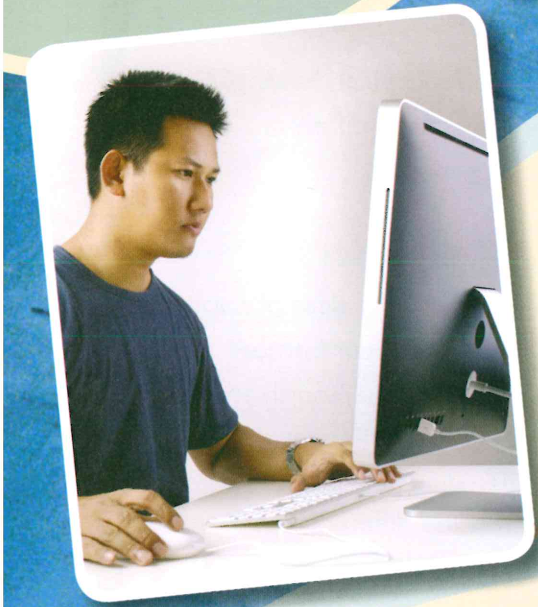
WorkSpace

Steven Wu

Technician, NJT Engineering



NJT Engineering is a small engineering company that employs six people in a small purpose-built industrial unit. Its undertakes small one-off contracts for the local commercial sector and community. Some customers call in to describe to the owner what they want, but most produce a simple sketch of the product they require.

When a medium-sized company transferred its production base overseas, NJT saw an opportunity to expand its business by filling this gap.

However, NJT's owner realised that new customers would require more than just a simple sketch on a rough piece of paper. They would want a formal drawing showing what they had ordered from NJT.

NJT doesn't have a drawing office and doesn't employ a draughtsperson. The company had not produced formal drawings before and it looked as if the chance to expand might be lost. Fortunately, one of the staff, Steven Wu, is a confident CAD user so the owner decided to invest in a standalone CAD system and A3 laser printer.

Steven has now added the role of draughtsperson to his varied list of duties at NJT and he finds the opportunity to spend some of his time in the office a welcome change.

Last week, the owner asked Steven if it would be possible to find a local company that could print off A0 size drawings as the latest job NJT has tendered for requires scaled drawing on large format paper. At the moment, Steven is still working on it.

Think about it!

1 Why might customers want formal drawings rather than simple sketches?

2 What would NJT's options have been if Steven had not had good CAD skills?

3 Would any of these options have had an impact on the local economy?

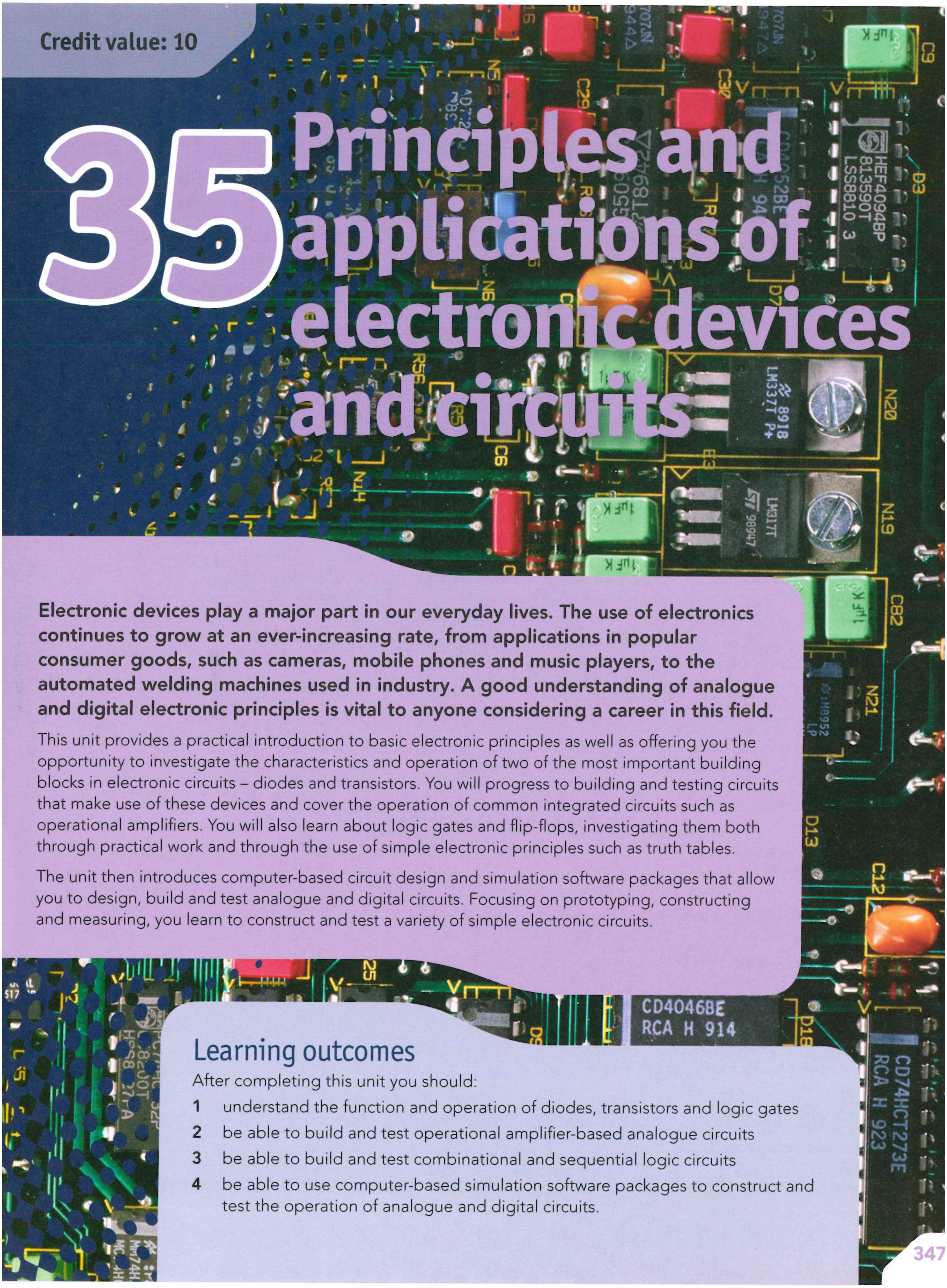
Just checking

1 Why are sketches sometimes used in preference to professionally produced technical drawings?
2 How do drawings of the same object produced in cavalier and cabinet projections differ?
3 Which type of drawing uses construction lines that are angled at 30° to horizontal?
4 What does the prefix 'ortho-' refer to?
5 List five pieces of information that should appear in the title block of a drawing.
6 Which paper size has the larger area – A4 or A3? Give the size in millimetres of both sizes of paper.
7 How many millimetres in from the edges of your drawing paper should you draw your border?
8 Which two of the these combinations of orthographic projections should you use: (a) fourth and first; (b) third and first; (c) second and first; (d) third and fourth; (e) fourth and second?
9 In a CAD drawing, what is the effect of turning the snap option on or off?
10 With respect to polygons and the circles used in their construction, what is the difference between a circumscribed and an inscribed polygon?
11 When modifying a CAD drawing, how does a chamfer differ from a fillet?
12 How does a sketch differ from a technical drawing?
13 Which of these scaling factors should *not* be used (a) 1:2; (b) 1:5; (c) 1:2.5; (d) 2:1; (e) 5:1; (f) 5.2:1?

edexcel

Assignment tips

- Learning outcome 1 requires you to produce a series of sketches and explain their benefits and limitations. As well as giving an accurate impression of the object you are sketching, make sure that the sketch is a good size. Don't produce a sketch the size of a postage stamp in the middle of a sheet of A4 paper. When discussing benefits and limitations, avoid phrases such as 'It's quick' or 'It's easy'. If you find a particular method easy, you need to explain why.
- Learning outcomes 3 and 4 require you to produce engineering drawings using both traditional (drawing board) and CAD methods. You may have limited time in your centre's drawing room or CAD suite. You should plan ahead to avoid wasting time and to reduce the amount of rework needed to correct errors. Where possible, decide well in advance what it is you are to draw and carry out some preliminary work outside the taught drawing sessions. Decide where to position the starting point(s) for your drawings, so that when you commence your actual assignment you can be sure that the drawing will fit the paper.
- The only assignments requiring written answers are those for P2, M1, M2 and D1. The tasks you will be set for M1 and M2 give you the opportunity to explain what you have learned about engineering drawing. D1 gives you the opportunity to express your opinions by evaluating the various methods of producing engineering drawings.



Credit value: 10

35

Principles and applications of electronic devices and circuits

Electronic devices play a major part in our everyday lives. The use of electronics continues to grow at an ever-increasing rate, from applications in popular consumer goods, such as cameras, mobile phones and music players, to the automated welding machines used in industry. A good understanding of analogue and digital electronic principles is vital to anyone considering a career in this field.

This unit provides a practical introduction to basic electronic principles as well as offering you the opportunity to investigate the characteristics and operation of two of the most important building blocks in electronic circuits – diodes and transistors. You will progress to building and testing circuits that make use of these devices and cover the operation of common integrated circuits such as operational amplifiers. You will also learn about logic gates and flip-flops, investigating them both through practical work and through the use of simple electronic principles such as truth tables.

The unit then introduces computer-based circuit design and simulation software packages that allow you to design, build and test analogue and digital circuits. Focusing on prototyping, constructing and measuring, you learn to construct and test a variety of simple electronic circuits.

Learning outcomes

After completing this unit you should:

1. understand the function and operation of diodes, transistors and logic gates
2. be able to build and test operational amplifier-based analogue circuits
3. be able to build and test combinational and sequential logic circuits
4. be able to use computer-based simulation software packages to construct and test the operation of analogue and digital circuits.

Assessment and grading criteria

This table shows you what you must do in order to achieve a pass, merit or distinction grade, and where you can find activities in this book to help you produce the required evidence.

To achieve a **pass grade** the evidence must show that you are able to:	To achieve a **merit grade** the evidence must show that, in addition to the pass criteria, you are able to:	To achieve a **distinction grade** the evidence must show that, in addition to the pass and merit criteria, you are able to:
P1 explain the purpose of two different types of diode, each in a different electronic circuit application **Assessment activity 35.1 page 364**	**M1** modify an existing analogue circuit to achieve a given revised specification by selecting and changing the value of one of the components **Assessment activity 35.1 page 364**	**D1** using a simulation package, analyse the effects of changing the values of circuit parameters on the performance of an analogue circuit containing an operational amplifier or transistors **Assessment activity 35.3 page 373**
P2 explain the operation of two different types of transistor, one in an analogue and one in a digital circuit **Assessment activity 35.1 page 364**	**M2** modify a digital circuit to achieve a given revised specification by selecting and changing up to two logic gates **Assessment activity 35.2 page 371**	**D2** compare and contrast two different types of logic family with reference to five characteristics **Assessment activity 35.2 page 371**
P3 explain the operation of three different logic gates with appropriate gate symbols, truth tables and Boolean expressions **Assessment activity 35.2 page 371**	**M3** evaluate and minimise a three-input combinational logic circuit containing three gates **Assessment activity 35.2 page 371**	
P4 build and test two different types of analogue circuit using operational amplifiers **Assessment activity 35.1 page 364**		
P5 build and test a combinational logic circuit that has three input variables **Assessment activity 35.2 page 371**		
P6 build and test a sequential circuit using integrated circuit(s) **Assessment activity 35.2 page 371**		
P7 use a computer software package to simulate the construction and testing of an analogue circuit with three different types of components **Assessment activity 35.3 page 373**		

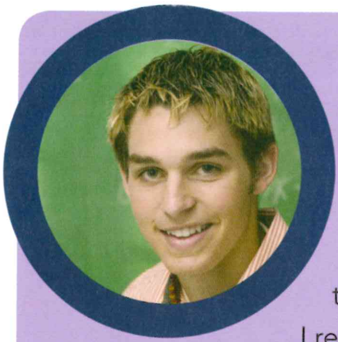
P8 use a computer software package to simulate the construction and testing of a digital logic circuit with three gates **Assessment activity 35.3** **page 373**		

How you will be assessed

This unit will be assessed by a series of assignments designed to allow you to show your understanding of the unit outcomes. One assignment may focus on analogue circuits and logic circuits, where you may construct, test and modify a variety of circuits. You may be required to explain the purpose and operation of the components in these circuits, and compare and contrast different types of components. You may also demonstrate your skills in using simulation software to construct and test both analogue and digital circuits, and to analyse the effect of changing circuit parameter values.

