Electronic Devices and Circuits
Getting to know your unit

In this unit you will investigate analogue electronic circuits based on diodes and transistors and combinational and sequential logic digital circuits. As part of the unit you will use software to simulate circuits, construct them safely and use typical bench instruments to test them. Electronic circuit designers make frequent use of software to simulate design ideas before building prototype circuits and testing them in the process of developing final products.

How you will be assessed

This unit will be assessed by a series of internally assessed tasks set by your tutor. Throughout this unit you will find assessment activities to help you work towards your assessment. Completing these activities will mean that you have carried out useful research or preparation that will be relevant when it comes to your final assignment.

In order for you to achieve the tasks in your assignment, it is important to check that you have met all of the assessment criteria. You can do this as you work your way through the assignment.

The assignments set by your tutor will consist of a number of tasks designed to meet the criteria in the table.

### Assessment criteria

This table shows what you must do in order to achieve a Pass, Merit or Distinction grade, and where you can find activities to help you.

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<td><strong>A.P1</strong></td>
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<td>Simulate, using captured schematics, the correct operation of at least one diode, transistor and operational amplifier circuit.</td>
<td>Simulate, using accurately captured schematics, the correct operation of at least one diode, transistor and operational amplifier circuit.</td>
<td>Evaluate, using language that is technically correct and of a high standard, the operation of at least one diode, transistor and operational amplifier circuit, comparing the results from safely and accurately conducted simulations and tests.</td>
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<td>Build at least one diode, transistor and operational amplifier circuit safely and test the characteristics of each one.</td>
<td>Build at least one diode, transistor and operational amplifier circuit safely and test the characteristics of each one accurately.</td>
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<td>Explain, using the simulation and test results, the operation of at least one diode, transistor and operational amplifier circuit.</td>
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## Learning aim B

**Explore the safe operation and applications of digital logic devices and circuits that form the building blocks of commercial circuits.**

### B.P4
Simulate, using captured schematics, the correct operation of at least one combinational logic circuit and two sequential logic circuits.

**Assessment practice 19.2**

### B.P5
Build at least one combinational logic circuit and two sequential logic circuits safely and test the characteristics of each one.

**Assessment practice 19.2**

### B.P6
Explain, using the simulation and test results, the operation of at least three logic circuits.

**Assessment practice 19.2**

## Learning aim C

**Review the development of analogue and digital electronic circuits and reflect on your own performance.**

### C.P7
Explain how health and safety and electronic and general engineering skills were effectively applied during the development of the circuits.

**Assessment practice 19.3**

### C.P8
Explain how relevant behaviours were applied effectively during the development of the circuits.

**Assessment practice 19.3**

### C.M7
Recommend improvements to the development of the electronic circuits and to the relevant behaviours applied.

**Assessment practice 19.3**

### C.M8
Explain how health and safety and electronic and general engineering skills were effectively applied during the development of the circuits.

**Assessment practice 19.3**

### C.D3
Demonstrate consistently good technical understanding and analysis of the electronic circuits, including the application of relevant behaviours and general engineering skills to a professional standard.

**Assessment practice 19.3**
Getting started

Do you understand the difference between analogue and digital circuits? What electronic applications have you already studied? Have you constructed any electronic circuits? What methods have you used? Look through the unit content and make a list of what you think you already know something about. As part of the unit you need to compare your initial skills and knowledge with your final ones and see how they have developed. Be honest!

A1 Safe electronic working practices

Electronics safety

Working with electronic circuits can be dangerous if you do not take sensible precautions. Here are some safety guidelines to keep you safe as you work.

▸ Only work with low-voltage supplies and never work on a circuit while power is applied.
▸ Check your work carefully before connecting power to a circuit.
▸ Keep your work area clean, dry and tidy.
▸ Be very careful when you solder because a hot soldering iron can easily burn you.
▸ Always work in a well-ventilated space, as soldering can give off potentially harmful fumes.
▸ Wear safety glasses when constructing circuits.
▸ Always follow the guidelines in appropriate risk assessments.
▸ Be able to identify people with responsibility for health and safety and always follow their instructions.

As well as protecting yourself and others, you should also take care to avoid damage to components. Some components are sensitive to static electricity, and you should take precautions to avoid damage by electrostatic discharge (ESD). A good start is to keep your work area clean and tidy so that there are no materials, such as plastic bags, that might build up a static charge. Handle circuit boards by their edges where possible. Keep sensitive components in their packaging until you need to use them. You might carry out construction in a designated area with static dissipation work surfaces and floor and proper grounding methods, such as a wrist strap.

Emergencies

You must know what to do, and what not to do, in case of fire, electrocution or other emergency.

Research

For your workplace and work practices:
- Find out who is responsible for health and safety.
- Find out who the identified first-aiders are and how to contact them.
- Find the appropriate risk assessments.
- Familiarise yourself with the evacuation procedures.
- Find out where you can find safety equipment such as fire extinguishers and first-aid kits.

Schematic capture and simulation

One of the important skills that you need to develop is the ability to understand and create schematic circuit diagrams. There are many software packages that allow you to do this – see Figure 19.1 for an example. They range from free downloads from the internet to expensive professional packages used in industry. They all have certain things in common. A key factor is the number of components stored in their libraries and how easy it is to use them. You want to be able to find the components you need quickly so that you can drag and drop them into your drawing window. Each component you include in your design is given a unique identifier, for example R1. You then need to be able to connect your components. This is usually done just by dragging from point to point.

The libraries also contain a variety of signal sources, sensors and actuators. You need to practise using the software applications so that you can work with them confidently and efficiently.
The clever part of the software lies in the way that the libraries do not just contain the circuit symbols – they also store details of the characteristics of the devices, such as the breakdown voltage and power limit of a Zener diode. You can select the values of common components, such as resistors and capacitors, and change them easily to modify your designs. The software uses this information to enable you to simulate the operation of the circuit. You can include a whole range of virtual instruments, such as voltmeters, ammeters, oscilloscopes and some more complex ones to measure signals at any point in the circuit.

The majority of packages use a program called SPICE to carry out the simulation. This is embedded in the software, so you do not really need to know a lot about it at this stage.

Your software package also needs to allow you to design and simulate digital circuits. The digital libraries contain the basic gates and standard logic families. Some packages allow you to build what are called hierarchical designs, where you design a unit, then use several of the units to build a bigger one and so on.

Digital circuits can have timing problems, which can sometimes be difficult to solve. Logic analysers exist that can compare signals at multiple points in a circuit to check that changes take place at the correct time, but they can be very expensive. Simulation allows you to check that signals have enough time to stabilise before they can affect another part of the circuit.

**Circuit construction techniques**

**Prototyping methods**

After the initial design and simulation, the next step is to build a prototype circuit to test that your design works in practice. There are many prototyping methods available. Plug-in systems are useful in the early stages because you can easily move components about and try different values. Soldered systems are more robust, but are not so easy to modify if you need to make changes.

The most common type of plug-in system is called a **breadboard** (see Figure 19.2). This is a plastic block with holes arranged in groups connected by spring clips. The holes are typically arranged at 0.1 inch spacing. The spacing between blocks across the centre-line is 0.3 inches, which is the same as the space between pins on a dual in-line package (DIP) used by many integrated circuits. You insert components such as resistors, capacitors and connecting wire links into the holes to complete the circuit. You may find breadboards frustrating if you try to use them for large complicated circuits, because you may have problems with connections and keeping components apart. You may also find that some component leads will not fit the holes.
An alternative, perforated grid board just has plated-through holes to mount the components. You solder the components to the board and join components point-to-point, either by soldering or (less commonly) by wire wrapping. This method is useful for small, simple circuits with only a few components.

