate that performs the OR operation, which gives an output of 1 when one or both of the inputs are 1
output	The information or energy that goes out of a system
output transducer	A device that converts electrical signals or quantities into non-electrical information or quantities
overloading	An event that occurs when the current through a wire or component exceeds the current rating
parallel circuit	A circuit where the components are connected to form two or more paths
peak repetitive reverse voltage	The maximum reverse voltage that should be applied across a diode
peak-to-peak voltage	The voltage measured from the lowest to the highest point of a waveform
peak voltage	The voltage measured from the DC level to the highest point of a waveform
percentage tolerance	The percentage value by which the actual resistance of a resistor may be higher or lower than the indicated value
period	The time taken to produce one cycle of the waveform
periodic	A term used to describe a waveform which repeats itself at regular intervals
photodiode	A diode that allows a current to pass through easily in the reverse direction when it is exposed to infrared
physical quantity	A quantity that can be measured
place value	The value assigned to the position of a digit in a number
PN junction	The junction between the n-type and p-type semiconductors that form a semiconductor diode
PN junction diode	*See* **semiconductor diode**
PNP BJT	A BJT that consists of a thin layer of n-type semiconductor sandwiched between two thicker layers of p-type semiconductor
polarised capacitor	A type of capacitor with fixed polarity

polarity	A term referring to the positive and negative terminals of a component
positive temperature coefficient (PTC) thermistor	A thermistor whose resistance increases with temperature
potential difference (p.d.)	The work done in driving a unit charge through the component
power	The rate of energy conversion
power rating	The maximum power at which a component can be used without being damaged
practical diode	A real-life diode
precedence	The order in which the tasks of a project should be carried out
prefix	A term placed before a unit to make it smaller or bigger
process	The action performed by a system on an input to turn it into an output
p-type semiconductors	A semiconductor that relies primarily on positive charges to conduct electricity
'pull-down' resistor	A resistor that 'pulls' the output of a logic switch to logic 0 when the switch is open
'pull-up' resistor	A resistor that 'pulls' the output of a logic switch to logic 1 when the switch is open
RC circuit	A circuit that consists of at least one resistor and capacitor
rectification	The process of converting an AC to a DC
rectifier	A circuit that converts an AC to a DC
reference voltage	The voltage at a point of a circuit that the voltages at other points take reference from
resistance	A measure of how difficult it is for a current to flow through a component
resistivity	The property of a material that affects how well it conducts electricity
resistor	A component that provides resistance
reverse-biased	The mode of a diode when its anode is connected to the negative terminal of a source and its cathode is connected to the positive terminal

reverse leakage current	The small reverse current that flows through a practical diode when it is reverse-biased
saturated region	The BJT operating region where the collector current reaches a maximum value and the collector-emitter voltage is close to zero
schematic diagram	*See* **circuit diagram**
scientific notation	A way of representing quantities in the form of $M \times 10^N$
semiconductor	A material with an electrical conductivity that lies between that of an electrical conductor and an insulator
semiconductor diode	A two-terminal component formed by joining an n-type and a p-type semiconductor; it allows current to flow easily in one direction only
series circuit	A circuit where the components are connected to form a single path
series-parallel circuit	A circuit with a combination of series and parallel connections
Set-Reset (S-R) latch	A digital circuit that can store a logic state (0 or 1)
short circuit	A low-resistance electrical path that is usually undesirable and harmful
simplified diode model	A model that consists of an ideal diode connected in series with a battery which represents the forward voltage of a practical diode
single-pole-double-throw (SPDT) switch	A three-terminal switch which is used to change the path of a current in a circuit
single-pole-single-throw (SPST) switch	A two-terminal switch which is used to open and close a circuit
soldering	The process of melting a metallic alloy (known as a solder) and allowing it to solidify to form an electrical connection
source	A device that provides an electromotive force for current to flow in a circuit
subsystem	A system within a bigger system that takes in input from another subsystem or provides input to another subsystem or both
sum-of-product (SOP)	A form of Boolean expression where two or more AND terms are ORed together
system	A collection of parts that work together to perform one or more functions
thermistor	A resistor whose resistance changes with temperature