Overall, your assessment will be in the form of:

- **practical tasks**
- **written assignments**
- **oral questioning.**



Jack, 17-year-old electrical apprentice

Working through this unit made me understand that there is a lot more to electronic devices than I had ever realised. It also made me think more about the electronic gadgets I use every day.

I really enjoyed studying this unit because it involved practical work. It is exciting designing and then building an electronic circuit, and getting it to work, especially as you can't see electricity! Learning theory and using simulation software is interesting too, but being able to build a circuit and show that it really does what it is supposed to do gave me a great sense of achievement. It was especially satisfying to change some of the components and see the circuit perform exactly how I predicted it would. This is the bit I enjoyed most.

Learning how the digital gates and circuits worked was quite strange at first, because I had to learn to think in a different way. However, once I'd begun to understand it everything just seemed so obvious. I guess that's why it's called logic.

35.1 Understand the function and operation of diodes, transistors and logic gates

Start up

Analogue or digital?

Think about the various electrical and electronic gadgets you see around you in your home. Focus on the devices you use every day. Write down the names of the six gadgets that you use most frequently.

Divide your list into two groups; those gadgets that you think use analogue circuits and those that you think use digital circuits. Alongside each device, explain why you think it should be in the analogue or digital list as appropriate.

A circuit can be described as being either analogue or digital. In an analogue circuit, the signal voltage and current levels vary continuously, as in an audio amplifier, but in a digital circuit the signal levels are usually only two-state, that is they are either fully on or fully off, as in a computer. In this unit, you are going study the electronic devices used to build and control both analogue and digital circuits. These devices must have appropriate performance characteristics. The devices used in an analogue circuit must be capable of handling gradual changes in signal level. The devices used in a digital circuit must be able to switch from one state to the other extremely quickly.

35.1.1 Diodes

A diode is a common device that is used in many **electronic circuits**. Very simply, it is an electronic device that only allows current to flow in one direction. It is rather like a one-way valve, but with no physical moving parts. In a circuit diagram, a diode is represented by a symbol that incorporates an arrow (see Figure 35.1). The current flows in the direction indicated by the arrow – no current can flow through the diode in the opposite direction.

Key terms

Electronic circuit a collection of electronic components, such as transistors, diodes, resistors and capacitors, connected together to provide a particular function, such as amplifying a signal.

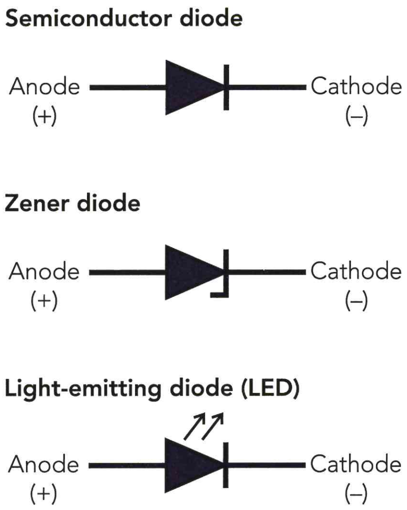


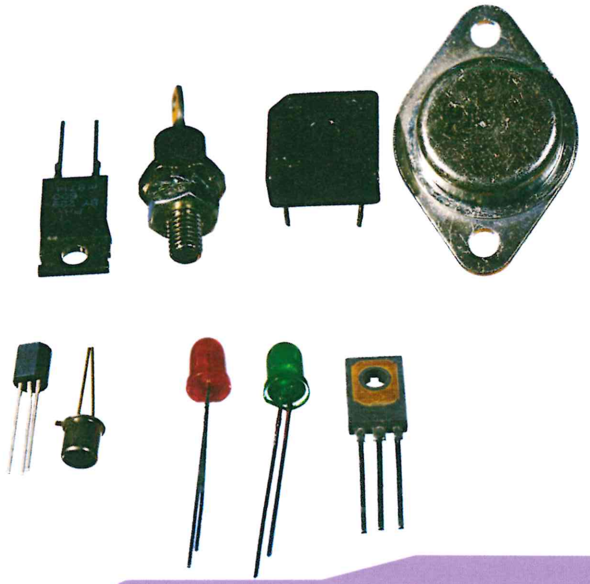
Figure 35.1: Diode symbols

There are various types of diodes designed to do specific jobs. You will be familiar with light-emitting diodes (LEDs). These are commonly used for the on/standby indicator light on TVs, DVD players etc. Unlike a miniature light bulb, which a diode replaces in these applications, an LED has no filament. LEDs only use a very small amount of electrical power to generate light and they are much cheaper to produce than bulbs. They are also available in different colours and sizes.

Diodes are also used in most remote control handsets. The diode uses invisible light to send signals to the appliance that is being controlled by the handset.

Another use for diodes is in a mains adapter, where they rectify alternating current (AC) to produce direct current (DC). Yet another type of diode is used for voltage stabilising: the Zener diode.

Before we look at diodes in some detail, you need to know about the properties of the materials used in their manufacture. This will also be of use when we come to consider transistors later in the unit.



Here is a selection of semi-conductors. Can you spot which are the light-emitting diodes?

Properties of materials used in electronic devices

Materials can be classified as conductors, semiconductors or insulators according to their electrical resistivity. Metals are usually seen as good conductors – that is, they have low electrical resistivity. Table 35.1 lists value of resistivity of some common materials used as conductors, semiconductors or insulators.

Table 35.1: Classification of materials by their resistivity

Classification	Material	Resistivity (at 20°C)
Conductors	Aluminium	$2.82 \times 10^{-8}\,\Omega$ m
	Brass	$8 \times 10^{-8}\,\Omega$ m
	Copper	$1.72 \times 10^{-8}\,\Omega$ m
	Gold	$2.44 \times 10^{-8}\,\Omega$ m
	Mild steel	$15 \times 10^{-8}\,\Omega$ m
	Nickel	$6.99 \times 10^{-8}\,\Omega$ m
	Silver	$1.59 \times 10^{-8}\,\Omega$ m
Semiconductors	Germanium	$4.60 \times 10^{-1}\,\Omega$ m
	Silicon	$6.4 \times 10^{2}\,\Omega$ m
Insulators	Glass	$10^{10}\,\Omega$ m to $10^{14}\,\Omega$ m
	Mica	$\geq 10^{11}\,\Omega$ m
	Paraffin	$10^{17}\,\Omega$ m
	PVC	$\geq 10^{13}\,\Omega$ m
	Rubber	approx. $10^{13}\,\Omega$ m

Germanium and silicon are the most common materials found in the semiconductors used in electronics. Their resistivity reduces as temperature rises, until at a sufficiently high temperature they basically become conductors. Conversely, at very low temperatures (well below room temperature) their resistivity increases to the point at which they become insulators.

A pure semiconductor contains no free electrons. Heating the semiconductor releases a few electrons, allowing for a small current flow. However, a much better way of increasing current flow is to add an impurity to the semiconductor. The process of taking a pure semiconductor and adding tiny amounts of impurities (a few parts per million) is called doping.

Atoms in a semiconductor are normally rigidly bonded together by a four-electron structure. Adding an impurity with a five electron structure causes a free electron to be left over – this electron has nothing to bond to. This is shown in Figure 35.2. An impurity that increases the number of free electrons is called n-type. Arsenic and phosphorus are n-type impurities. A semiconductor doped with an n-type impurity is called an n-type material.

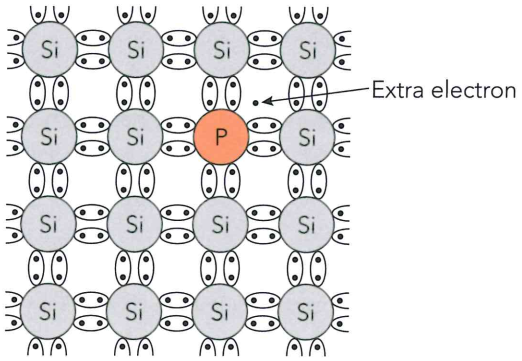


Figure 35.2: Silicon doped with phosphorus (n-type impurity)

Adding an impurity with a three-electron structure, means one semiconductor electron has nothing to bond to. This deficiency is called a hole and is shown in Figure 35.3. A material that creates holes is called a p-type impurity. Aluminium, boron and indium are p-type impurities. When a small amount of these impurities is added to a semiconductor, p-type material is formed.

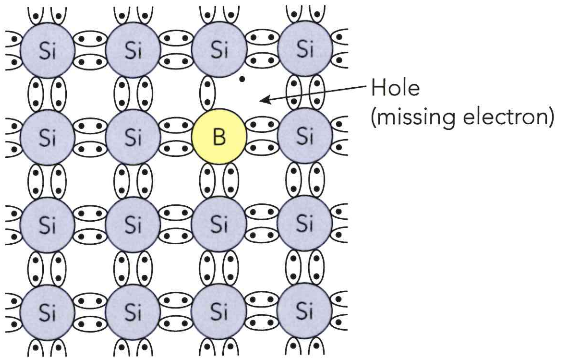


Figure 35.3: Silicon doped with boron (p-type impurity)

Did you know?

When doping introduces spare electrons, the atoms in the impurity are known as pentavalent atoms, meaning they have five valence electrons. The spare electrons are called majority carriers in the n-type material. Trivalent atoms have three valence electrons and create holes called the majority carriers in the p-type material.

The p-n junction

When a piece of p-type semiconductor material is joined to a piece of n-type semiconductor material, a p-n junction is created. If you think of a hole as a positive charge and an electron as a negative charge, it follows that they will be drawn towards each other and will bond together at the junction of the p-type and n-type materials. This forms a stable area called the **depletion layer**. Eventually the movement of holes and electrons stops due to the potential difference that exists across the junction. This is called the **contact potential**.

A diode consists of a sandwich of p-type and n-type material, inside either a glass or moulded container, with connecting leads. In other words a diode is made from a p-n junction, so the simple diode is also known as the p-n junction diode or semiconductor diode. We can see how a diode works by considering what happens when a voltage is applied across a p-n junction.