**Permanent construction methods**

Once you have simulated your design and tested that it works by using a prototype method, you will probably want to make a more permanent circuit that can be economically reproduced. Your design software may have a facility to convert your schematic design into a printed circuit board (PCB) layout. Some software will automatically route the connecting tracks for you. More complex circuits may require double-sided PCBs, which have tracks on both sides of the board. A big advantage of PCBs is that they can be mass produced.

Designing your own PCB means that you can allow for different-sized component leads, chips, surface mount components and so on, which might have been difficult to allow for on the prototype.

**Testing electronic circuits**

It is important that you know what the expected voltages, currents and waveforms should be at key points in the circuit you are testing. This is so you can compare them with your measured values. The main instruments that you need to be able to use to test analogue circuits are a stabilised bench supply, a multimeter, an oscilloscope and a function generator.

Make sure that you know how to connect and use a **multimeter** correctly to measure voltages and currents. You can also check resistor values and test diodes and, on most multimeters, transistors provided that the circuit is not powered.

A **function generator** is a source of signals of different frequencies. The functions available are normally sine, triangular and square wave. You can vary the frequency and amplitude of the signal and may also be able to adjust the duty cycle of the waveform. Most function generators you are likely to use will be audio-frequency generators with a range of about 0.03 Hz to 3 MHz. They may have ‘low’ and ‘high’ output impedances to allow for matching to different loads – for example, low impedance to connect directly to a loudspeaker or high impedance to connect to an oscilloscope.

An **oscilloscope** plots voltage on the vertical axis against time on the horizontal axis. You can alter the sensitivity of the voltage axis by adjusting the **gain**

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Veroboard (see **Figure 19.3**) has a grid of holes at 0.1 inch spacing. You fit components through the holes, with the components on the blank side of the board. The board is usually made of a phenolic resin or is sometimes a fibreglass-reinforced board. The reverse side of the board has parallel copper tracks running the length of the board. Component leads and connecting links are soldered to the tracks. Dual in-line packages fit the matrix. The layout needs to be planned carefully. You have to cut the tracks in places to separate components that are not connected. It is best to plan the layout on a grid before starting construction.

You can use an alternative to Veroboard, a strip board, to build a more permanent circuit, and the connections will be more reliable. You can buy several variants of strip board.

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**Figure 19.2** Breadboard prototype circuit

**Figure 19.3** Veroboard
(V cm⁻¹). Dual-trace oscilloscopes allow you to compare two signals simultaneously. This is really useful when you are measuring the gain of an amplifier, because you can see the input and output signals on the same screen at the same time. You can control the gain of each trace separately. The time base (s cm⁻¹) alters the speed at which the spot travels across the screen. Normally you would adjust the time base to view just over two complete cycles of the signal(s) you are measuring. It is important to make sure that the gain controls are in the ‘calibrate’ position if you want to take accurate measurements. You may also have to adjust the ‘stability control’ to make sure that each trace across the screen starts at the same point so that you will see a steady trace.

Figure 19.4 shows some basic equipment for electronic testing. More complex instruments that you might use occasionally are a Bode plotter, a spectrum analyser and a frequency counter.

A multimeter and an oscilloscope can also be used to test digital circuits, though you may need to use some additional instruments.

A logic probe gives a visual indication of whether a signal is at logic level 0 or logic level 1. It may be switchable to use with different logic families. A logic probe can be used with a logic pulser to check that a logic level changes as expected. Many digital circuits use multiple logic inputs and outputs. You can use a logic clip to connect onto an integrated circuit (IC) to monitor all the pins at the same time. A logic analyser is a more complex test instrument that captures many signals simultaneously and displays them on-screen. You can set up the analyser to trigger on a given event, collect samples and display them. The analyser can check for such things as signals that never change their logic level (‘stuck at’ faults) or signals that always change together (potential short circuit). You can also check for timing problems, which could cause glitches. You can use a word generator to generate bit patterns.

Follow these steps to prepare for the work you will be doing in this unit:

1. Get to know the measuring instruments that you need to use.
2. Examine the type of multimeter that you will be using. Practise measuring low-voltage direct current (d.c.) and alternating current (a.c.) voltages and currents in simple circuits.
3. Use the multimeter to measure resistor values and note what happens when you measure values in circuits. (Make sure the power is not connected!)
4. Set up a function generator to give a sinusoidal output of frequency 1 kHz. Connect the signal to an oscilloscope and adjust the amplitude to 2 V. Set the oscilloscope voltage gain so that the full trace is visible and it is as high as possible. Adjust the oscilloscope time base to give approximately two complete cycles on the screen.
5. See what happens if you change the function to output a triangular waveform, then a square waveform.

A2 Diode devices and diode-based circuits

Semiconductors

Key terms

Conductor – a material that has very low resistance and easily passes an electric current. Most good conductors are metals, such as copper, aluminium and silver.

Insulator – a material that has very high resistance. It is generally a non-metal. Examples of good insulators include plastics and rubber.

Semiconductor – a material such as silicon (Si), germanium (Ge) or gallium arsenide (GaAs) that has electrical properties somewhere between those of a conductor and an insulator.

• Pure semiconductor materials are called intrinsic semiconductors.

• Extrinsic semiconductors contain very small amounts of impurity chosen to increase the conductivity. The introduction of measured amounts of impurity is called doping.
The most commonly used semiconductor material is silicon. Silicon has the atomic number 14 and is in Group IV of the periodic table. A silicon atom has four valence electrons, which form covalent bonds with four other atoms to form a crystal structure (see Figure 19.5). Covalent bonds are very strong, so at low temperatures there are very few electrons ‘free’ to move around. Therefore, intrinsic silicon behaves more like an insulator. As the temperature is increased, the atoms gain energy and more covalent bonds can be broken. The more you raise the temperature, the greater the number of bonds broken and hence the number of charges free to conduct. Whenever an electron gains sufficient energy to break a bond, the resulting covalent link is no longer electrically balanced. In effect, the ‘hole’ that remains has a positive charge that is equal in magnitude to the charge on an electron.

The PN-junction diode

If you dope a single crystal of silicon with acceptors on one side and donors on the other, then a PN-junction is formed. Initially there is a concentration gradient of charge across the crystal, so electrons will move towards the p-type region and holes towards the n-type region. Holes and electrons will recombine in the central region, forming a zone that has no free charges, called the depletion zone (see Figure 19.7). An equilibrium state will be reached such that the width of this depletion zone is more or less constant. The actual width will depend on several parameters, including the relative doping concentrations of p-type and n-type, as well as the temperature. There is a potential barrier to the movement of free charge carriers across the boundary.
**Key terms**

**Anode** – the connection to the p-type material.

**Cathode** – the connection to the n-type material.

**Forward bias** – describes a diode where the anode is more positive than the cathode.

**Reverse bias** – describes a diode where the anode is more negative than the cathode.

**Barrier potential** – the minimum forward bias voltage needed for conduction to start.

**Majority carriers** – the charge carriers due to doping, which are holes in p-type material and electrons in n-type material.

**Minority carriers** – the holes in n-type material and electrons in p-type material due to thermally generated hole–electron pairs in the silicon lattice.

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**Forward-biased PN-junction**

If you connect the positive terminal of a suitable voltage supply to the anode of a PN-junction (left diagram in **Figure 19.8**), the voltage effectively narrows the depletion zone. When the applied potential is sufficient to overcome the barrier potential, electrons and holes can move freely across the junction, both contributing to the overall current.

**Reverse-biased PN-junction**

Reversing the voltage supply effectively widens the depletion zone, establishing a greater barrier to the movement of majority carriers (right diagram in **Figure 19.8**).