time constant	The value that determines the charging and discharging time of a capacitor in an RC circuit
timing diagram	A diagram that shows how the output of a digital system changes with time
transducer	A device that converts information or quantities from non-electrical to electrical form, or vice versa
troubleshooting	The process of finding and correcting the faults in an electronic system
truth table	A table which shows the outputs of a logic gate or combinational logic circuit for all possible input combinations
universal gate	A logic gate that can be used to implement other logic gates
variable resistor	A resistor with an adjustable resistance
volt	The SI unit for electromotive force, potential difference and voltage
voltage	A general term used in place of electromotive force and potential difference
voltage comparator	A device that compares the voltage levels of two analogue signals and produces a digital output signal based on the comparison
voltage-divider bias	A way of biasing a BJT in which the base is connected to a voltage divider formed by two resistors, the collector is connected to a positive voltage supply through a resistor and the emitter is connected to the ground through a resistor
voltage-divider formula	A formula that is used to calculate the voltages across resistors connected in series
voltage gain	The ratio of the peak voltage of the output signal to that of the input signal
voltage-smoothing capacitor	A capacitor that is used to reduce the extent to which a voltage varies
watt	The SI unit of power
waveform	A graphical representation of how a current or voltage changes with time
wire-wound resistor	A type of resistor in which the resistance is provided by a length of resistive wire wound around an insulating cylinder
Zener diode	A diode that is designed to operate in its breakdown region; when operating in this region, the voltage across it will be held constant

ANSWERS FOR REVIEW QUESTIONS

Review Questions 1.1

1. Input, process and output

2. A subsystem is a system that is part of a larger system. It provides input to or obtains input from another subsystem, or both.

3. Public address system

   microphone (input) → amplifier (process) → loudspeaker (output)

   Automatic cooling system

   temperature sensor (input) → switch (process) → cooling fan (output)

Review Question 1.2

1. Block diagrams and circuit diagrams

   Block diagrams are made up of blocks, which represent the subsystems, and arrows, which show the flow of information.

   Circuit diagrams are drawn using standard symbols to show how the components are connected together.

Review Questions 1.3

1. Information from the surroundings is converted into electronic signals by input transducers. After the signals have been processed by the system, they are converted back into non-electrical quantities by output transducers.

2. Analogue signals vary continuously over time while digital signals only vary in steps.

Review Questions 2.2

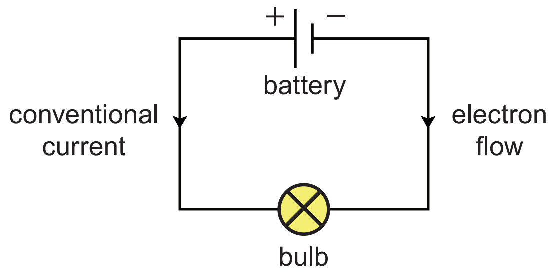
1. (a) $6.8 \times 10^{6}\ \Omega$

   (b) 1.22×10^{-3} A

2. (a) 47 kΩ

   (b) 26 mA

Review Questions 2.3

1. 

2. 1.0 C

3. 4.2 A

Review Question 2.4

1. (a) 1.5 V
   (b) 10.5 V

Review Questions 2.5

1. (a) Obeys Ohm's law as the I-V graph is a straight line through the origin
   (b) Does not obey Ohm's law as the I-V graph is not a straight line through the origin

2. (a) 0.67 A
   (b) The current will be halved since the resistance is doubled.

3. (a) 3.0 V
   (b) 12 V

Review Questions 2.6

1. Hair dryer: 920 W
   Computer: 180 W
   Microwave oven: 690 W

2. (a) 6.0 V
   (b) 0.90 W
   (c) 45 J

3. (a) 70 MJ
   (b) 93%

Review Questions 3.1

1. 3.3×10^{-7} m^2

2. This is not a good practice as the resistivity of nichrome is higher than that of copper. This will cause the wire to have a higher resistance.

3. The resistance of the connecting wires should be as low as possible. Using unnecessarily long wires would make the resistance higher than it should be.

Review Questions 3.2

1. 3 A is a large current – this will cause the actual power used by the resistor to be high too. Wire-wound resistors usually have higher power ratings than those of carbon resistors and thus would be a better choice.

2. Rotary potentiometer, trimmer potentiometer and rheostat

Review Questions 3.3

1. (a) Orange, orange, brown, gold
   (b) Brown, black, red, gold

2. 82 Ω ± 5%; 240 kΩ ± 5%

3. 470 Ω

Review Question 3.4

1. (a) 7.5 Ω
   (b) 36 Ω
   (c) 22 Ω
   (d) 710 Ω
   (e) 7.6 Ω
   (f) 7.9 Ω

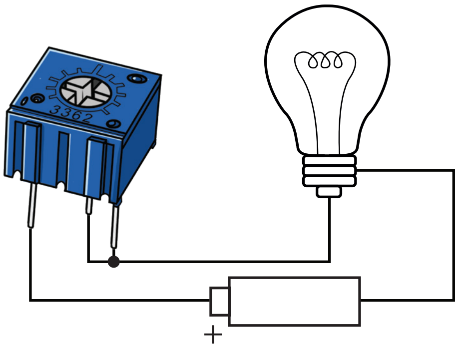
Review Questions 3.5

1. (a) 0.22 W
   (b) 0.5 W (approximately twice as large as the actual power output)

2. (a) 0.10 W
   (b) 0.40 W; 1 W

Review Questions 3.6

1.