Key terms

Depletion layer the area at the junction of p-type and n-type material that contains no free electrons or holes because they have all joined together.

Contact potential the voltage that builds up at the p-n junction that stops the movement of electrons and holes across it.

When you apply an external voltage that makes the p-type material positive with respect to the n-type material, the depletion layer is forced closer together and becomes thinner, allowing the holes and electrons to move through the junction again with the result that a current flows. This is shown in Figure 35.4, and this is known as forward bias.

For silicon, approximately 0.7 V forward bias is required to narrow the depletion layer sufficiently to allow current to flow. For germanium, approximately 0.4 V forward bias is required. Increasing the forward bias further results in a rapid rise in current flow and the material becomes a good conductor.

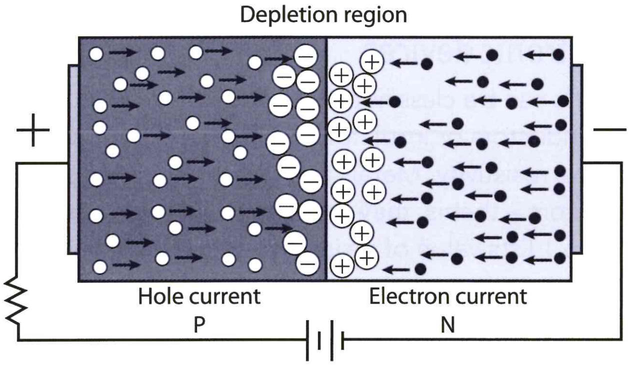


Figure 35.4: Forward bias results in hole and electron movement

When a p-n junction is reverse biased, the external voltage is applied the opposite way round so that the p-type material becomes more negative with respect to the n-type material. This strengthens the depletion layer and no current will flow. This is shown in Figure 35.5.

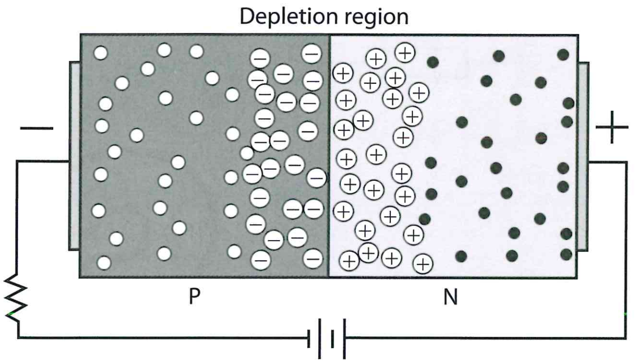


Figure 35.5: Reverse bias widens the depletion region and prevents hole and electron movement

Did you know?

Early radio receivers used a type of crystal diode called the 'cat's whisker' to detect radio signals. It rectified the received signal to provide a DC voltage that could power headphones. The diode was quite big and needed careful adjustment to make it work properly.

Activity: Forward and reverse bias

In pairs or small groups, discuss your understanding of what happens when you apply an external voltage across a p-n junction diode.

With the aid of diagrams, explain in your own words the effect on the depletion layer of applying the external voltage so that:

a) the p-n junction is forward biased

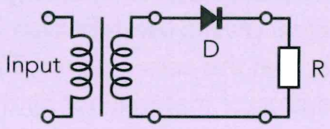
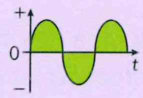
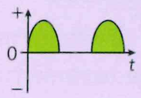
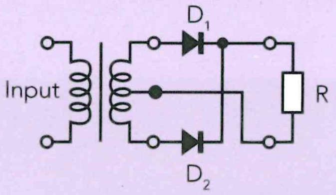
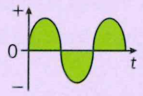
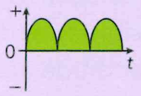
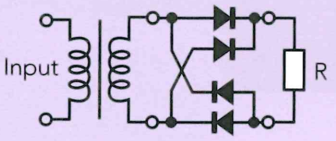
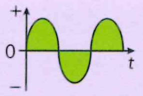
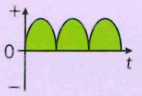
b) the p-n junction is reverse biased.

Discuss how forward and reverse biasing affects how a diode works when it is connected into an electronic circuit.

The diode as a rectifier

You should now have an understanding of how a diode works and why it only allows current to flow in one direction. This property is particularly useful when you want to convert alternating current and voltage

Table 35.2: Simple rectifier circuits

Rectification	Circuit diagram	Input	Output
Half wave (1 diode)			
Full wave (2 diodes)			
Bridge (4 diodes)			

into direct current and voltage. This is the function of a mains adapter. For example, you will have been supplied with a mains adapter for your mobile phone. This is used to charge the battery in the phone. It takes the AC mains supply and changes it to DC supply suitable for charging the battery. This process is called rectification. Table 35.2 shows three simple circuits for achieving different types of rectification, which use one, two and four diodes respectively.

Activity: Rectification

Working in pairs, consider the various reasons why engineers would want to rectify an AC input. List occasions or situations in which an AC input would be rectified. Draw up a table to record your ideas. This should have three columns: one column headed 'usage', one headed 'type of device' and one headed 'example'. List each situation you identify, such as 'to charge batteries', in the usage column, and then specify the type of device that would achieve that purpose and an example of that type of device in the other columns.

Zener diodes

A Zener diode is manufactured in such a way that when the reverse bias voltage is increased, at some point the diode will begin to conduct. The voltage at which a Zener diode begins to conduct when reverse biased depends on the amount of semiconductor doping. Increasing the doping, causes the **breakdown voltage** to drop. By precisely controlling the doping, it is possible to specify the breakdown voltage for a particular diode accurately.

Zener diodes are available with breakdown voltages ranging from 2.7 V to over 150 V. When used in conjunction with a resistor (see Figure 35.6), a Zener diode can be used to provide voltage regulation, helping to maintain a specific voltage output as the current being drawn changes.

Key terms

Breakdown voltage the reverse bias voltage at which a diode begins to conduct. This feature is called the Zener effect, hence the name Zener diode.

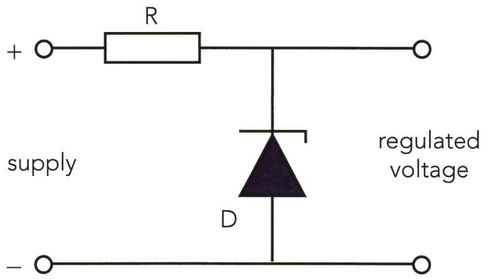


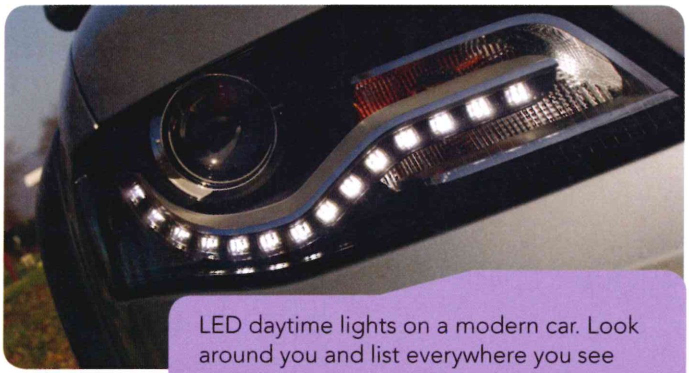
Figure 35.6: A Zener diode used with a resistor as a simple voltage regulator

Light-emitting diodes

A light-emitting diode (LED) consists of a p-n junction formed from a semiconductor material that releases particles of light energy called photons when electrons recombine with holes across the depletion layer. They are available in red, orange, amber, yellow, green, blue and white. Blue and white LEDs are much more expensive than the other colours.

Light-emitting diodes are produced in a variety of shapes and sizes. The colour of the plastic body is often the same colour as the light emitted by the diode. A purple plastic is usually used for infrared LEDs and a clear plastic used for blue LEDs. Remember, though, that the colour of an LED is determined by the semiconductor material not by the colouring of the plastic body in which the diode is housed.

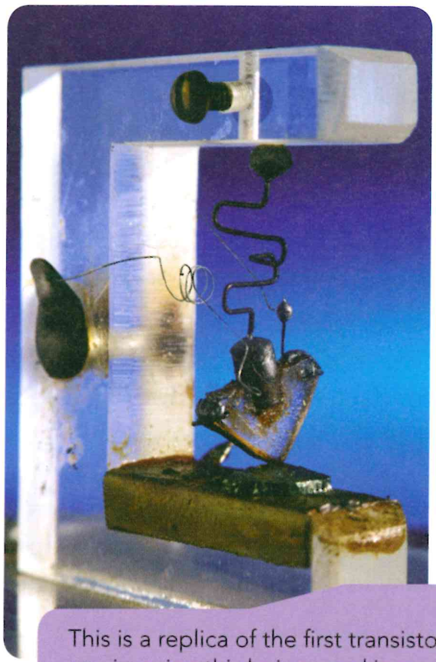
LED technology has advanced greatly in the last few years. Light-emitting diodes are now used for many different applications, such as in traffic lights and on cars.



LED daytime lights on a modern car. Look around you and list everywhere you see LEDs being used. Look out for the less obvious applications, such as in ceiling lighting. In each example you find, explain why you an LED is being used in preference to a light bulb.

35.1.2 Transistors

A transistor also makes use of the p-n junction. It is simply three pieces of semiconductor material connected in a way that lets you control the flow of current. The very first bipolar transistor was made at Bell Laboratories in the USA by John Bardeen and Walter Brattain in 1947. Three years later William Shockley produced a much improved bipolar junction transistor. The transistor quickly started replacing valves in electronic circuits. It proved such an important invention that John Bardeen, Walter Brattain and William Shockley were awarded the Nobel Prize for physics in 1956.



This is a replica of the first transistor. Can you imagine this being used in an electronic circuit today?

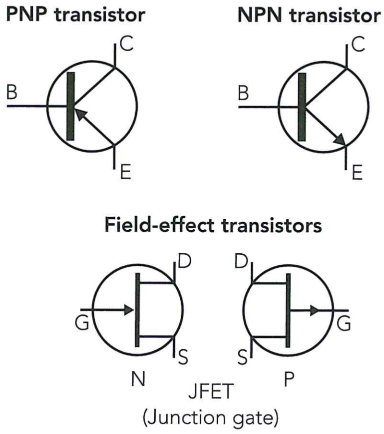


Figure 35.7: Transistor symbols

There are three common types of transistor: PNP transistors, NPN transistors and field-effect transistors (FETs). The symbols for each of these devices are shown in Figure 35.7.

PNP transistors

In a PNP transistor a thin layer of n-type material is sandwiched between two pieces of p-type material. The transistor has three connections – the connections to the two p-type pieces of material are called the emitter (E) and collector (C), and the connection to the n-type material is called the base (B).

By connecting the transistor to an electrical source in such a way that the base-emitter junction is forward biased and the base-collector junction is reverse biased it is possible to control the output from the collector (see Figure 35.8).