The n-type region contains not only majority free electrons from the donor atoms but also minority holes that have been created by thermal agitation of the silicon lattice. Similarly, there are minority electrons in the p-type region. These will find the bias conditions such that the electric field (potential gradient) across the junction ‘pulls’ them across. Although this reverse current is normally very small, it is extremely important. If the reverse voltage is high, then the minority carriers are accelerated and ‘avalanche breakdown’ can occur, which is usually non-recoverable.

Anode (+) ☐ Cathode (–) 

Forward bias

Anode (–) ☐ Cathode (+) 

Reverse bias

**Figure 19.8** PN-junction diode biasing

The type of diode that you are most likely to use has a standard PN-junction as described above. Such diodes can be grouped into small-signal types, used for low-current applications, and rectifier diodes, used for high-current and high-voltage applications.

The **light emitting diode (LED)** is another common type of diode. If you forward-bias an LED, current flows and light is produced. There are a variety of colours available. Developments in LED technology are fast finding their way into lighting and display applications, such as the backlighting of television screens. **Laser diodes** also produce light, but a major difference is that the light produced by laser diodes is coherent. They are used in DVD and CD players and laser pointers.

**Photodiodes** are used for detecting light. There are several types, and they are typically used in reverse bias. They are widely employed in communications applications.

**Zener diodes** are used in reverse bias to provide a stable reference voltage. They typically have a narrow depletion zone due to the doping concentrations of the p-type and n-type regions. They break down at a known voltage (called the Zener voltage). You need to limit the current with a series resistor to avoid permanent damage.

**Research**

Investigate the types of diodes mentioned above and their typical applications.

Here are some additional diode types that you could investigate:
- Schottky diode
- tunnel diode
- varactor (varicap) diode.

**Rectification**

The ability of a diode to conduct current in one direction and block it in the other is useful in a number of applications. The most common is **rectification** – converting an alternating current (a.c.) signal into a direct current (d.c.) signal.

In the rest of this section we explore circuits used to develop a low-voltage d.c. regulated power supply. For each type of circuit:

- Use a computer-aided design (CAD) package to draw the schematic.
- Simulate the output using virtual meters and an oscilloscope.
- Connect the circuit using a prototype system and measure the signals.
- Compare the results you obtained from measurement and from simulation.
**Half-wave rectifier**

![Half-wave rectifier diagram]

Figure 19.9 shows a half-wave rectifier circuit. The diode is forward biased on the positive half-cycle, so it conducts. The current through the load will be the same shape as the voltage supply producing it. The diode is reverse biased on the negative half-cycle, so no current will flow through the load on the negative half-cycle. The diode has to be chosen so that it can withstand the peak inverse voltage (PIV).

**Full-wave rectifier**

We consider two types of full-wave rectifier circuit.

- **Centre-tapped transformer**

![Centre-tapped transformer diagram]

Figure 19.10 shows one circuit for full-wave rectification, the bi-phase rectifier. The voltages in each half of the transformer secondary are in opposite phases to each other. The centre tap is taken as the reference point. Diode D₁ is forward biased on the positive half-cycle and diode D₂ is reverse biased. Current flows through the load (from top to bottom as drawn) via D₁. On the negative half-cycle D₁ is reverse biased and D₂ forward biased. Current flows through the load (from top to bottom as drawn) via D₂. The result is that current flows on both half-cycles through the diode that is forward biased. Current cannot flow in the other direction. The output stays at the same polarity all the time, but it is no longer alternating – it is pulsed d.c. The frequency is twice the supply frequency. Note that each diode needs to be able to withstand twice the PIV of the half-wave rectifier.

A multimeter connected across the load would not read the peak value of the waveform; it would read an average value over a cycle, which can be found from calculating the area under the curve and dividing by the time period. It can be shown that this average value is given by

\[
V_{\text{avg}} = \frac{V_{\text{peak}}}{\pi}
\]
Full-wave bridge rectifier

The full-wave bridge rectifier (Figure 19.11) uses four diodes, D1, D2, D3, and D4, connected in such a way that opposite pairs conduct together. The current through the load is steered in the same direction (see Figure 19.12).

Practical supplies often use bridge rectifier blocks, which have the four diodes built as a single circuit element.

Smoothing (filter)

The simplest way to smooth the pulse output of a rectifier is to use a reservoir capacitor (see Figure 19.13). This capacitor charges on the rising edge of the waveform and discharges on the trailing edge. The capacitor value has to be chosen so as to reduce the ripple voltage.

Zener diode regulator

You have already seen that Zener diodes are used in reverse bias. They are designed to give a fixed reverse breakdown voltage. For example, an NXP BZX79-C5V1, 113 Zener diode, 5.1 V 5% 0.5 W, has a Zener voltage of 5.1 V ± 5% and a
maximum power dissipation of 0.5 W. Note that the Zener diode must be able to carry all of the output current if the load is disconnected. The series resistor protects the Zener diode by limiting the current that can flow (see Figure 19.14).

![Figure 19.14](image)

**Worked Example**

Calculate the minimum preferred value of series resistor for a 5.1 V Zener diode regulated power supply if the input voltage to the regulator is 12 V and the maximum power rating of the Zener diode is 0.5 W.

**Solution**

The maximum current that can flow through the Zener diode is

\[ I_{\text{max}} = \frac{P}{V_z} = \frac{0.5}{5.1} = 0.09804 \text{ A or } 98.04 \text{ mA}. \]

The minimum value of the series resistor is

\[ R_s = \frac{V_s - V_z}{I_{\text{max}}} = \frac{12 - 5.1}{98.04 \times 10^{-3}} = 70.4 \Omega. \]

Select the nearest preferred value of resistor: \( R_s = 82 \Omega \).

**Pause Point**

1. Explain the difference between conductors, insulators and semiconductors.
2. What is doping and how does it affect the properties of a semiconductor material?
3. Identify different types of diode from their circuit diagram symbols. Explain how they work and what they are used for.

**Hint**

Use the internet to find out more details about the construction and operation of diodes. Use a CAD package to draw schematic circuit diagrams and simulate their operation. Build prototype circuits and practise taking measurements.

**Extend**

Compare the outcomes from the simulations and measurements you have taken. Do they match what you expect?

### A3 Transistor devices and transistor-based circuits

There are two main classes of transistor: the **bipolar junction transistor (BJT)** and the **field-effect transistor (FET)**. The transistor principle was first reported in 1948 by Bardeen and Brattain. The term ‘transistor’ was coined as a contraction of ‘transfer resistor’, indicating that a large current is controlled by a smaller one. Further work by Schockley led to the development of the bipolar structure and the subsequent evolution of a range of electronic amplifying and switching elements. Schockley proposed the structure of field-effect transistors in 1948, but their development was restricted until the benefits of their use in integrated circuits were recognised.
**Bipolar transistor**

The bipolar junction transistor is a three-terminal device. Each terminal is connected to one doped region of either an NPN or a PNP ‘sandwich’. The three regions are known as the **emitter**, the **collector** and the **base** (see Figure 19.15).

![Figure 19.15 Diagram and circuit symbol for an NPN bipolar transistor](image)

The arrow on the emitter in the circuit symbol indicates the direction of conventional current flow. You will find that NPN bipolar transistors are more widely used than PNP transistors. The PNP symbol differs only in the direction of the arrow, and circuits using PNP transistors will have opposite polarities. The diagram shows a symmetrical sandwich with identical doping of both emitter and collector regions, but this is very rarely the case in practice. Usually the emitter region is physically smaller than the collector region and has a higher doping concentration.