2. Connect a 100 Ω fixed resistor in series with a 0–50 Ω variable resistor and adjust the variable resistor until the total resistance is 120.5 Ω.

Review Questions 4.1

1. Battery and power supply unit

2. When the switch is moved to position A, there will be a short circuit.

3. SPST: pushbutton (mini tact) switch, knife switch and plug switch
SPDT: slide switch, pushbutton switch and toggle switch

4. Overloading occurs when a component (e.g., a wire) is made to carry a current larger than what it is designed for. A possible cause of overloading is a short circuit where the resistance in circuit becomes unusually low, thus making the current very large.

Review Question 4.2

1. (a) 5.0 Ω
   (b) 2.0 A
   (c) 2.0 A for both bulbs
   (d) 4.0 V for bulb 1; 6.0 V for bulb 2

Review Question 4.3

1. (a) 10 V for all the resistors
   (b) 5.0 mA for R_1, 3.0 mA for R_2 and 1.0 mA for R_3
   (c) 9.0 mA

Review Question 4.4

1. (a) 550 Ω
   (b) 22 mA
   (c) 10 V
   (d) 1.7 V

Review Questions 4.5

1. $V_1 = 3.0$ V; $V_2 = 6.0$ V
2. $I_1 = 356$ mA; $I_2 = 444$ mA

Review Questions 4.6

1. $I_1 = 7.0$ A; $I_2 = 1.0$ A
2. (a) $E_1 - V_1 - E_2 = 0$; $E_2 - V_2 - V_3 = 0$
   (b) $V_1 = 4.0$ V; $V_3 = 2.4$ V

Review Questions 5.3

1. Sine; rectangular; triangular
2. (a) 10 V
   (b) 20 V
   (c) 20 ms
   (d) 50 Hz
3. (a) 83%
   (b) 18%

Review Questions 6.1

1. A capacitor consists of a layer of insulating material (called a dielectric) sandwiched between two metal plates.
2. During charging, electrons flow from the metal plate connected to the positive terminal of the battery to the metal plate connected to the negative terminal through the battery. During discharging, electrons flow from the metal plate that is negatively charged to the metal plate that is positively charged through the load.

Review Questions 6.2

1. 28 μC

2. 0.13 V

3. (a) 10 V
   (b) 33 mC

Review Questions 6.3

1. Polarised capacitors have two leads of different lengths but non-polarised capacitors have leads of equal length. In general, polarised capacitors are larger than non-polarised capacitors.

2. The best way would be to look for the negative sign labelled on the capacitor, which identifies the negative terminal. Another way would be to compare the lengths of the leads (the longer lead is the positive terminal), provided that the leads have not already been trimmed.

3. 33 pF; 100 pF; 2200 pF or 2.2 nF

Review Question 6.4

1. (a) 690 μF
   (b) 150 μF
   (c) 70 μF

Review Questions 6.5

1. Resistance and capacitance

2. After one time constant, the capacitor will be charged to approximately $\frac{2}{3}$ of the applied voltage. After five time constants, the capacitor can be considered fully charged.

   After one time constant, the capacitor will be discharged to approximately $\frac{1}{3}$ of its initial voltage. After five time constants, the capacitor can be considered fully discharged.

3. (a) 0.68 s
   (b) 0.68 s
   (c) 3.4 s

Review Questions 7.1

1. To increase the conductivity of a pure semiconductor

2. N-type and p-type

3. It is made up of an n-type semiconductor and a p-type semiconductor joined together.

Review Questions 7.2

1. When an ideal diode is forward-biased, it acts as a closed switch and there is no voltage drop across it. When a practical diode is forward-biased, there is a voltage drop across it (around 0.7 V for silicon diodes).

   When an ideal diode is reverse-biased, it acts as an open circuit and no current is allowed to flow through. When a practical diode is reverse-biased, there is still a small leakage current flowing through the diode.

2. Forward-biased; reverse-biased

3. The forward voltage tells us the voltage drop across a diode when it is forward-biased.

   The maximum forward current tells us the maximum current that should be allowed to flow through the diode to avoid damaging it.

   The maximum reverse voltage tells us the maximum voltage that should be applied across a reverse-biased diode to avoid damaging it.

Review Questions 7.3

1. The ideal diode does not have any voltage drop across it when it is forward-biased. However, the simplified diode model has a voltage drop of V_F across it when it is forward-biased.