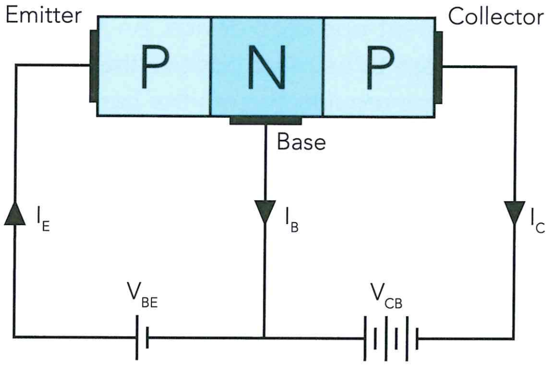


Figure 35.8: PNP transistor configuration

NPN transistors

As the name suggests, an NPN transistor consists of a thin layer of p-type material sandwiched between two pieces of n-type material. This transistor also has three connections, the emitter and collector connected to the n-type material and the base connected to the p-type material.

By connecting an electrical source so that the n-p base-emitter junction is forward biased and the p-n base-collector junction is reverse biased – this means connecting it to an electrical source in the opposite way to that of a PNP transistor – it is again possible to control the collector output.

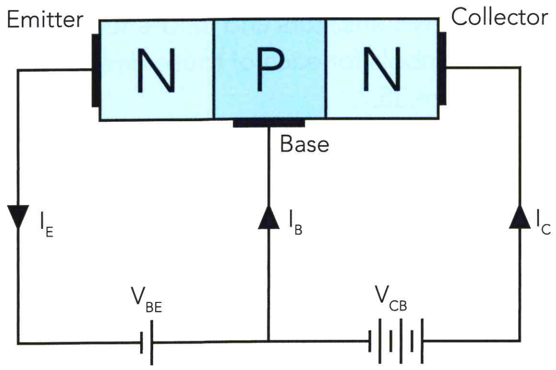


Figure 35.9: NPN transistor configuration

The PNP and NPN transistors are called bipolar transistors. Each bipolar transistor is a three-layer device constructed from two semiconductor diode junctions joined back to back, one forward biased and one reverse biased. The amount of collector output current is controlled by the amount of current flowing into the base connection. A bipolar transistor is therefore a current-operated device. An NPN transistor requires the base to be more positive than the emitter, while a PNP type requires the emitter has to be more positive than the base.

Field-effect transistors

The third type of transistor, the field-effect transistor (FET), is a voltage-operated rather than current-operated device. It uses the voltage applied to the input to control the output current. It works by means of the electric field generated by the input voltage, hence the term field-effect.

Unlike the bipolar transistor, the basic FET has no junctions. Instead it has a narrow channel of either p-type or n-type silicon with connections at either end called the source (S) and the drain (D). By adding a third connection of n-type or p-type material to the channel, called the gate (G), you get the junction field-effect transistor (JFET).

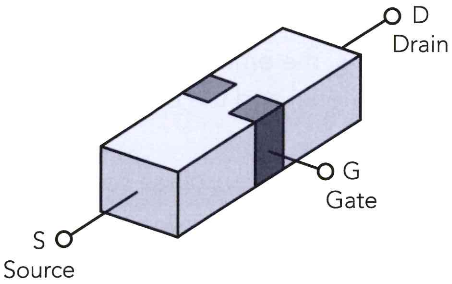


Figure 35.10: Field-effect transistor configuration

Typical uses of transistors

Transistors are used in numerous applications. Their function depends both on how a transistor is connected in a particular circuit and how it is biased.

When choosing a transistor for use in a circuit that you are building, you need to consider how it functions as circuit voltages and currents are varied. You can obtain data sheets that explain the characteristics of each transistor. These data sheets contain graphs that show the characteristics of the transistor. For example, you will find that some transistors work in a linear manner. In other words, the graphs show a consistently varying current/voltage relationship across the operating range of the transistor. This type of transistor would be suitable for use in an amplifier or oscillator circuit.

Other transistor types can be heavily biased, such that in one state they don't conduct but then in another state they fully conduct. A transistor with these characteristics would work well in a circuit where its function is to operate as a switch. A device of this type is called a switching transistor, and it has many uses in different circuits. It can be used to directly switch a circuit or to control a relay that does the actual switching.

The most typical circuit configurations for a transistor are common-base and common-emitter configurations. In a common-base configuration the base terminal is connected to ground, and it is therefore common to both the emitter and the collector terminals. In a common-emitter configuration the base terminal of the transistor is the input, the collector terminal is the output and the emitter terminal is connected to ground and thus common to both, hence the name. Common-emitter configurations have been used for many years in circuits where the transistor is used as an amplifier.

Transistors can be used in both analogue and digital circuits. For example, they can be used to build a single-stage amplifier in analogue circuits (single-stage amplifier) or used within comparators and switches in digital circuits.

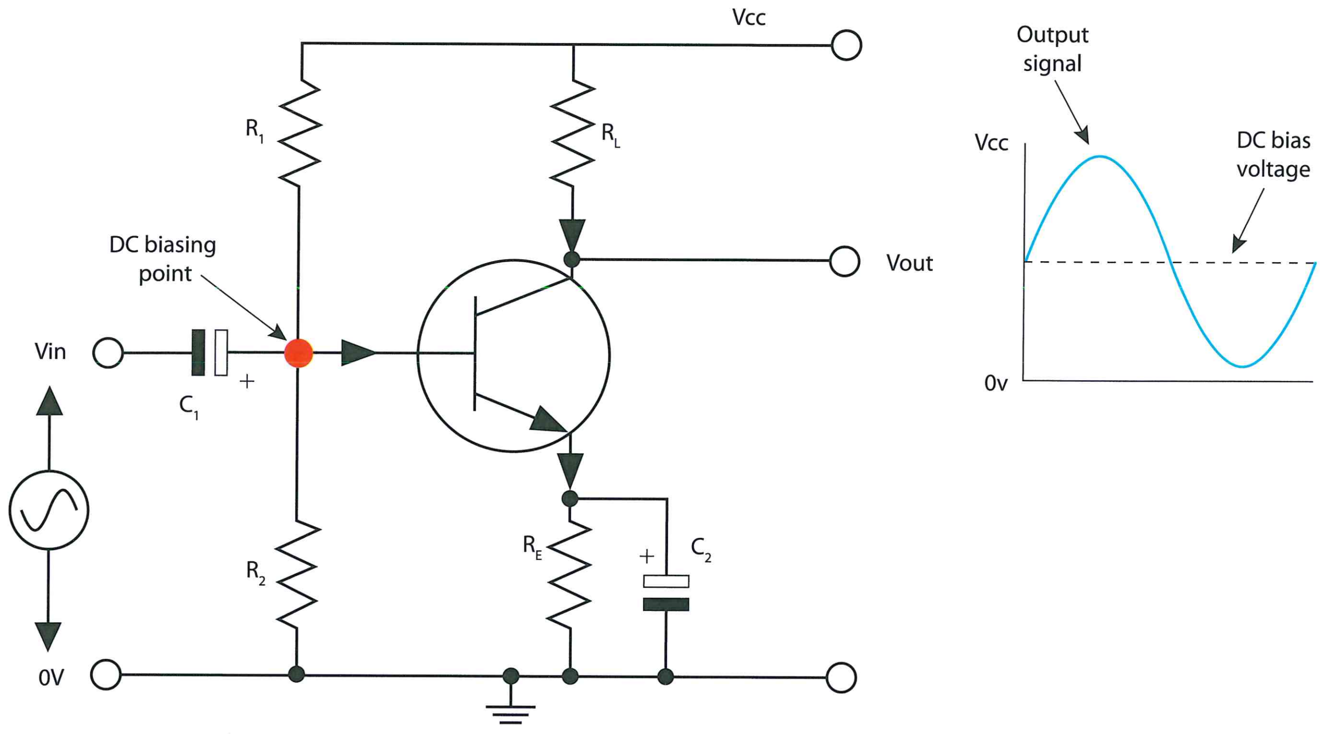


Figure 35.11: A single-stage amplifier circuit

Figure 35.11 shows a single-stage common-emitter transistor amplifier circuit. A small signal is applied to the base input and appears across the load resistance connected between the collector and the supply rail. Resistors R1 and R2 hold the base at a set voltage, called the bias point. The voltage developed across the load can be many times larger than the input voltage. The output signal is identical to the input signal but larger, hence the term amplifier.

A transistor with the right characteristics can be directly used as a small current switch. However, it is not advisable to force a transistor to switch large voltages or currents in case the transistor fails because it overheats or exceeds its maximum rating. You may also want to switch a number of circuits from just one transistor. It is common, therefore, to have the transistor operate a relay, which in turn does the actual switching. The relay contacts can easily switch any high power levels that might cause the transistor to fail. A relay can also be constructed with more than one set of contacts and so more than one circuit can be switched using a single transistor.

Figure 35.12 shows a simple transistor switch controlling a changeover relay. This transistor is used to operate a relay whose contacts then perform a switching function. Using a relay in this way allows a large current to be switched using a low current input. The diode is included to protect the transistor.

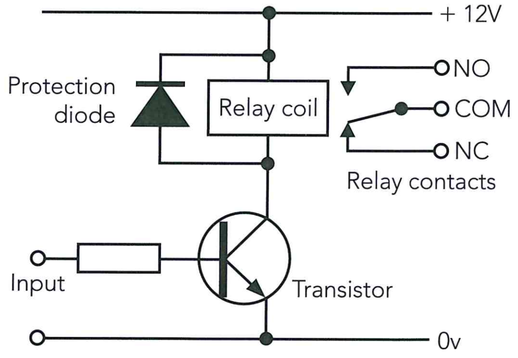


Figure 35.12: A simple switch circuit

When a transistor is used as a switch, it must be either 'off' or fully 'on'. In the fully on state the voltage across the collector and emitter is almost zero, so the transistor is said to be saturated because it cannot pass any more collector current.

Activity: Using transistors

The circuits in Figures 35.11 and 35.12 show a transistor being used for completely different functions. Both, however, involve a form of switching. Study these circuits carefully, and write down the term that identifies the type of switching that takes place in each circuit. As a hint, think back to the starter stimulus at the beginning of this chapter.

Discuss and write down why you think a diode is needed to protect the transistor in Figure 35.12. Now draw up a list of everyday applications where you might find a circuit such as that in Figure 35.12 being used.

35.1.3 Logic gates

A **logic gate** is the term given to a circuit that performs a basic logic function. Logic gates are used extensively in computers. Table 35.3 lists the most common functions performed by logic gates. The table also gives the standard symbols used to denote logic gates in circuit diagrams. Three symbol conventions are shown American National Standards Institute (ANSI), International Electrotechnical Commission (IEC) and British Standards (BS 3939), and you might come across examples of all three symbols, because you may be using integrated circuits that have been produced in different parts of the world.

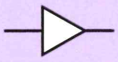
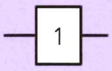
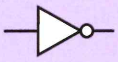
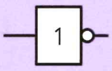
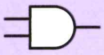
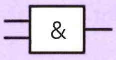
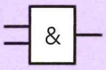
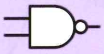
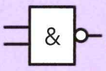
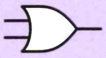
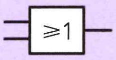
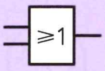
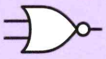
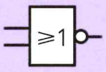
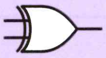
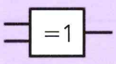
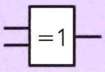
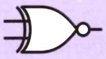
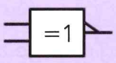
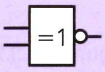
Key terms

Logic gates circuits designed to perform the basic logic functions, such as AND, OR and NOT, that are used in digital circuits and computers.