If you think of a system as having two connections for the input signal and two for the output signal, it follows that since a transistor has three terminals, one of them must be made common to both input and output signals. The three possible modes of connecting a transistor in a circuit are known as **common emitter**, **common base** and **common collector**. Their symbols are shown in Figure 19.16. You are more likely to use the common emitter configuration. The common collector circuit is also known as the emitter (or voltage) follower.

![Figure 19.16 Three modes of bipolar junction transistor connection](image)

The output characteristic of a transistor describes how the collector current ($I_C$) varies with the potential difference across the collector and emitter ($V_{CE}$) at a fixed value of the base current ($I_B$) or base–emitter voltage ($V_{BE}$). Figure 19.17 shows the output characteristics for different values of the base current.

The characteristics show that the collector current is proportional to the base current for a good proportion of the working area. The ratio is known as the ‘forward current transfer ratio in common emitter mode’ or, more simply, the **current gain**. It can be written in a number of ways, such as

$$\frac{I_C}{I_B} = h_{fe} = \beta$$

![Figure 19.17 Typical bipolar junction transistor characteristics](image)
Consider the circuit shown in Figure 19.18:

- Try simulating it and see what happens when the switch is in position A. Measure the voltage between pairs of terminals (base–emitter, base–collector, collector–emitter).
- What happens when the switch is in position B?
- Does the same happen if you build a prototype circuit?

![Figure 19.18 Bipolar junction transistor as a switch](image)

**Biasing a BJT**

The transistor needs to be correctly biased to conduct current. From the practical activity with Figure 19.18 you should have seen that when the switch is in position A, the collector is at a higher potential than the base, which is at a higher potential than the emitter. If you think about the junctions, then the base–collector junction is reverse biased and the base–emitter junction is forward biased. The base–emitter voltage is approximately 0.7 V. The collector–emitter voltage is very small. In this case the transistor is ‘fully on’. It is said to be **saturated** because no more collector current can pass.

When the switch is in position B, the base and emitter are at the same potential and the transistor is fully off. It is said to be **cut-off**.

Transistors can be used as switches, but there is a limit to the current they can carry. Care must be taken when switching inductive loads, such as a relay, and a reverse-biased diode is usually used with a relay to prevent damage to the transistor caused by a **back e.m.f.** (electromotive force or voltage) (see Figure 19.19).

![Figure 19.19 Bipolar junction transistor switching a relay](image)

**Common emitter amplifier**

A common emitter amplifier, such as that shown in Figure 19.20, is an example of a **Class A amplifier** because the transistor amplifies both positive and negative parts of the input signal. The output is an accurate amplified copy of the input signal waveform. You need to select the component values so that the transistor is perfectly biased within its active region (Figure 19.21). This ensures that the output signal fits between the saturated and cut-off regions with no distortion.

![Figure 19.20 BJT common emitter amplifier](image)

**Key term**

**Back e.m.f.** – a voltage in the reverse direction which results from a current through an inductor being switched. (See Lenz’s law on page XX.)
The bipolar transistor is a current-controlled device. The collector load resistor \( R_3 \) converts the varying collector current into a voltage. \( R_4 \) is included to prevent thermal runaway. If \( R_4 \) were not included, an increase in \( I_C \) would lead to a temperature rise in the transistor, which would reduce its input resistance and cause \( I_B \) to increase. This then increases \( I_C \) and would rapidly lead to thermal breakdown of the device. With \( R_4 \) included, any increase in \( I_C \) causes the potential at the emitter to rise, which decreases \( V_{BE} \), which in turn reduces \( I_C \), and hence \( V_{BE} \) is restored. Unfortunately, \( R_4 \) prevents the very changes required in an amplifier. \( C_3 \) is included to allow the a.c. signal to bypass \( R_4 \) without affecting the d.c. bias conditions (see Figure 19.22).

One of the important measures of an amplifier is its **voltage gain** \( (A_v) \). You calculate voltage gain using the formula

\[
\text{voltage gain} = A_v = \frac{\text{voltage output}}{\text{voltage input}}
\]

**Key term**

**Voltage gain** – the ratio of voltage output to voltage input.
Voltage gain can also be expressed in decibels (dB):

\[
\text{voltage gain (dB)} = 20 \log (A_v) = 20 \log \left( \frac{\text{voltage output}}{\text{voltage input}} \right)
\]

Another important measure is the **bandwidth**. This is the range of frequencies for which the voltage output is above (approximately) 70% of its maximum value. These 70% thresholds are called **3 dB points**, because

\[
20 \log (0.7) = -3 \text{ dB}
\]

Consider the circuit shown in **Figure 19.23**.

**Figure 19.23** BJT common emitter amplifier with component values

- Try simulating the circuit and see what happens when you change the values of the components one at a time (see **Figure 19.24**).
- Does the amplifier work in the way you expected?
- Plan a layout for the circuit that works best on a prototyping system such as a breadboard.
- Does the real circuit behave in the same way as the simulation?

**Figure 19.24** Testing a BJT common emitter amplifier
Field-effect transistors

There are two basic types of field-effect transistor (FET): the junction FET (JFET – see Figure 19.25) and the metal oxide semiconductor FET (MOSFET). Both types depend on the use of an applied electric field to control the current flowing through a doped channel (which could be n-type or p-type). A FET is usually simpler to fabricate, and takes up less space than a BJT. As a result, FETs are suitable for use in very large-scale integration (VLSI) devices such as memory and processors.

![Diagram of JFET construction](image)

Figure 19.25 JFET construction

There are two types of MOSFET – a) depletion or b) enhancement (see Figure 19.26).

![Diagram of MOSFET construction](image)

Figure 19.26 MOSFET construction

Note the direction of the arrow on the JFET symbol in Figure 19.27:

- into the device indicates an **N-channel** device
- away from the device indicates a **P-channel** device.

You can analyse a FET amplifier in a similar way to the BJT by using its characteristics, its load line or small-signal models.

Figure 19.27 shows the circuit for a JFET common source amplifier.
A4 Operational amplifier circuits

Operational amplifiers (op amps) are the most widely used analogue integrated circuits. An op amp is a multi-stage integrated circuit containing approximately 20 transistors. The output voltage is proportional to the difference between the inputs. The two inputs are referred to as inverting and non-inverting (see Figure 19.28).

Real op amps do not have infinite gain at all frequencies. If you measure the open-loop gain of a typical operational amplifier such as a uA741, you will find it to be approximately 100 dB between 0 Hz (d.c.) and about 100 Hz. The output voltage gain then decreases linearly with frequency down to unity gain (1) at about 1 MHz, as shown in Figure 19.29.
From the characteristic shown in the figure, at 10 kHz the gain is 40 dB, so

\[
40 \text{ dB} = 20 \log(A_v)
\]

\[
\frac{40}{20} = 2 = \log(A_v)
\]

\[
A_v = 10^2 = 100
\]

Therefore the gain–bandwidth product is

\[
A_v B = 100 \times 10000 = 1000000.
\]

**Applications of operational amplifiers**

**Comparator (or difference) amplifier**

If the operational amplifier is used in an open-loop configuration (that is, with no feedback), the gain is very high (theoretically infinite). The linear portion of the characteristic shown in Figure 19.30 is exaggerated to show that it is there, but it is extremely steep and you would find it very difficult to measure. (Imagine trying to balance a very long pole at its centre - a very slight movement will make it topple one way or the other.)

\[
\text{Voltage gain } = A_v = \infty
\]

- If \(v_2 > v_1\) then \(v_{out} \approx +v_{cc}\)
- If \(v_1 > v_2\) then \(v_{out} \approx -v_{cc}\)

\[
\text{Figure 19.30 Operational amplifier open-loop transfer function}
\]

- If you connect the inverting input more positive than the non-inverting input, then the output is approximately \(-v_{supply}\).
- If you connect the non-inverting input more positive than the inverting input, then the output is approximately \(+v_{supply}\).