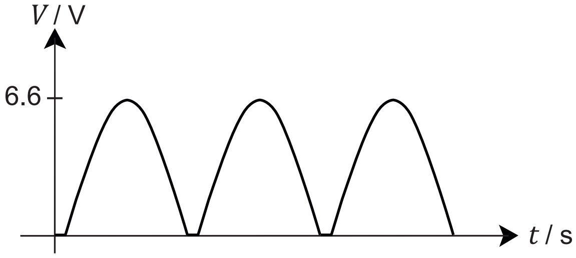
   The ideal diode will be turned on as long as it is forward-biased. The simplified diode model requires the diode to be forward-biased and the voltage of the source to be higher than V_F in order to turn on the diode.

2. 8.3 mA

Review Questions 7.4

1. (See Figure 7.25 and Figure 7.31 respectively for the circuit diagrams of a half-wave and a full-wave rectifier)

2.



Review Question 7.5

1. (a) The resistor acts as a current-limiting resistor to prevent an overly large current from damaging the LEDs.

   (b) 18 mA

Review Questions 7.6

1. Segments *a*, *b*, *c*, *d* and *g*

2. Segments *a*, *c*, *d*, *f* and *g*: 0 V
   Segments *b*, *e* and *dp*: 5 V

Review Questions 7.7

1. (a) 3.6 V

   (b) 5.1 V

2. (a) 0 W

   (b) 26 mW

Review Questions 8.1

1. Input transducers convert non-electrical information or quantities into electrical signals or quantities.

   Output transducers convert electrical signals or quantities into non-electrical information or quantities.

2. Thermistor – converts temperature into electrical signals
   Light-dependent resistor – converts light intensity into electrical signals
   Microphone – converts sound energy into electrical signals

3. LED – converts electrical energy into light energy
   Buzzer – converts electrical signals into sound energy
   Motor – converts electrical energy into mechanical energy

Review Questions 8.2

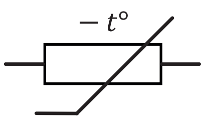
1. When the temperature increases, the resistance of the thermistor decreases. According to $V_{out} = \dfrac{R_{TH}}{R_1 + R_{TH}} \times E$, the output voltage will also decrease.
2. 660 Ω

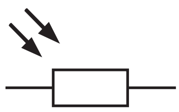
Review Questions 8.3

1. 800 Ω
2. When the brightness of the surroundings decreases, the resistance of the LDR increases. According to $V_{out} = \dfrac{R_{LDR}}{R_1 + R_{LDR}} \times E$, the output voltage will also increase.

Review Questions 8.4

1. (a) Converts temperature into electrical signals
   (b) Converts light intensity into electrical signals
   (c) Converts sound energy into electrical signals
   (d) Converts electrical signals into sound energy
   (e) Converts electrical signals into sound energy
   (f) Converts electrical energy into mechanical energy

2. (a)


(b)


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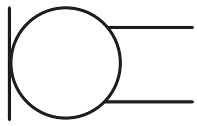

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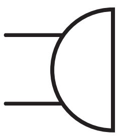

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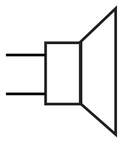

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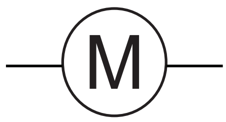


3. (a) LDR
   (b) Thermistor
   (c) Buzzer or loudspeaker
   (d) Relay

Review Questions 9.1

1. Base, emitter and collector

2. (See Figure 9.5)

3. We should refer to the datasheet of the BJT in order to correctly identify the terminals of a BJT.

Review Questions 9.2

1. A small current flowing into or out of the base controls a larger current flowing between the collector and emitter.

2. Cutoff, active and saturation

3. $I_E = I_B + I_C$

Review Question 9.3

1. R_B < 13 kΩ (e.g., 10 kΩ)

Review Question 9.4

1. (a) 2.53 V
   (b) 1.83 V
   (c) 1.53 mA
   (d) 1.53 mA
   (e) 3.95 V
   (f) 2.12 V
   (g) 2.75

Review Questions 9.5

1. CE amplifier: input is applied at B, output is taken from C
   CB amplifier: input is applied at E, output is taken from C
   CC amplifier: input is applied at B, output is taken from E

2. It is able to drive a low-resistance load.

Review Question 9.6

1. Figure 9.35: the base current is insufficient to drive the BJT into the saturation region

   Figure 9.36: the base current is sufficient to drive the Darlington pair into the saturation region