The signals used in logic gates are either off or on, hence the terms logic 0 or logic 1. This means that the inputs and output can only ever represent one of two states – a 0 (also known as a low state) or a 1 (known as a high state).

All the gates shown in the Table 35.3 provide logic functions except for the buffer. It always gives the same state on output as that on input. For example, a 1 on the input results in a 1 on the output. The buffer is often used to boost the current output of other gates.

Table 35.3: Standard logic gate symbols

Logic gate	ANSI/MIL	IEC	BS 3939
Buffer			
NOT			
AND			
NAND			
OR			
NOR			
XOR			
XNOR			

The NOT gate (also called an inverter) and the buffer only have one input, while the basic AND, OR, NAND and NOR gates are available with up to eight inputs. The XOR and XNOR gates have two inputs.

Truth tables

An easy way of showing the function of a logic gate or circuit is to use a truth table. You simply list all the possible input combinations in the table (with one row for each combination), and note the resulting output state in the final column of the table. If you have a circuit consisting of several logic gates connected together, then you also show the output of each gate in your truth table to help you work out the eventual output result.

The AND gate

Let's look at the AND gate first. It only produces a logic 1 output when all its inputs are at a logic 1. Think of this in terms of needing a logic 1 on the first input AND a logic 1 on the second input, and so on, to get a logic 1 at the output – hence the name AND gate. This can be shown as a truth table (see Table 35.4).

Table 35.4: Truth table for a two-input AND gate

Input A	Input B	Output
0	0	0
0	1	0
1	0	0
1	1	1

The NAND gate

If you add a NOT function to the output of a gate, you simply get the opposite result. Instead of logic 0 you get a logic 1 output, and instead of a logic 1 you now get a logic 0 output. For example, the NAND gate, which we see in the 7400 logic chip below, performs the logic function NOT AND. In other words, it gives the opposite result for any input to that which would be obtained by the AND function. Table 35.5 shows its truth table.

Table 35.5: Truth table for a two-input NAND gate

Input A	Input B	Output
0	0	1
0	1	1
1	0	1
1	1	0

The OR gate

The OR gate is so called because you get a logic 1 output when you have a logic 1 on the first input OR a logic 1 on the second input OR a logic 1 on both inputs – hence the name OR gate. Table 35.6 shows the truth table for a two-input OR gate.

Table 35.6: Truth table for a two-input OR gate

Input A	Input B	Output
0	0	0
0	1	1
1	0	1
1	1	1

The exclusive OR gate

The exclusive OR gates – shortened to the XOR gate – is very similar to the OR gate. As long as one of the inputs is at a logic 1 and the other is at a logic 0, the output is always logic 1. However, when both inputs have the same logic state – that is, they are both at logic 1 or a logic 0 – the output is a logic 0. In other words, to produce a logic 1 output, only one of the two inputs has to be exclusively a logic 1 (see Table 35.7).

Table 35.7: Truth table for an XOR gate

Input A	Input B	Output
0	0	0
0	1	1
1	0	1
1	1	0

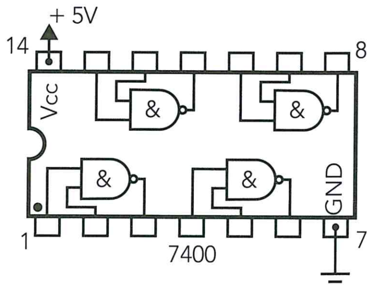
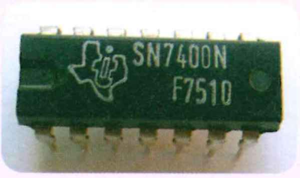


Figure 35.13: Circuit diagram of a 7400 logic chip

Case study: A 7400 logic chip

There are many different types of integrated circuits (ICs) used for processing digital signals. The simplest ones contain the basic logic gates we are exploring here. Because these simple gates have relatively few connections, it is possible to fit more than one of these gates into a single IC package.

The 7400 chip, shown here, contains four totally independent two-input NAND gates. The circuit diagram for this chip is shown in Figure 35.13. When designing a circuit using this chip, you can make use of all four gates or just one if that is all you need. You can even use one of the NAND gates to function as a NOT gate by connecting its two inputs together. This is useful when you just need one NOT gate and only have a spare NAND gate available. In fact, you can make NOT, AND, OR and NOR functions using only NAND gates.



Look at the truth table for a NAND gate (see Table 35.5) and see if you can work out why it works as a NOT gate when its inputs are connected together.

Boolean expressions

You can write down the logic functions performed by logic gates. You do this using Boolean algebra. This is not as complex as it sounds because there are only three symbols to remember (see Table 35.8).

Boolean expressions and truth tables are simply mathematical descriptions of logic functions. It is possible to write out complex logic using Boolean algebra, though take care with your NOT symbols or you could end up with an expression that is more complex than it needs to be. Remember that if you NOT NOT an input called A, this is exactly the same as just writing A – in this case, two wrongs do make a right.

Table 35.8: Boolean functions

Symbol	Logical function	Examples	Meaning	Logic gate
·	AND	$A \cdot B$ $A \cdot B \cdot C$	A AND B A AND B AND C	two-input AND three-input AND
+	OR	$A + B$	A OR B	two-input OR
—	NOT	$\overline{A}$ $\overline{A \cdot B}$ $\overline{A + B + C}$	NOT A A NAND B NOT (A OR B OR C)	the output of a NOT gate two-input NAND three-input NOR

Did you know?

The inventor of Boolean algebra was called George Boole. He was the son of a shoemaker, and born in 1815 long before logic circuits were created. He wanted to show that true or false could be expressed as a formula.

Activity: Truth tables and Boolean algebra

1. See if you can work out some inverted output truth tables for yourselves. Produce truth tables for the NOR and XNOR two-input gates.
2. Now consider a gate that has more than two inputs. Produce truth tables for a four-input NAND gate and a four-input NOR gate.
3. Now write out the Boolean expressions for all these gates: two-input NOR, two-input XNOR, four-input NAND and four-input NOR.

35.2 Be able to build and test operational amplifier based analogue circuits

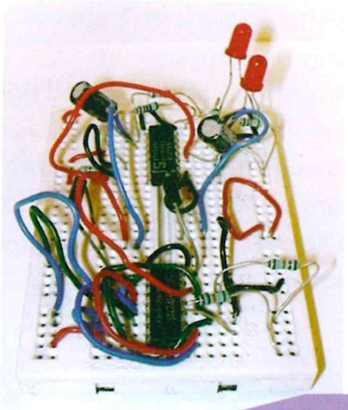
You will probably have seen electronic circuits built on printed circuit boards. The component positions are laid out in a neat manner and the connecting wires are already in place and etched from copper. Mounting holes are pre-drilled so that the components can simply be inserted into the board and soldered in place. The board may only have connections on one side, or you may come across more complex circuit boards with connections on both sides or even built into the board in different layers.

Circuit boards look neat and tidy. However, they are usually only produced after a circuit has been tested and passed for production. During its development, the circuit will have been built in a very simple and often untidy manner. Designers will often change their minds about the best approach, and they will want the flexibility to modify the circuit as it develops.

35.2.1 Building analogue circuits

There are several ways of building electronic circuits. Table 35.9 lists three common circuit construction methods. If you are at the early stages of designing a circuit, you will use a fairly simple method that allows you to easily change the circuit if it doesn't work properly. When the design is complete, you will probably want to build it using a printed circuit board.

When you first design a circuit, you should probably build and test it using the **breadboard** method to see if it works as expected. If it doesn't, you will want to change some of the wiring, and perhaps substitute components or even add extra components to the circuit. A printed circuit board is not suitable for this type of circuit development.



Constructing a circuit using a breadboard

Key terms

Breadboard construction a method that allows components and wiring to be easily changed if the circuit needs modifying. It is easy to access parts of the circuit with test probes. Used in the early stages of circuit design, breadboard construction is not suitable for permanent use or for large circuits with many components.

Table 35.9: Circuit construction methods

Method	Use	Advantages	Disadvantages
Breadboard	Suitable for the initial building and testing of circuits, before being built in a more permanent form	Changes can be easily and quickly made Components can be reused	Not suitable for permanent use Not suitable for circuits having more than about six active devices
Stripboard	Suitable for building circuits at the prototype stage	Cheaper and more permanent than breadboard as components are soldered in place Board can be reused a number of times	Copper tracks on the reverse of the board need to be cut with a knife Care is needed to avoid short circuits while soldering
Printed circuit board	Suitable for permanent circuit construction	All the connecting wires are etched onto the board, no loose wires Can be assembled by machine for mass production	Difficult to modify if changes are made to the circuit Difficult to change failed components, quicker to replace the complete board

Did you know?

The printed circuit board was invented in 1936, but the use of printed circuits did not become commonplace in consumer electronic products until the 1950s. The board is soldered automatically by passing it over a wave of molten solder.

Types of circuits

A circuit is a collection of electronic components connected together to perform a specific function. Some circuits only perform one function, others may perform several functions depending on their complexity. However, there are some basic circuits that form the individual electronic building blocks for circuit design. These are typical types of circuits that you will regularly come across in circuit design (their functions should be obvious from their names):

- oscillators
- filters
- comparators
- inverting/non-inverting amplifiers.

You can design a circuit by selecting individual components that are ideal for a specific application, such as a high frequency oscillator. Figure 35.14 shows a radio frequency oscillator circuit. You could build this from individual components, but most common basic circuits are now available as a single chip device. The device contains the complete circuit, except for the components that determine how it will operate. This device is called an integrated circuit. All you need to do is work out the values of the external components from the manufacturer's data sheets and you have a very stable and accurate circuit.

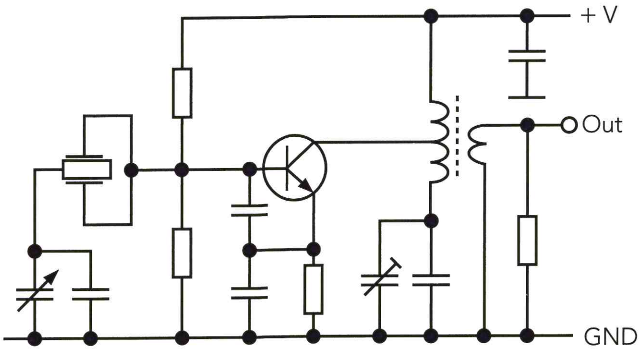


Figure 35.14: A radio frequency oscillator circuit

There are many different designs for each main type of circuit – oscillators, filters, comparators and amplifiers. Individual designs are tailored for specific applications. Some are named after their inventor, such as the Hartley and Colpitts oscillators. Some are designed using individual components while others are available as a single chip and use few external components.

Activity: Types of circuits

Working in pairs, use the internet to research oscillator, filter, comparator and amplifier circuits. Familiarise yourself with their properties, function and uses.

For each type of circuit, list at least three applications where you would expect to find such a circuit being used. For example, you would find an oscillator in a radio circuit. Now find other uses for an oscillator.

When you have researched all four types of circuits, compare your results with other groups to see how many different uses have been found for these basic circuit types.

PLTS

Building and testing circuits will help you develop your creative thinking skills.