You would expect the output to be zero when the input terminal voltages are equal. However, it is impossible to make absolutely identical input transistors, and this results in unequal bias currents. In practice you will find that op amps have two terminals to apply an input offset voltage to balance the amplifier. The power supply and input offset connections are often not shown on circuit diagrams for simplicity. You may need to refer to the manufacturer’s data to find all the detail you need to use an op amp.

**Inverting amplifier**

The inverting amplifier (Figure 19.31) uses negative feedback to control the gain of the amplifier. For an ideal op amp the input resistance is infinite, which means there is no current flow between the two input terminals. If there is no current flow, then there is no potential difference between point J and ground, so J is said to be a ‘virtual earth’.

\[
\text{Gradient} = -\frac{R_2}{R_1}
\]

\[
\text{Figure 19.31 Inverting amplifier}
\]
The voltage gain for an inverting amplifier is

\[ A_v = \frac{v_{out}}{v_{in}} = -\frac{R_2}{R_1} \]

The negative sign is present because this is an inverting amplifier.

**Non-inverting amplifier**

The non-inverting amplifier (Figure 19.32) also uses negative feedback to control the voltage gain. The input signal connects via the non-inverting input.

![Figure 19.32 Non-inverting amplifier](image)

In this case the voltage gain is given by

\[ A_v = \frac{v_{out}}{v_{in}} = 1 + \frac{R_2}{R_1} \]

**Worked Example**

Calculate the voltage gain of the amplifier circuits shown in Figure 19.33. What will be the amplitude of the output voltage of each circuit if the amplitude of the input signal is 50 mV?

**Solution**

Circuit (a) is an inverting amplifier:

- voltage gain \( A_v = \frac{R_2}{R_1} = -\frac{220 \times 10^3}{10 \times 10^3} = -22 \)

- \( v_{out} = A_v v_{in} = -22 \times (50 \times 10^{-3}) = -1.1 \) V

Circuit (b) is a non-inverting amplifier:

- voltage gain \( A_v = \frac{R_1 + R_2}{R_1} = \frac{10 \times 10^3 + 220 \times 10^3}{10 \times 10^3} = 23 \)

- \( v_{out} = A_v v_{in} = 23 \times (50 \times 10^{-3}) = 1.15 \) V
As a practical investigation:

- Try simulating inverting and non-inverting operational amplifier circuits. Change the values of the resistors and see if the equations for voltage gain still work.
- Build a prototype of each circuit and check that it behaves in the same way as the simulation.

**PAUSE POINT**
Use the open-loop characteristic to estimate the open-loop bandwidth of the operational amplifier.

**Hint**
Bandwidth for the open-loop amplifier is from 0 Hz to the −3 dB point. Follow the example to calculate the voltage gain converted from the decibel value.

**Extend**
Estimate the bandwidth if the same operational amplifier is used to make a non-inverting amplifier with a gain of 20 dB.

### Passive filters

A filter circuit allows frequencies in a certain range to pass while blocking other frequencies. There are several filter types, the most common being the **low-pass** filter, the **high-pass** filter and the **band-pass** filter. **Figure 19.34** shows the ideal behaviours of these filters.

![Figure 19.34](image)

**Figure 19.34** The ideal frequency response of a) a low-pass filter, b) a high-pass filter and c) a band-pass filter

A simple passive low-pass or high-pass filter can be built using a resistor and a capacitor in a potential divider arrangement. A band-pass filter is a combination of a high-pass and a low-pass filter. **Figure 19.35** shows circuit diagrams for these three types of filter.

![Figure 19.35](image)

**Figure 19.35** RC networks of a) low-pass, b) high-pass and c) band-pass filters

The output voltage of the filter is lower than the input voltage, so the gain factor is less than 1. This means that the circuits attenuate the signal:

\[
gain = 20 \log \left( \frac{v_o}{v_i} \right) < 1
\]

The frequency responses of real RC filters do not have the sharp cut-offs shown in **Figure 19.34**. This is because the reactance of the capacitor varies with frequency, causing the output voltage also to vary. Therefore the gain (attenuation) is dependent on the frequency of the input voltage. The reactive element (the capacitor) also causes a phase change between the input and output signals.
In a low-pass filter, because it is a potential divider network, the output voltage is

\[ v_o = v_i \frac{X_C}{\sqrt{R^2 + X_C^2}} \]

where \( X_C \) is the capacitive reactance: \( X_C = \frac{1}{2\pi f C} \).

- At low frequencies, the impedance of the capacitor is much greater than that of the resistor, so \( v_o \approx v_i \).
- At high frequencies, the impedance of the capacitor is much less than that of the resistor, so the output voltage is attenuated.

The cut-off frequency of the filter is defined as the frequency at which the output power has dropped to half the level of the input power. This happens when the impedances of the resistor and capacitor are equal, that is,

\[ R = \frac{1}{2\pi f C} \]

Rearranging gives

\[ f_C = \frac{1}{2\pi RC} \]

The phase angle at the cut-off frequency is given by \( \Phi = -\tan^{-1} \left( \frac{X_C}{R} \right) \).

Because \( X_C = R \), we have \( \Phi = -45^\circ \).

The combination of the plots of gain and phase angle against frequency is known as a **Bode plot**.

*Figure 19.36* shows the Bode plot for a low-pass filter.
Active filters

An active filter uses an operational amplifier to amplify the attenuated signal from the RC filter.

Figure 19.37 shows the circuit of an active low-pass filter that uses an operational amplifier in its non-inverting configuration. The overall gain of the circuit is the product of the gain determined by the resistors $R_1$ and $R_2$ (in the way explained in the section on op-amp configurations) and the low-pass filter attenuation.

![Figure 19.37 An active low-pass filter](image)

**Worked example**

Calculate component values for a low-pass filter with a cut-off frequency of 500 Hz and a low-frequency gain of 20.

**Solution**

For the non-inverting amplifier:

$$\text{gain} = 1 + \frac{R_2}{R_1} = 20$$

$$\frac{R_2}{R_1} = 19$$

Select a suitable value for $R_1$:

if $R_1 = 10 \, \text{k}\Omega$ then $R_2 = 190 \, \text{k}\Omega$.

This calculated value of $R_2$ is not one that is normally available, so use two resistors in series (such as $180 \, \text{k}\Omega$ and $10 \, \text{k}\Omega$).

For the low-pass filter:

$$RC = \frac{1}{2\pi f_C} = \frac{1}{2\pi(500)}$$

Select a suitable value for $R$:

if $R = 10 \, \text{k}\Omega$ then $C = \frac{1}{2\pi(500) \times 10 \times 10^3} = 31.8 \times 10^{-9} \, \text{F} = 31.8 \, \text{nF}$.

This calculated value of $C$ is not one that is normally available. The closest preferred value is 33 nF.
Assessment practice 19.1

Explore a range of analogue devices and circuits by simulation and by building and testing circuits, and compare their theoretical and physical operation.

The circuits you investigate should include:
• a diode-based regulated full-wave rectification circuit
• a single-stage common emitter transistor amplifier circuit
• an inverting or non-inverting operational amplifier circuit.

In each investigation you should:
• simulate at least one diode, transistor and operational amplifier analogue circuit using a CAD software package
• build each type of analogue electronic circuit and take measurements to demonstrate the operational characteristics of the circuit
• evaluate the differences in operation between simulation and testing of the physical circuit for at least one diode, transistor and operational amplifier analogue circuit.

Plan
• What resources do I need for the task? How can I get access to them?
• How much time do I have to complete the task? How am I going to successfully plan my time and keep track of my progress?