Review Questions 10.1

1. (a) Digital
   (b) Analogue
   (c) Analogue

2. Analogue signals vary continuously over time while digital signals can only vary in steps.

3. Logic 1 (or HIGH) and logic 0 (or LOW)

Review Questions 10.2

1. (See Figure 10.6 and Figure 10.7 for a logic switch which uses a ‘pull-up’ resistor and a logic switch which uses a ‘pull-down’ resistor, respectively)

2. Without a ‘pull-up’ or ‘pull-down’ resistor, the output terminal will be ‘floating’ when the switch is open.

Review Question 10.3

1. Compared to analogue systems,
   - digital systems are less affected by electrical interference;
   - digital signals can be easily restored to their original conditions;
   - digital systems are easier to design;
   - digital information is easier to store; and
   - digital systems cost less.

Review Questions 10.4

1. (a) ④296, place value = 10^3
   (b) ①0111, place value = 2^5

2. (a) 150_{10}
   (b) $101\ 0011_2$
   (c) $0100\ 0101_{BCD}$
   (d) 8369_{10}

3. Advantage: easier to convert between decimal and BCD than between decimal and binary

   Disadvantage: requires more bits to store the same value

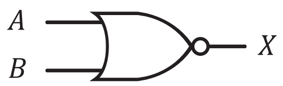
4. 1111101

Review Question 11.1

1. 8

Review Questions 11.2

(a)



$X = \overline{A + B}$

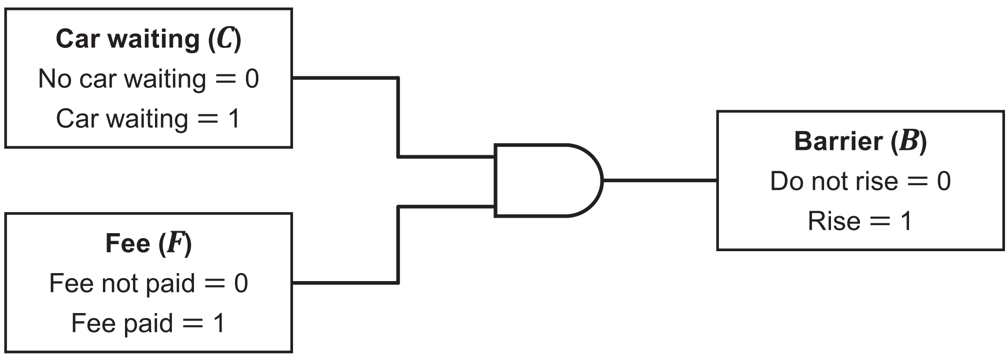
(b) Case 1

(a) Let the inputs be 'Car waiting' and 'Fee'. Let the output be 'Barrier'.

(b)

Car waiting (C) No car waiting = 0 Car waiting = 1	**Fee (F)** Fee not paid = 0 Fee paid = 1	**Barrier (B)** Do not rise = 0 Rise = 1
0	0	0
0	1	0
1	0	0
1	1	1

(c)



(d) $B = C \cdot F$

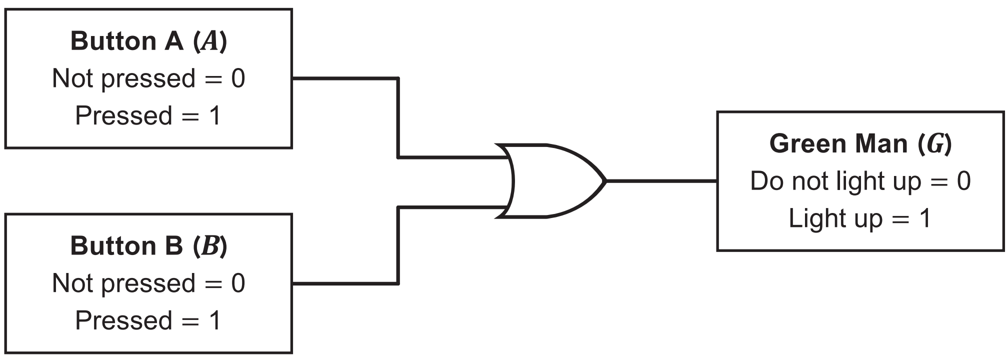
<u>Case 2</u>

(a) Let the inputs be 'Button A' and 'Button B', which are on opposite sides of the road, and let the output be 'Green Man'.