35.2.2 Testing analogue circuits

Once you have designed a circuit, you need to build a prototype using breadboard or stripboard construction so that it can be tested. This is to ensure that the circuit does exactly what it is supposed to do. If it doesn't pass testing, then you modify the design, incorporate the changes into the prototype and test the circuit again. This process is repeated until your results prove that the circuit is working exactly as you intended.

Design requirements

Initially, a list of requirements will have been set out for a new circuit. When drawing up the circuit diagram, you will choose active components that are suitable for the circuit. If working on an oscillator for a radio receiver, you would choose small signal transistors designed to work at radio frequency. If designing a music amplifier, you would choose power transistors that work best at audio frequencies.

Formulae can be used to determine the correct values of other components, such as resistors and capacitors, to ensure that the circuit is correctly biased, that the input and/or output signals are at the correct level, and that no component burns out because it has too low a power rating. Most manufacturers issue data sheets for their devices. For a transistor, the data sheet will include a circuit showing how to use the device, with many of the component values already calculated for you. You can use this information to help design your own circuit.

When you have finished the design, you now have a circuit that should work in theory. Now you need to prove this by building and testing the circuit.

Did you know?

When a component gets warm its electrical characteristics could change, possibly affecting the operation of the circuit. Fortunately, this is no longer as big a problem as it once was, because manufacturers now 'burn in' components at the testing stage.

Testing performance

Testing the circuit doesn't mean just injecting a signal at the input and checking that there is a signal at the output. You need to measure the actual voltage levels at different parts of the circuit to ensure that the bias voltages are correct, that a component isn't taking too much current and that, above all, the circuit is stable and continues to work correctly after it has been powered up for a long time.

For example, a music amplifier may work perfectly well when it is first switched on, but it may start giving distorted sound after it has been on for an hour or so. Even though the voltage levels all measure correctly, one of the devices may be taking a bit too much current, getting warm and starting to distort the signal. This may not always be a problem with the circuit; you may just have a faulty component, but it still needs accurate testing.

Testing includes:

- recording voltages at different parts of the circuit and producing a data table or plotting a graph of the results
- measuring the **resonant frequency** and/or the **cut-off frequency** of a circuit, and comparing these with the design specification
- varying and recording the bias levels in a circuit to determine the point at which the circuit switches
- plotting the gain of a circuit by measuring input and output signal levels
- measuring frequency response to plot the **bandwidth** of a circuit.

Key terms

Resonant frequency the 'natural' frequency of a circuit. Circuit design often incorporates a means of slightly varying the resonant frequency to bring the circuit 'in-tune'.

Cut-off frequency the frequency at which the efficiency of a circuit drops off rapidly. There is often a lower and an upper cut-off point

Bandwidth a measure of the range of frequencies that a circuit can operate at or pass. This is the range between the lower and upper cut-off points.

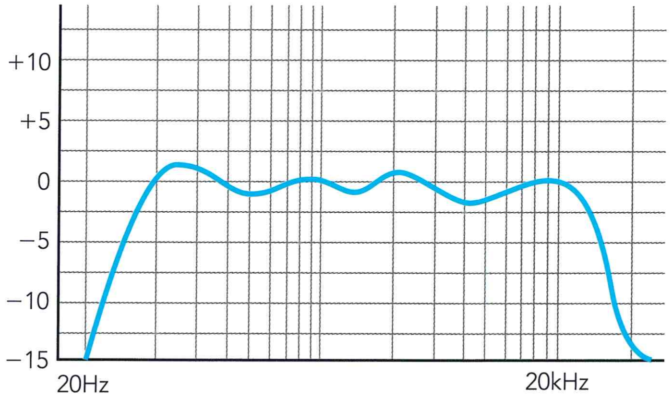


Figure 35.15: A frequency response graph produced during circuit testing

Figure 35.15 shows the frequency response measured during testing a circuit. Can you identify the lower and upper cut-off points of this circuit? What is the maximum frequency at which the circuit will work efficiently?

Assessment activity 35.1

P1 P2 P4 M1 BTEC

P4 Study Circuits A and B. Choosing suitable components build and test the circuits and ensure that they work correctly. Carefully record your observations.

P1 **P2** Record the type of diode used in both circuits, then produce a detailed explanation of the purpose of each diode. Record the type of transistor used and explain its operation in the circuit in Circuit B.

P2 Study the digital circuit diagram shown in Circuit C. Make a note of the type of transistor used and explain its operation in the circuit.

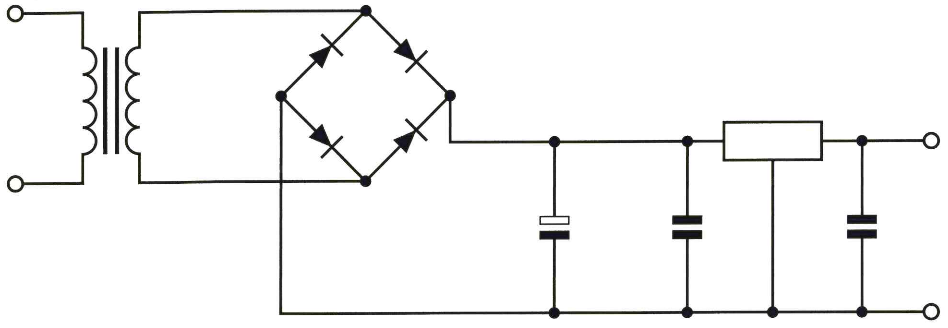
M1 Measure the minimum and maximum values for darkness and bright light of the light-dependent resistor (LDR) in Circuit B. Modify the circuit by selecting and changing just one of the components so that it can be made to operate over a different range of light levels.

Grading tips

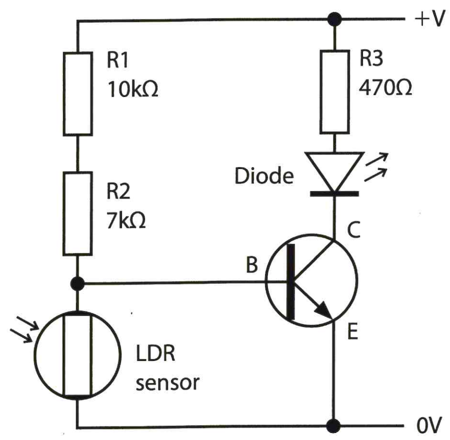
P1 **P2** There are many basic circuits that use diodes and transistors where, simply put, the function of the device depends on how it is biased or connected into the circuit. By carefully studying the circuits you should be quickly able to identify what they do and the function of the diodes or transistor.

M1 Because a transistor requires few resistors to establish the bias point, it should be possible to alter when it begins to conduct by only altering the value of one component. Can you identify which one?

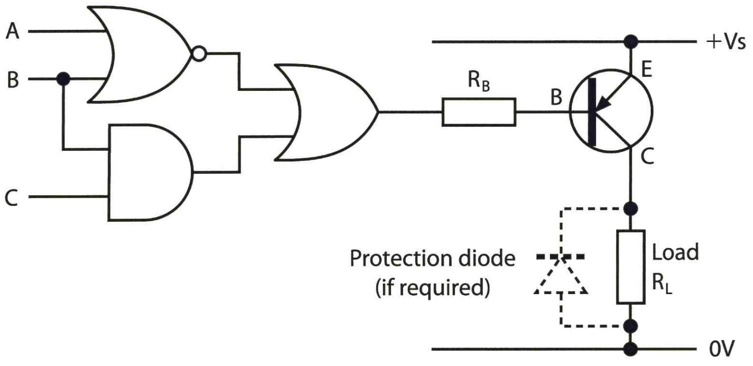
Circuit A



Circuit B



Circuit C



35.3 Be able to build and test combinational and sequential logic circuits

So far in this unit we have considered basic logic gates. There are many other types of logic gates and logic circuits – more complex than the simple ones we have covered so far – each having its own specific function. In this section we will look at the function and characteristics of some other types of logic circuits.

Logic circuits fall into two categories – **combinational logic** and **sequential logic**. In combinational logic circuits, the output is always a result of a particular set of input conditions. If one of those input conditions changes, then the output may or may not change, depending on the gate functions of the rest of the circuit.

It is easy to represent how a combinational logic circuit works using a truth table. Each possible input condition is shown in the table together with all of the other signal conditions as you work through the circuit. This is very useful when you are testing a circuit because you know exactly what signal should appear where.

Producing a truth table for sequential logic circuits is more difficult. These circuits can give an output state that is dependent both on the state of the inputs and on the state of any previous output condition. In other words, an output may be fed back and used as an input at an earlier point in the circuit. This makes sequential logic circuits suitable for use as data registers and counters, for example.

35.3.1 Building combinational and sequential logic circuits

Having become familiar with the simple logic gates, we can use this knowledge to put together actual logic circuits.

Combinational logic circuits

A simple logic circuit might contain three logic gates and three input variables. You show what output the circuit will give by working out its truth table.

Look at the circuit in Figure 35.16. The output of each individual gate is labelled and shown in the truth table in Table 35.10. See if you can follow this truth table. Note that this works out the expected output for the appropriate input condition for *each* gate. The completed table shows the expected output for all possible circuit input conditions.

Key terms

Combinational logic a logic circuit where the output is directly dependent on the state of the inputs. Used for circuits where you know the output you require for known input conditions.

Sequential logic a logic circuit where the output is not only dependent on the state of the current inputs but also on previous input states. In other words, the circuit has a memory.

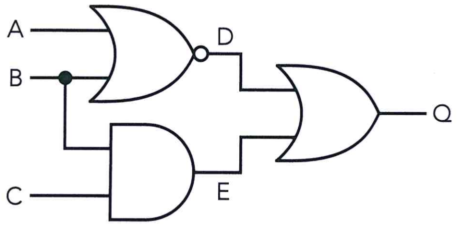


Figure 35.16: A three-input logic circuit

Table 35.10: Truth table for the circuit in Figure 35.16

A	B	C	D	E	Q
0	0	0	1	0	1
0	0	1	1	0	1
0	1	0	0	0	0
0	1	1	0	1	1
1	0	0	0	0	0
1	0	1	0	0	0
1	1	0	0	0	0
1	1	1	0	1	1

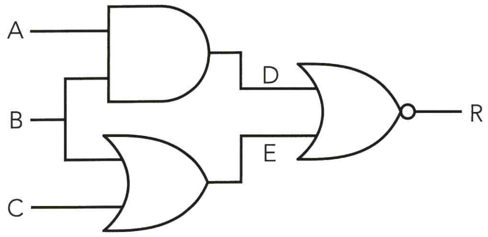


Figure 35.17: A simple logic circuit

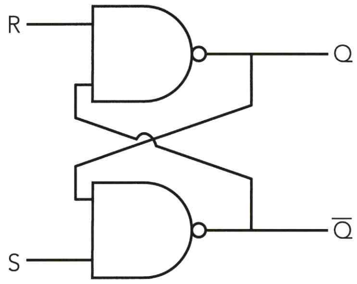


Figure 35.18: An R-S bistable circuit

Activity: Constructing a truth table

Now try one on your own. Study the logic circuit in Figure 3.17, identify each of the gates used in the circuit, and then produce a truth table for the circuit.

Compare your results with someone else's and see if you have worked everything out correctly.