Do
• I know what strategies I could employ for the task. I can determine whether these are right for the task.
• I can assess whether my approach is working and, if not, what changes I need to make.
• I can set milestones and evaluate my progress at these intervals.
• I can identify when I’ve gone wrong and adjust my thinking/approach to get myself back on course.

Review
• I can evaluate whether I met the task’s criteria (i.e. succeeded).
• I can draw links between this learning and prior learning.
• I can explain what skills I employed and which new ones I’ve developed.

Explore the safe operation and applications of digital logic devices and circuits that form the building blocks of commercial circuits

B1 Logic gates and Boolean algebra

Logic gates are the building blocks of digital circuits. The most common digital logic gates available are the TTL 74xxx series (made using BJTs) and the CMOS 40xxx series (made using MOSFETs). Both types have a large number of standard gates and functions available. Most of these are available in a number of configurations, including dual in-line package (DIP – see Figure 19.38) and surface-mount technology (SMT). Packages containing simple gates normally have 14 or 16 pins. More complex integrated circuit packages are likely to have more pins.

Key terms

Logic gate – a circuit that carries out a Boolean logic function.
Boolean algebra – a two-state logic algebra (named after George Boole).

Figure 19.38 Logic gates in DIP configuration

The basic logic functions available as logic devices are AND, OR and NOT gates. The inputs and output of each gate use only two voltage levels or states: logic 1 and logic 0.
The behaviour of each type of gate is described by a Boolean statement and can be summarised in a **truth table**, which lists the output for each possible combination of inputs. The basic gates can be extended to include **NAND** (NOT AND), **NOR** (NOT OR), **XOR** (EXCLUSIVE OR) and **XNOR** (EXCLUSIVE NOR) to provide more functionality. **Table 19.1** shows the standard circuit symbols and truth tables for the different types of logic gate.

### Table 19.1 Logic gates and their corresponding symbols and truth tables

<table>
<thead>
<tr>
<th>Gate</th>
<th>Symbol</th>
<th>Boolean expression</th>
<th>Input A</th>
<th>Input B</th>
<th>Output Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>AND</td>
<td>![AND Symbol]</td>
<td>$A \cdot B$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>ANSI</td>
<td></td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>DIN</td>
<td></td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>OR</td>
<td>![OR Symbol]</td>
<td>$A + B$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>ANSI</td>
<td></td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>DIN</td>
<td></td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>NOT</td>
<td>![NOT Symbol]</td>
<td>$\overline{A}$</td>
<td>0</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>ANSI</td>
<td></td>
<td></td>
<td></td>
<td>0</td>
</tr>
<tr>
<td>NAND</td>
<td>![NAND Symbol]</td>
<td>$\overline{A \cdot B}$</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>ANSI</td>
<td></td>
<td>0</td>
<td>1</td>
<td>1</td>
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<tr>
<td></td>
<td>DIN</td>
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<td>1</td>
<td>0</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>NOR</td>
<td>![NOR Symbol]</td>
<td>$\overline{A + B}$</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>ANSI</td>
<td></td>
<td>0</td>
<td>1</td>
<td>0</td>
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<tr>
<td></td>
<td>DIN</td>
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<td>0</td>
<td>0</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>XOR</td>
<td>![XOR Symbol]</td>
<td>$A \oplus B$</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>ANSI</td>
<td></td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>DIN</td>
<td></td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>XNOR</td>
<td>![XNOR Symbol]</td>
<td>$\overline{A \oplus B}$</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>ANSI</td>
<td></td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>DIN</td>
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<td>1</td>
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<td></td>
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<td></td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Logic gates can have more than one input, but they usually have only one output. For example, the 7400 has four 2-input NAND gates in a 14-pin DIP; each gate has one output. The 7410 has three 3-input NAND gates in the same-size DIP.
Comparing TTL and CMOS characteristics

The CMOS and TTL families have different electrical characteristics, summarised in Table 19.2, which means that the output of one type cannot usually drive (correctly operate) the input of the other. Although only two logic levels are allowed, in practice there is a range of acceptable voltages for logic 0 and logic 1. The logic levels for input and output are also slightly different. See Figure 19.39. The output specification is tighter than the input, to allow for signal degradation in transmission.

**Table 19.2** Comparison of logic families

<table>
<thead>
<tr>
<th>Property</th>
<th>74LS series</th>
<th>74HC series</th>
<th>74LHCT series</th>
<th>4000 series</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>TTL low-power Schottky</td>
<td>High-speed CMOS</td>
<td>TTL-compatible high-speed CMOS</td>
<td>CMOS</td>
</tr>
<tr>
<td>Supply (+V_s)</td>
<td>5 V</td>
<td>2 V to 6 V</td>
<td>5 V</td>
<td>3 V to 15 V</td>
</tr>
<tr>
<td>Inputs</td>
<td>Pull up to 1 if unused</td>
<td>Very high impedance</td>
<td>As 74HC but compatible with 74LS outputs</td>
<td>Very high impedance</td>
</tr>
<tr>
<td>Outputs</td>
<td>Low current</td>
<td>As 74LS but higher current, can source and sink 20 mA</td>
<td>As 74LS but higher current, can source and sink 20 mA</td>
<td>Very low current, can source and sink about 5 mA</td>
</tr>
<tr>
<td>Fan-out (per one output)</td>
<td>Can drive up to 10 74LS or 50 74HCT inputs</td>
<td>Can drive up to 50 CMOS, 74HC and 74HCT or 10 74LS inputs</td>
<td>Can drive up to 50 CMOS, 74HC and 74HCT or 10 74LS inputs</td>
<td>Can drive up to 50 CMOS, 74HC and 74HCT inputs or one 74LS input</td>
</tr>
<tr>
<td>Maximum frequency</td>
<td>35 MHz</td>
<td>25 MHz</td>
<td>25 MHz</td>
<td>1 MHz</td>
</tr>
<tr>
<td>Power usage</td>
<td>mW</td>
<td>µW</td>
<td>µW</td>
<td>µW</td>
</tr>
</tbody>
</table>

TTL was designed to be used with a regulated 5 V d.c. supply. Early CMOS could use a supply ranging from 3 V to 15 V. Developments in CMOS technology have resulted in an increase of switching speeds while maintaining lower power consumption. **Fan-out** is the number of similar inputs that can be driven by an output. The **propagation delay** is the time taken for a signal to pass from the input to the output.

**B2 Combinational logic**

The output of a **combinational logic circuit** is always the same for the same combination of inputs – it is a logical combination of the inputs. In a similar way to individual gates, the behaviour of the circuit can be summarised in a truth table.
**Worked Example**

A burglar alarm has a sensor on the door (A), a movement sensor in the lounge (B) and an alarm set switch (C). The alarm (Q) should sound if the alarm set switch is set and either the door sensor or the movement sensor (or both) is activated.

a) Write the truth table for the system.

b) Write a logic expression for when Q is logic 1.

c) Convert the Boolean equation into logic gates.

**Solution**

a) The truth table is shown in Table 19.3.

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

b) The output is logic 1 if any of the following three conditions is true:

\[
\overline{A} \cdot B \cdot C \quad (A \cdot \overline{B} \cdot C) \quad (A \cdot B \cdot C)
\]

Therefore \( Q = (\overline{A} \cdot B \cdot C) \) OR \((A \cdot \overline{B} \cdot C)\) OR \((A \cdot B \cdot C)\).

c) Writing the expression from b) in Boolean algebra:

\[
Q = (\overline{A} \cdot B \cdot C) + (A \cdot \overline{B} \cdot C) + (A \cdot B \cdot C)
\]

Each of the bracketed terms is a 3-input AND gate. You also need:

- a 3-input OR gate to combine the three bracketed terms
- two NOT gates (inverters) to make the \( \overline{A} \) and \( \overline{B} \) terms.