(b)

Button A (A) Not pressed = 0 Pressed = 1	Button B (B) Not pressed = 0 Pressed = 1	Green man (G) Do not light up = 0 Light up = 1
0	0	0
0	1	1
1	0	1
1	1	1

(c)

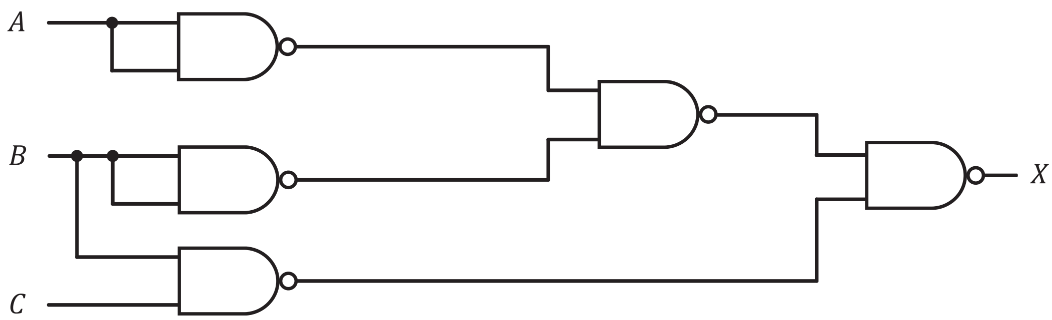


(d) $G = A + B$

Review Questions 11.3

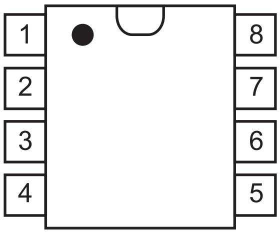
1. Universal gates are logic gates that can be used to implement other logic gates on their own.

2.



Review Questions 11.4

1. They differ in terms of their dimensions and mounting type.

2. 

3. 1, 2, 3 or 4, 5, 6 or 9, 10, 8 or 12, 13, 11

Review Questions 12.1

1.

A	***B***	***C***	***X***
0	0	1	1
0	1	1	0
1	0	0	1
1	1	0	1

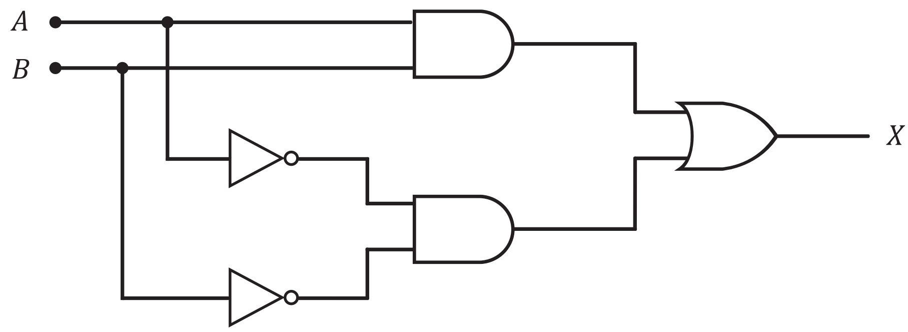
D	***E***	***F***	***G***	***H***	***Z***
0	0	0	1	0	0
0	0	1	1	0	0
0	1	0	1	0	0
0	1	1	1	1	0
1	0	0	0	0	1
1	0	1	0	0	1
1	1	0	0	0	1
1	1	1	0	1	0

2. It is a form of Boolean expression where the AND terms are ORed together.

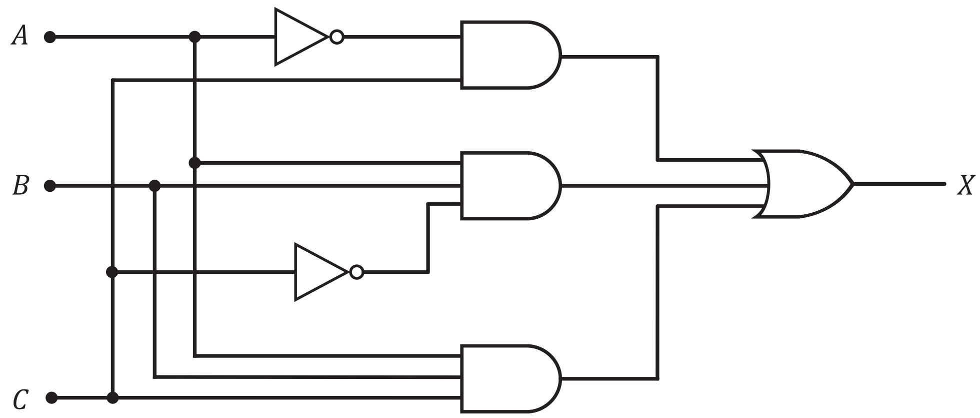
3. $X = \bar{A} \cdot \bar{B} + A \cdot \bar{B} + A \cdot B$
$Z = D \cdot \bar{E} \cdot \bar{F} + D \cdot \bar{E} \cdot F + D \cdot E \cdot \bar{F}$