Sequential logic circuits

Sequential logic circuits can be found in most electronic devices you have around the home. There are four common types of sequential logic circuits:

- R-S bistable
- JK bistable
- three-stage counter
- three-stage shift register.

An R-S bistable circuit has two stable outputs (hence the name bistable), which are almost always the opposite of each other, each feeding back to inputs. It has two external inputs called reset (R) and set (S). An R-S bistable circuit is shown in Figure 35.18.

An R-S bistable is sometimes called a flip-flop because it flip-flops from one stable state to the other. Although the outputs are usually the opposite of each other, there is one unwanted condition where they could both be the same.

A JK bistable circuit is a modified version of the R-S bistable, which ensures that the two outputs are always the opposite of each other. The inputs are called J and K, plus there is a clock input to latch the output states.

A three-stage counter circuit is made up of three JK bistable circuits connected one after the other, the output from the first feeding the input of the second, and the output from the second feeding the third. They share a common clock signal so that an input signal eventually ripples through to the output after a certain number of clock pulses, hence the name counter.

A three-stage shift register (see Figure 35.19) is very similar to a three-stage counter. In operation, the circuit temporarily stores three bits of data and delays it by three clock periods from input to output. It is also called a serial-in/serial-out shift register.

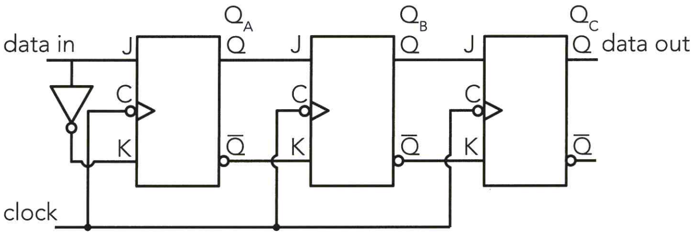


Figure 35.19: A 3-stage serial in/serial out shift-register

Logic families

Logic circuits belong to 'families' depending on the technology used to construct them. Early logic integrated circuits were the equivalent of circuits made from resistors, capacitors, transistors etc. This technology is called transistor-transistor logic (TTL). The circuits switched states very quickly, but consumed quite a bit of power in doing so.

Next came complementary metal oxide semiconductor (CMOS) technology, which uses considerably less power but with much slower switching speeds. Apart from the low power requirement, the other main advantage of CMOS devices is that they can work within a 3–15 volt supply range. In comparison, TTL technology requires a 5 volt power source.

Today's logic families have the low power characteristics of CMOS while being able to switch much faster than the early TTL devices. Logic integrated circuits (ICs), which process digital signals, can be split into two main groups (or families) according to their pin layout – the 74 series and the 4000 series. The main differences between the two are power requirements and operating frequency. The 74HC family will be the best choice for your projects. Table 35.11 lists some logic families in use today and gives a comparison of their characteristics.

Did you know?

There is a wide range of integrated circuits available, including logic gates, flip-flops, counters, registers and even display drivers. Care should be taken when handling the 4000 CMOS series as static electricity could damage the circuitry inside the circuit.

35.3.2 Testing of logic circuits

When you design and build a new logic circuit, you need to test that it functions as expected. These tests should be designed to establish that the circuit both satisfies the truth table and gives stable results.

Although it is in the order of nanoseconds, a logic circuit takes time to switch from one state to the other. Because digital signals are switching at high speeds, you must make sure that signals arrive at the input of a gate at the correct time and stay there for long enough for the output to switch to the appropriate state before the inputs change again, otherwise the output could switch back to (or remain in) its previous state.

Table 35.11: Comparison of logic families

Property	74LS series	74HC series	74HCT series	4000 series
Type	TTL low-power Schottky	High-speed CMOS	TTL-compatible high-speed CMOS	CMOS
Supply (+Vs)	5 V	2 V to 6 V	5 V	3 V to 15 V
Inputs	Pull up to logic 1 if unused	Very high impedance Connect unused inputs to 0 or 1 as appropriate	As 74HC but compatible with 74LS outputs	Very high impedance Connect unused inputs to 0 or 1 as appropriate
Outputs	Low current Use a transistor to switch higher currents	As 74LS but higher current, can source and sink 20 mA	As 74LS but higher current, can source and sink 20 mA	Very low current, can source and sink about 5 mA
Fan-out (per one output)	Can drive up to ten 74LS or fifty 74HCT inputs	Can drive up to fifty CMOS, 74HC and 74HCT or ten 74LS inputs	Can drive up to fifty CMOS, 74HC and 74HCT or ten 74LS inputs	Can drive up to fifty CMOS, 74HC and 74HCT or one 74LS inputs
Maximum frequency	35 MHz	25 MHz	25 MHz	1 MHz
Power usage	mW	µW	µW	µW

Transition time

The time it takes for the output of a gate to stabilise to the appropriate state for a given set of input conditions is called the transition time. If an input changes state in a shorter time than the transition time for that gate, then the gate cannot be relied upon to accurately function in accordance with its truth table. When testing a logic circuit that does not appear to function as the truth table says it should, use a logic analyser to follow the signals through the circuit and check that transition times are being observed.

Transition times become even more important when constructing and testing sequential logic circuits. Remember that in these types of circuits the output is often dependent on a previous output state. You must therefore always allow sufficient time for an output to stabilise *and* give it time to work its way through any gates and back into the circuit as an input before allowing it to switch again.

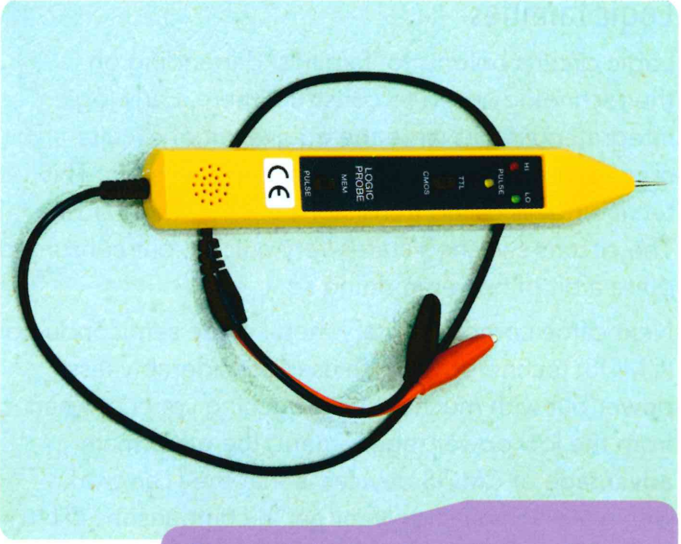
One method of recording a signal at a specific time is to use a clock signal to 'lock' or latch the signal at the input of a circuit. Once latched, the input can change states but it will not be registered until the next occurrence of a clock signal.

Digital test equipment

Switching, as the change from one state to the other is called, happens extremely quickly so it is not really possible to test or fault find digital circuits with test equipment that you would use for analogue circuits. A multimeter or an oscilloscope would not be much use because they are not capable of operating at digital switching speeds. Instead, you should use a logic probe, a logic analyser or a signature analyser.

A logic analyser is similar to an oscilloscope, but works much faster. It lets you compare many signals on the screen at the same time, and allows you to see what the circuit is doing and if an input or output is not switching correctly. You use a logic probe to test the logic state at the various gate inputs or outputs. A signature analyser is more sophisticated and can help you pinpoint which component is at fault.

In summary, the testing of logic circuits is accomplished through recording performance against design requirements, comparing the input and output states with the truth table, and through the use of suitable test equipment.



The simple logic probe is a very useful instrument for testing digital circuits.

35.3.3 Minimisation of logic circuits

Once you have designed a logic circuit, it is often possible to reduce the number of gates in the circuit and still get the same truth table result. This is called circuit minimisation, and it can be achieved using Boolean algebra, De Morgan's laws and Karnaugh maps.

Boolean algebra

There are several Boolean formulae or laws, but not all reduce the number of gates needed in a circuit. Some simply allow you to write the expression in an easier-to-understand way. However, you can use the distributive law to simplify a circuit as the examples below demonstrate.

For example, this logic expression uses three gates (two AND plus one OR):

$$(A \cdot B) + (A \cdot C)$$

This can be simplified using the distributive law to:

$$A \cdot (B + C)$$

This only uses two gates (one AND plus one OR).

Similarly this logic expression also uses three gates (two OR plus one AND):

$$(A + B) \cdot (A + C)$$

Again it can be simplified using the distributive law to:

$A + (B \cdot C)$

This again allows the expression to be written using two gates (one OR plus one AND).

De Morgan's laws

These laws let you make similar simplifications. The first law can be written as:

$\overline{A} \cdot \overline{B} = \overline{A + B}$

Note that the left-hand side of this equation uses three gates (two NOT plus one AND), but the right-hand side uses just one NOR gate.

A second De Morgan law can be written as:

$\overline{A} + \overline{B} = \overline{A \cdot B}$

Again the left-hand side of this equation uses three gates (two NOT plus one OR), but the right-hand side uses just one NAND gate.

Activity: Circuit minimising

Study each expression that has been simplified using Boolean algebra and De Morgan's laws. For each expression, draw the logic circuit before minimising and the logic circuit after minimising to show that each results in fewer gates. Now produce truth tables for each circuit to prove that, in each case, the circuits before and after minimising give the same result.

Karnaugh maps

You can also use a Karnaugh map to simplify a circuit. A Karnaugh map is a pictorial way of grouping together expressions from a truth table with common factors. By doing this, you end up eliminating or discounting any unwanted variables. You can think of a Karnaugh map as just another way of drawing a truth table.

To show the relationship between a truth table and a Karnaugh map, let's consider an example. Table 35.12 shows a truth table for a simple two-input gate. The squares in a Karnaugh map are completed from the output values in the truth table, so for every row in the truth table, there will be one square in its corresponding Karnaugh map (see Figure 35.20).

The values of the two inputs are marked around the edge of the map, with A along the top and B down the left-hand side. The map is completed by filling in the squares – each square has the output value that is generated by the input states specified by the position of the square in grid. So, for example, the bottom right-hand square takes the output value when input A is 1 and input B is 1.

Table 35.12: Truth table for a two-input gate

Input A	Input B	Output
0	0	a
0	1	b
1	0	c
1	1	d

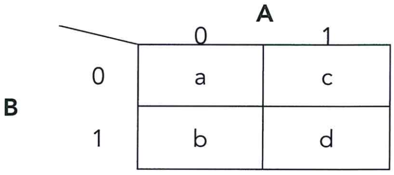


Figure 35.20: Karnaugh map for a two-input gate

We can use patterns in a Karnaugh map to help find simplified expressions for a logic function. To show how this is done, let's consider a very simple example. Figure 35.21 shows the Karnaugh map for the function OR (see Table 35.6 for the truth table for this function). Look for and circle adjacent pairs of 1s. There are two in this table: the horizontal loop represents the B and the vertical loop the expression A. So the resulting expression is:

$A + B$

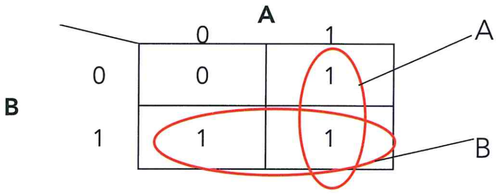


Figure 35.21: Karnaugh map for an OR gate

Now let's consider a more complicated example. Consider how you would produce a Karnaugh map for the truth table shown in Table 35.13.