**Figure 19.40** shows the logic circuit diagram.

**Figure 19.40** Logic circuit diagram for burglar alarm

You may have to find an alternative way to make the gate. For example, use a 3-input NOR followed by a NOT.
What would you do if you could not find the exact gates you want?

a) Investigate using two 2-input gates to make a 3-input gate.

b) It is difficult to find a TTL 3-input OR gate. Investigate making it another way by using two 2-input OR gates or a NOR gate with a NOT gate.

Hint
Use truth tables to compare the logic of the equivalent circuits.

As a practical activity, consider the burglar alarm in the worked example:

- Try drawing the schematic diagram and simulating it. You will have to find suitable gates in the libraries.
- Build a prototype and check that it works as expected.

Minimising a logic circuit

You can often reduce the number of gates used to construct a circuit by using a minimisation technique. A Karnaugh map is a way of writing the truth table in a slightly different way. Each box represents one line from the truth table. The grid is arranged so that each box has only one input that differs from the boxes immediately above, below, left and right. See Figure 19.41.

<table>
<thead>
<tr>
<th>INPUTS</th>
<th>OUTPUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0</td>
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<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 19.41 Truth table and corresponding Karnaugh map for a 3-input logic circuit

To perform the minimisation, you circle groups that are next to each other vertically and horizontally. The size of a group can be any power of 2 (i.e. 1, 2, 4, 8 etc.). The aim is to make the groups as large as possible. In the example of Figure 19.41 there are two overlapping groups, as shown in Figure 19.42.

<table>
<thead>
<tr>
<th>AB</th>
<th>00</th>
<th>01</th>
<th>11</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 19.42 Grouping values in a Karnaugh map

- In the horizontal group: A is always logic 1; B can be logic 1 or logic 0, so eliminate it; C is logic 0. Therefore the Boolean expression for the horizontal group is \( A \cdot \overline{C} \).
- In the vertical group: A is always logic 1; B is always logic 0; C can be logic 1 or logic 0, so eliminate it. Therefore the Boolean expression for the horizontal group is \( A \cdot \overline{B} \).

Combining the groups, the overall Boolean expression minimises to

\[ Q = A \cdot \overline{C} + A \cdot \overline{B} \]
**De Morgan’s laws**

Sometimes you need to change the type of gate so that you use only one type. NAND or NOR are called universal gates because you can make all the other gates from them. De Morgan’s laws are most simply stated as

\[ \overline{A \cdot B} = \overline{A} + \overline{B} \]
\[ \overline{A + B} = \overline{A} \cdot \overline{B} \]

In words, the steps are:

- invert the variables
- change the operator (AND to OR, OR to AND)
- invert the whole expression.

**Research**

Investigate the use of de Morgan’s laws to make AND, OR, NOT, OR and XNOR gates with NAND gates only and with NOR gates only.

Why would you want to build a circuit using only one type of gate?

**B3 Sequential logic circuits**

The output of a **sequential** logic circuit depends on the combination of inputs and the current state of the outputs.

**Bi-stable devices**

There are several kinds of bi-stable circuits, also known as flip-flops.

The basic building block of sequential circuits is the R-S bi-stable circuit. This uses two NAND gates, with the output of one feeding back to the input of the other and vice versa (Figure 19.43). When \( R = \text{logic 1}, Q = 0 \); this is called RESET. When \( S = \text{logic 1}, Q = 1 \); this is called SET. When \( R = S = \text{logic 0}, Q \) stays at the value it was originally; this is called LATCH. The combination \( R = S = \text{logic 1} \) is not allowed because it gives an undesired result. In addition, switching from \( R = S = \text{logic 0} \) directly to \( R = S = \text{logic 1} \) gives an indeterminate result depending on which gate switches faster.

![Figure 19.43 R-S flip-flop using NAND gates](image)

The limitations of the R-S flip-flop can be overcome by using modified versions. The most commonly used modifications are the clocked **D-type** flip-flop (Figure 19.44) and the **J-K** flip-flop (Figure 19.45). D-type and J-K flip-flops usually trigger on either the rising or the trailing clock edge. You need to check the manufacturer’s data to know which.
The D-type flip-flop is sometimes called a ‘data-type’ flip-flop because the data is clocked into the output. It may also be referred to as ‘delay-type’, because the movement of data from input to output is delayed until the next clock pulse.

**Shift register**

A register is an array of flip-flops used to store binary data. The most suitable flip-flop to use in a register is the D-type (see Figure 19.46). A J-K flip-flop can be configured to operate as a D-type by placing an inverter between the J and K inputs. A register in which the data bits can be moved to the left or right (or vice versa) is known as a shift register.

### Transition Table

<table>
<thead>
<tr>
<th>Input</th>
<th>Before Clock</th>
<th>After Clock</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>Qn</td>
<td>Qn+1</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>RESET (Q = 0)</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>1</td>
<td>SET (Q = 1)</td>
</tr>
</tbody>
</table>

[Output latched at previous value if Clock = 0]

**Research**

Investigate the development of flip-flops from the basic R-S bi-stable circuit to practical applications of D-type and J-K flip-flops. Why do practical J-K flip-flops use a ‘master-slave’ arrangement? Discover what the implications are of flip-flops being triggered on either the rising or the falling edge.

![Figure 19.46 Three-stage shift register using D-type flip-flops](image-url)
A logic 0 or logic 1 at the data input will be clocked through to Q0 on the first rising clock edge. On the next rising edge this signal is passed to Q1, and so on. At the same time, the new logic level at D0 is passed to Q0. Three bits of data can be passed in series by three clock pulses. These can be read in parallel. The shift register is converting serial data to parallel data – ‘serial in parallel out’ (SIPO). The data can be stored in the register by disabling the clock signal. It can also be clocked out in series by three further clock pulses – ‘serial in serial out’ (SISO).

**Asynchronous (ripple) counter**

![Figure 19.47](image_url) Three-stage asynchronous (ripple) counter using J-K flip-flops

The counter in **Figure 19.47** is termed **asynchronous** because the outputs Q0 to Q2 do not change simultaneously, but rather the value ‘ripples’ through – Q0 causes changes in Q1, which in turn causes changes in Q2. This effect causes a delay between the initial clock pulse and a settled result, known as the propagation delay. Connecting the J and K inputs together means that the output of a flip-flop toggles if held at logic 1, but does not change if held at logic 0. This is called a **T-type** (toggle) flip-flop.

**Synchronous counter**

The synchronous counter shown in **Figure 19.48** aims to overcome the propagation delay of a long asynchronous counter by clocking all the outputs simultaneously. You can use J-K flip-flops connected as T-types. Note how the stages connect together using the input and output of the previous stage.

![Figure 19.48](image_url) Three-stage synchronous counter (using T-type flip-flops)

### PAUSE POINT

What methods do you need to use to test digital circuits?

Are there any differences in simulating, building and testing combinational and sequential circuits?

**Hint** Look for a range of resources that explain the topics simply and clearly. Learn the circuit symbols for the basic gates and be able to use their truth or function tables.

**Extend** Research how logic gates and circuits are used to carry out arithmetic and logic functions and how they can be used to control the flow of data.
Assessment practice 19.2

Explore a range of digital devices and circuits by simulation and by building and testing circuits, and compare their theoretical and physical operation.

The circuits you investigate should include:
• a combinational logic circuit containing at least three inputs and five gates
• two sequential logic circuits, such as a counter and a shift register with at least three stages.