Review Question 12.2

1. (a)



(b)



Review Questions 12.3

1. $X = A \cdot \bar{B} + \bar{A} \cdot C$

2. $X = B$

Review Questions 12.4

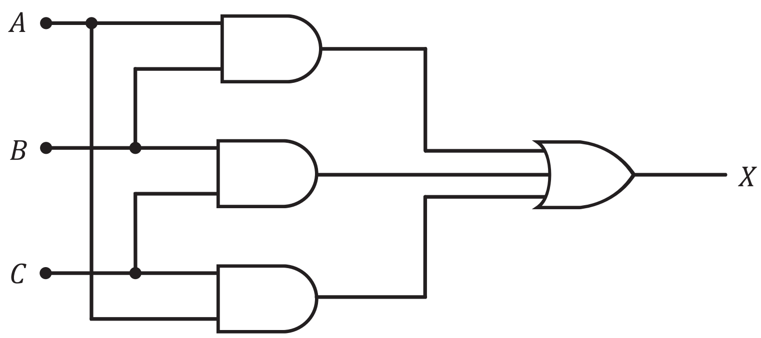
1. $X = A \cdot \bar{B} + \bar{A} \cdot C$

2. (a) $X = B$

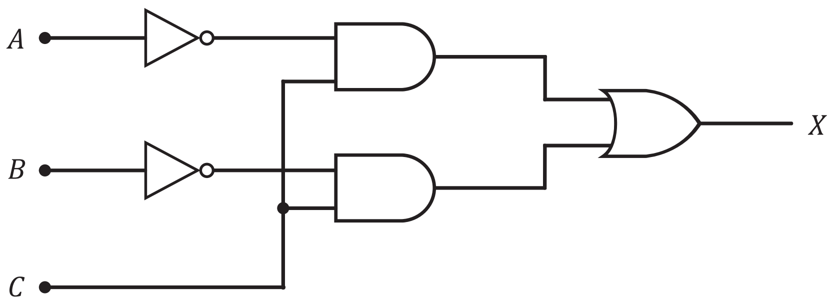
   (b) $X = A \cdot B$

Review Questions 12.5

1.



2.

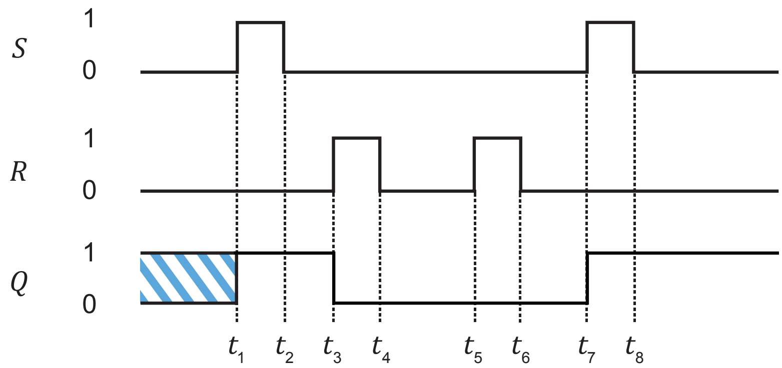


Review Question 13.1

1. (See Figure 13.5)

Review Questions 13.2

1. $S = 0$; $R = 1$
2. $S = 0$; $R = 0$
3.



Review Questions 13.3

1. S-R latch
2. When the pushbutton switch of a lamp is pushed, the lamp will turn on and remain on even after the switch is released.

Review Questions 13.4

1. When a mechanical switch is used as a logic switch, there will be multiple transitions between the HIGH and LOW states when the switch is opened and closed. A debounced switch will remove these multiple transitions and produce only a single transition.
2. (See Figure 13.16)

Review Questions 14.1

1. When the voltage at pin 2 is higher than that of pin 3, the output at pin 7 will be HIGH. When the voltage at pin 2 is lower than that of pin 3, the output at pin 7 will be LOW.

2. When the temperature increases, the resistance of R_{TH} decreases. This causes the voltage across R_1 to increase. When this voltage exceeds 2.5 V, the output will be LOW and the buzzer will sound.