Table 35.13: Truth table for a 3-input gate

A	B	C	Output
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	0
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

This has three inputs. So we need to do something slightly different to produce a Karnaugh map for this table. The approach that is taken to represent three inputs on a two-dimensional map is to group two of the inputs. As Figure 35.22 shows, the inputs A and B have been grouped together along the top of the map. Notice that the map still represents all possible combinations of inputs. There are eight rows in the truth table and eight squares in the map. Again look for adjacent pairs of 1s and write down the expression that these represent. Link the expressions together to produce an expression for the logic function represented by the truth table. In this case it is:

(A · B) + (A · C)

In practice you might actually use a combination of Boolean algebra, De Morgan's laws and Karnaugh maps to minimise a circuit. Because of their complexity, Karnaugh maps only tend to be used for reducing two-, three- and four-input circuits.

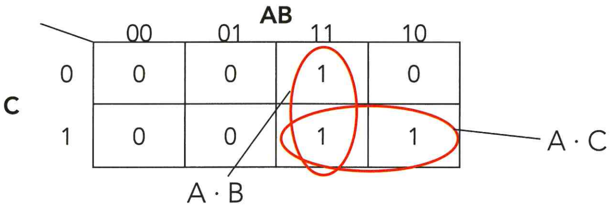


Figure 35.22: Karnaugh map for the truth table shown in Table 35.13

Activity: Testing logic circuits

Explain why it is necessary to use a truth table when testing a logic circuit, and demonstrate how you would use a logic probe to check a circuit against its truth table.

Assessment activity 35.2

P3 P5 P6 M2 M3 D2

The electronics company you work for designs logic circuits. Your employer has asked you to produce some material for new apprentices, which includes showing how to build and test some logic circuits to meet a new design requirement.

P3 Using the appropriate gate symbols, truth tables and Boolean expressions, explain the operation of:

a) a NAND gate

b) a NOR gate

c) an XOR gate.

P5 Work out the truth table for the circuit shown in Figure 35.23. Then build and test the circuit.

M2 Now modify the circuit so that its output matches the truth table shown in Table 35.14.

M3 Draw the logic diagram and truth table for this Boolean expression:

$$(A + B) \cdot (A + C)$$

Then minimise the expression, and produce the new logic diagram and truth table to prove your work.

P6 Build and test a simple three-stage shift register using integrated circuits.

D2 Compare and contrast the 74HC series and 4000 series logic families with reference to at least five characteristics.

Grading tips

M3 The laws of Boolean algebra will help you design and minimise logic circuits. Check your results by producing a new truth table for the minimised circuit and comparing it with the original circuit's truth table.

PLTS

Building and testing logic circuits will help you develop your creative thinking and self-management skills.

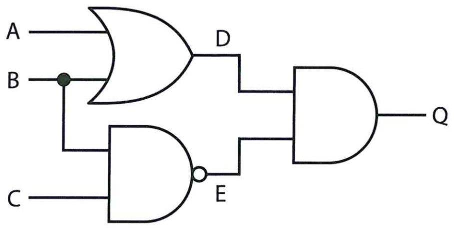


Figure 35.23: Circuit for the P5 task of assessment activity 35.2

Table 35.14: Truth table for the M2 task of assessment activity 35.2

Inputs			Outputs		
A	B	C	D	E	Q
0	0	0	0	1	1
0	0	1	0	1	1
0	1	0	1	1	0
0	1	1	1	0	1
1	0	0	1	1	0
1	0	1	1	1	0
1	1	0	1	1	0
1	1	1	1	0	1

35.4 Be able to use computer-based simulation software packages to construct and test the operation of analogue and digital circuits

It is very handy to be able to check if a circuit you are designing will work as intended before you actually build it. You can do this using simulation software on a computer. The program lets you build a virtual circuit and then test how it works when different input signals are applied. You can easily modify the circuit and see the effect of changing component values, supply voltages and other parameters.

Simulation software is available for both analogue and digital circuit design. Why do you think we need separate programs for developing digital and analogue circuits? You might find it useful to use the internet to research some of the main features of analogue and digital circuit simulation software.

35.4.1 Simulation of analogue circuits

Because there are so many things to consider when designing analogue circuits, it is a really good idea to use a simulation package to develop and test the design. There are many analogue circuit simulators available. Some can be downloaded free of charge from the internet, while the more sophisticated packages have to be purchased.

Using simulation software

Any simulation software package will have some similar features. It should have a library containing the symbols and function of all the common electronic components, such as resistors, capacitors, diodes and transistors. All you need to do is select the appropriate device, place it in the drawing area and allocate it a value. Some components, such as diodes and transistors, may already be pre-programmed with their working characteristics. Having placed all of your components on the drawing area, including any power source, you can connect the components together.

Once you have constructed your virtual circuit, you are ready to simulate the workings of the circuit. The simulator can be used to trace graphs from any part of the circuit, from which you can see how the circuit is working. If you want, you can add components or change component values to see how this affects the circuit. In this way, you can develop a circuit that works exactly how you intend without having to use a single real component. This saves both time and money.

You can use simulation software to draw complete circuits such as amplifiers, op-amps, rectifiers and even active filters. By changing signal source characteristics, you can see how the circuit will function under different conditions. You can check its gain or frequency response, test how hard you can drive it before distortion takes place, and so on. All of this can be done without ever picking up a soldering iron or handling an actual component.

A useful feature of most simulation software is that it can warn you if you have made a mistake in the design. For example, you could have accidentally connected two outputs together or forgotten to complete all of the connections to a component.

One of the most common general-purpose analogue simulation programs is called Spice, which stands for simulation program with integrated circuit emphasis. You can use it to check the design of your circuit and to predict how it will behave by tracing a graph of the signal at any point you choose in the circuit.

Did you know?

SPICE was developed at the Electronics Research Laboratory of the University of California. It is widely distributed and used. It has been continuously developed over the years, and there are now several different versions of the program.

35.4.2 Simulation of a digital circuit

There are also many popular computer-based simulation software packages available for designing and testing digital circuits. Most are simple to use. You simulate your circuit using the basic logic gates (such as NOT, AND, OR, NAND and NOR), sequential logic circuits (such as R-S and JK flip-flops) and the built-in range of digital integrated circuits (ICs).

You select the devices you require from the library, lay them out on the screen and add the connections. Because the software has been programmed with how the various gates and ICs work, you can easily simulate the circuit and see if it performs the function you require.

Signal traces

Digital simulation software is particularly useful, because it allows you to develop and test circuits for faults without using expensive analyser equipment. A simulator software package will draw traces of all the relevant signal paths so that, for example, you can check out the all-important transition times and confirm that, in theory at least, outputs and inputs have stabilised before being clocked into a gate.

The traces can also be used to analyse if an input stabilises too late, that the circuit is performing according to the original design requirements and whether any interference or 'noise spikes' are inadvertently triggering a gate and affecting how the circuit functions.

Assessment activity 35.3

P7 **P8** **D1**

You have been asked by your employer to demonstrate the potential of analogue and digital circuit simulation software to them. Use suitable simulation software to undertake these three tasks.

P7 Demonstrate the simulation of the construction and testing of an analogue circuit using at least three different types of components.

P8 Demonstrate the simulation of the construction and testing of a digital logic circuit containing at least three gates.

D1 Demonstrate the construction and testing of a simple amplifier circuit containing an operational amplifier. Now change the values of components that affect the gain of the circuit. Demonstrate and explain the revised performance of the circuit.

Grading tips

D1 Although simulation software is very useful, there are times when the simulated results do not exactly match the actual results. Did you consider this, especially when demonstrating the effects of changing the values of circuit parameters that affect the gain of a circuit?

PLTS

Using a simulator program will help you develop your creative thinking, self-management and ICT skills.

Did you know?

You can find screenshots of analogue and digital simulation software online – either do your own search or visit this book's Hotlinks (www.pearsonhotlinks.co.uk – see page ii).

Susie Brown

Electronics engineer

I work for a well-known electronics company. Its product development division is involved in the design of both analogue and digital circuits. My team consists of five engineers, each with their own specialist skills in a different area of electronics.

I am responsible for contributing to the design specification. I design the digital part of the circuit, as logic and logic gates is my specialist field. However, I also organise the test schedules and supervise computer simulation tests of all circuits to ensure that they will perform as required.

There is also a management aspect to my job. I must ensure that circuit design, building and testing goes to schedule and is completed on time. I must then arrange for the circuit to go into production, once it has passed testing, and ensure that all the relevant paperwork is completed.

My typical day usually starts with a short meeting with the rest of the team to discuss progress on the current projects. We look at any problems that have cropped up and how to best deal with them. It might be that a part of a circuit doesn't work or is failing its test routine, or it could be a problem with putting a design into production.

I then move on to working on specific circuit design issues. I usually spend at least four hours a day using computer-based simulation software, ensuring that the circuit under design works as it should and feeding the results back to other members of the team. From this, I work out if any modifications are needed and then produce a test specification. The day is usually rounded off with a short progress report for my head of department.

The best thing about the job? I enjoy being able to come up with an idea and then turn it into a circuit that actually does something. I get a real buzz when I power up a design for the first time and it works. Mind you, sometimes it doesn't and then I have to go back over the design to see why. When I find the reason I feel pleased, because I now know it will work properly and it gives me a big sense of achievement. I like working with my team because we share our ideas and help each other if someone has a difficult problem.

Think about it!

1. What topics have you covered in this unit that provide you with the skills and background knowledge to become a good electronic circuit designer?
2. Think about what further skills might you need to develop. For example, you might need additional training on the use of simulation software in order to make your work more efficient.

Just checking

1 Define 'logic gate' and explain what a 0 and a 1 state equate to.
2 Describe these three basic methods of circuit construction: (a) breadboard, (b) stripboard and (c) printed circuit board.
3 Describe two methods that can be used to minimise a logic circuit.
4 What is a truth table?
5 What is the term for introducing a small impurity into a semiconductor?
6 Where would you use a Zener diode?
7 Draw a circuit diagram suitable for achieving half-wave rectification and one for full wave rectification.
8 Describe how an LED works.
9 What does R and S stand for in the term 'R-S bistable?'
10 How many connections does a transistor have?
11 Why is it important to handle the 4000 series CMOS family of integrated circuits with care?
12 Describe what happens at the depletion layer in a p-n junction when a forward biased voltage is applied.
13 Why is a multimeter an unsuitable instrument for use on a digital circuit?

edexcel

Assignment tips

- You may sometimes research a topic that appears to become too technical as you delve into it. Don't be put off; just keep looking for alternative sources and you will soon find a source that gives easier-to-follow information.
- Make sure that you familiarise yourself with the standard symbols for both analogue and digital components. This will come in useful and save time when building a circuit from its circuit diagram.
- Make accurate and detailed notes of any practical work carried out. The notes can contribute towards evidence that the work has been completed successfully. You can also record how you expect a circuit to function before simulating it, and then compare the simulation results with the results you predicted. Remember to also record the results of the simulation.
- There are many interactive tutorials on the internet that you can use to test your understanding of how logic gates work and how to simplify logic circuits and expressions. Check out how well you can use a Karnaugh map, for example, to minimise a logic circuit.