The tasks for each investigation are:
• to simulate at least one combinational logic circuit and two sequential logic circuits using a CAD software package
• to build at least one combinational logic circuit and two sequential logic circuits and take measurements to demonstrate the operational characteristics of the circuits
• to evaluate the differences in operation between simulation and testing of the physical circuit for at least one combinational logic circuit and two sequential logic circuits.

Plan
• What resources do I need for the task? How can I get access to them?
• How much time do I have to complete the task? How am I going to successfully plan my time and keep track of my progress?

Do
• I know what strategies I could employ for the task. I can determine whether these are right for the task.
• I can assess whether my approach is working and, if not, what changes I need to make.
• I can set milestones and evaluate my progress at these intervals.
• I can identify when I’ve gone wrong and adjust my thinking/approach to get myself back on course.

Review
• I can evaluate whether I met the task’s criteria (i.e. succeeded).
• I can draw links between this learning and prior learning.
• I can explain what skills I employed and which new ones I’ve developed.

C

Review the development of analogue and digital electronic circuits and reflect on own performance

Improving your own performance

Just doing something does not necessarily lead to learning. You need to be actively engaged and deliberately reflect on the activity to gain fully from the experience.

While working through this unit you have encountered a lot of technical knowledge, developed practical and thinking skills, collected data and critically analysed the results. As a professional engineer in the future, you will need to draw upon the things you have learned to progress in your career. You need to develop the ability to continue learning as technology advances at a rapid pace. All professional engineers have to carry out continuous professional development (CPD) activities as part of maintaining their status. Reflective practice is a key tool in bringing together theory and practice and helps to place what you have learned into context. Reflection does not just mean looking back at the past; it also includes developing personal qualities and skills and assessing how they can help you reach higher levels in the future. It is a way for you to become an increasingly independent learner who knows what you want to achieve and can work purposefully towards it.

You will have become used to the concept of ‘Plan–Do–Review’ while carrying out assignments.
The **Plan** stage is where you identify such things as:

- what you need to do
- why you are doing it
- how you are going to do it
- what resources you need
- what evidence you will need to collect
- how you can keep records so that you can use them later.

In the **Do** stage you need to:

- follow your plan and meet deadlines
- prioritise tasks and not become distracted
- review progress and change your plan if necessary
- know when to ask for help or advice
- collect evidence as you generate it and keep records in an organised way, for example, by using a logbook
- review your work continually as you go along, and check any results that look as though they might be out of place.

In the **Reflect** stage you need to consider:

- what you did
- what you learned
- how you learned it
- how you felt about it
- whether or not it was a good way for you to learn
- what learning methods did not work for you
- what skills you developed
- what went well, what went less well and what you would do differently the next time
- whether you needed to change your plan, and why you made any changes
- whether your changes were effective
- what you would do differently in the future
- whether or not you met your targets.

Although it is important that you achieve your goals, the focus of reflection is more on the learning process, what you did and how you overcame any difficulties.
Assessment practice 19.3

Review and reflect on the practical activity to explore electronic devices and their use in analogue and digital logic circuits.

Prepare a 'lessons learned' report of around 500 words to explain how you applied health and safety, electronic and general engineering skills. Your report should also include an explanation of the importance and use of particular behaviours (such as communication skills).

The tasks are:

- to review and reflect on the activities that you have completed and make notes about what went well, what improvements you could make and what you would do differently next time
- to review and reflect on what you have learned from carrying out the activities in terms of knowledge, skills and techniques
- to produce a professional report.

Plan

- What am I being asked to do?
- What are the success criteria for this task?
- What am I learning? Why is this important?

Do

- I can make connections between what I’m reading/researching and the task I need to do, and I can identify the important information.
- I am recording my own observations and thoughts.
- I can identify when I’ve gone wrong and adjust my thinking/approach to get myself back on course.

Review

- I can draw links between this learning and prior learning.
- I can explain what skills I employed and which new ones I’ve developed.
- I can make informed choices based on reflection.
- I can use this experience in future tasks and learning activities to improve my planning and to monitor my progress.

Further reading and resources

Websites

Electronics Tutorials: www.electronics-tutorials.ws

An excellent set of short tutorials covering a wide range of devices and applications. Very clearly written, with excellent illustrations.

Everyday Practical Electronics: www.epemag3.com

An online magazine with useful articles and guides for the keen amateur electronics engineer.

Elektor: www.elektor.com

A magazine containing lots of project ideas and kits to develop skills and knowledge.
Focusing your skills

Constructing and testing electronic circuits
It is important that you develop your knowledge and skills so that you can confidently:

- identify components from their circuit symbols
- identify real components and their values using colour codes etc.
- draw schematic diagrams using a suitable software package
- simulate analogue and digital circuits
- prepare components to connect them in prototype and permanent circuits – for example, strip and trim wires and leads, form component legs to fit

- position components in prototype circuits using breadboards and matrix boards such as Veroboard
- solder components neatly and accurately
- follow risk assessments and other guidance to work safely
- select and use appropriate measuring instruments accurately
- tabulate data and present it in suitable graphical forms such as waveform sketches, graphs, photographs
- compare measurements with expected values and investigate any anomalies
- keep accurate, organised records

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Simon Bentley  Senior electrical engineer

I have been working as an electrical design engineer for 15 years. I have worked on a wide variety of projects, from multimillion-pound university buildings to the renovation of a Grade I listed building. Being an engineer is exciting because each day can be very different. My role involves the design of electrical services for buildings. These include power, lighting, data, fire alarm and lightning protection systems and many more. A great many devices these days can be controlled remotely, and it is important to keep up to date with new developments.

My work involves me working closely with professional engineers from other disciplines, so it is really important for me to have a working knowledge of what they do, even if I do not have their expert knowledge. Working in teams is an important skill that you need to develop as an engineer. Time management and personal organisation are also really important because contracts have to be completed on time, not only to avoid financial penalties but also to maintain the company’s good reputation.

As an engineer I am always working to guidelines and regulations, so it is really important for me to link theory to practice. For example, all cables within a building have to be sized, light levels calculated and spacing of fire alarm equipment set out to guidance given within regulations. Completing my qualifications at college has really helped me understand what information I need to know and where to find it. Although I am well qualified, it is still very important to continue with professional development and keep up to date with changing technology. I regularly attend continuous professional development (CPD) events. It is important to keep my work profile as up to date as possible so that my company remains competitive.
Getting ready for assessment

Emily has recently completed a BTEC National in Engineering and is now studying for a Higher National Certificate (HNC). She attended college part-time as part of her apprenticeship. Emily shares her experience below.

**How I got started**
I started college as part of my apprenticeship. I tried to make sure that I was always on top of the work because I was worried that if I let it slip I would find it difficult to catch up.

**How I brought it all together**
- I took careful notes during the day at college.
- As soon as I got home I organised the notes into folders.
- I set aside time at home to organise my college work and to sort out anything I did not understand so I could ask about it next time. I did some college work at home and let my family and friends know that I was working at those times. Doing college work on a regular basis meant I did not have to spend a lot of time in one go. I got into the habit so it was not a problem.
- Practical assignments were all carried out in college. I made sure that my results looked OK and I knew what to do with them before leaving.

**What I learned from the experience**
I was worried when I first started the course that I might have difficulty keeping up. I thought that if I let the coursework slide I would find it difficult to catch up, because I needed to balance college, work and family life. As it turned out I did a lot better than I thought. I think being organised really helped. The college staff were really helpful.

**Think about it**
- Do you know what you have to do in each assignment?
- Is there anything that you need to find out before you start?
- Have you saved all your notes and results and stored them safely so that you can use them to do the assignment?
- Have you planned your time to make sure that you can meet the deadline?
- Have you checked that what you’ve written meets the assessment criteria? Aim for the highest grade.