Review Questions 14.2A

1. (See Figure 14.18)

2. C_1 = 100 μF and R_1 = 27 kΩ (Use a 22 kΩ fixed resistor in series with a 0–10 kΩ variable resistor or any other valid combination)

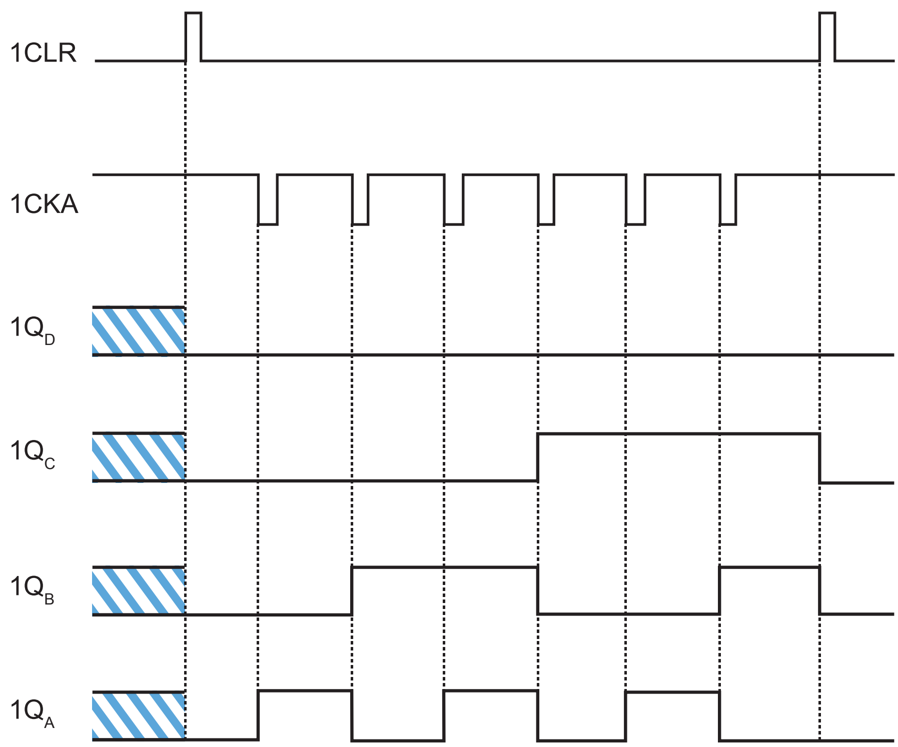
Review Questions 14.2B

1. (See Figure 14.22)

2. 220 ms

Review Question 14.3

1.

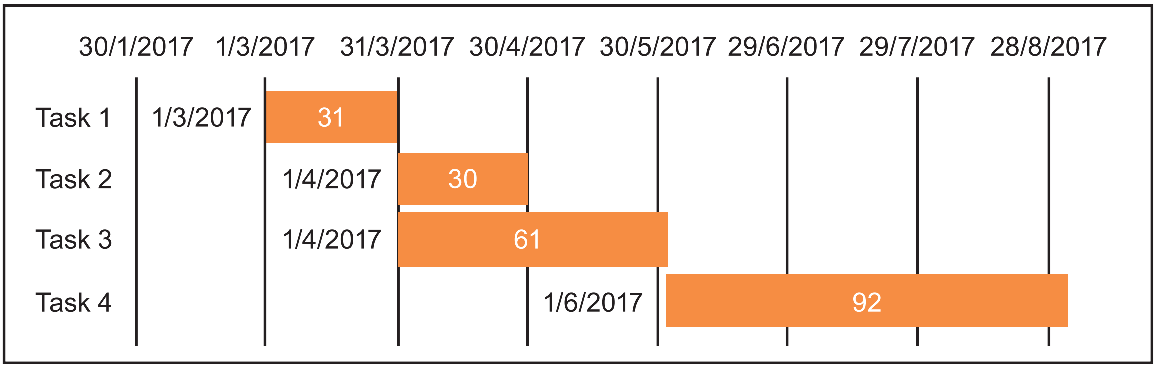


Review Question 15.1

1. • Define problem – describe the problem clearly
   • Specify requirements – describe what an electronic system should be able to do
   • Research – find the information needed to solve the problem
   • Develop and evaluate possible solutions – find out if a solution works and determine the best solution from a few possible solutions
   • Design – draw the circuit diagram based on the results of the research and evaluation steps
   • Build – construct a circuit using one type of circuit board
   • Test – use test equipment and observations to find out if the circuit performs according to the design
   • Troubleshoot – find and correct faults in an electronic system
   • Communicate – report on the work done

Review Question 15.2

1.



Review Question 15.3

1. Circuit simulation software helps to save costs and time as there is no need to build the actual circuit. However, the software is not able to simulate certain conditions such as changes in temperature.

Review Question 15.4

1. PSU – provides a reliable DC voltage

   Digital multimeter – measures electrical quantities such as voltage, current and resistance

   Function generator – supplies periodic signals

   Digital storage oscilloscope – allows us to observe how the voltages at different points of a circuit change with time

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