CHAPTER 24

Electronic Systems

24.1 INTRODUCTION

Semiconductor devices are able to do much more than rectify AC voltages. When semiconductors replaced the older vacuum-tube valve devices in electronic applications, the circuits were termed 'transistorised' or 'miniaturised' since the transistors were so robust and small compared with the delicate and bulky thermionic vacuum-tube valves that had been the mainstay of electronics until then. It has been said that if the car industry progressed at the same rate as the electronics industry, a Rolls Royce would be the size of a matchbox, cost fifty cents and get a million kilometres per litre!

In this chapter we will look at the development of electronic systems involving input–output transducers such as microphones, loudspeakers and motors as well as transistors and **integrated circuits** (ICs). The resistance of semiconductor material is dependent on the level of impurity doping. The capacitance of a reverse bias PN diode is altered by the voltage applied to the base–emitter junction of a transistor. These properties make it possible to combine arrays of resistors, capacitors and transistors onto a single piece (or **chip**) of silicon, which ultimately becomes an integrated circuit. These ICs can be mass-produced to accomplish any desired electronic function. Today, there exist hundreds of integrated circuit families. Very large scale integration (VLSI) circuits and very high speed integration (VHSI) circuits in recent years have seen tremendous improvements in device reliability, performance speed and lowering of cost within electronic systems such as audio, video, telephone and computer technology. There is hardly a domestic or industrial machine existing today that is not, in part at least, an electronic system.

In 1969 the American corporation Intel developed a range of medium-sized ICs for use in hand-held calculators. An Intel engineer, Edward Hoff, realised that it was simpler to design a single-purpose IC for all calculators and to make this chip 'programmable' so that it could be controlled by a unique external chip containing a specific set of instructions. This general-purpose chip was called a **microprocessor**, or single chip central processing unit (CPU). The microprocessor has become the heart of many modern electronic systems. The chip can perform a vast range of functions depending on the external instructions given to it. The modern personal computer is nothing more than a microprocessor joined to an array of external chips such as memory and the basic input–output system as well as keyboard input and video output circuitry.

24.2 INPUT–OUTPUT TRANSDUCERS

To produce the control functions carried out by circuits in electronics, **electrical signals** (the actual voltages and currents), usually, are manipulated by components in various ways. Electrical information is obtained as voltages and currents from the input to a particular circuit or circuit system. For example, a radio receives small electrical voltages (a radio signal) from the input antenna, or a public address system uses an input signal produced by a microphone. The circuit performs some function such as amplification and this new electrical information is available to the electronic system output. This output may be a loudspeaker or a visual display such as an LED array or a video screen. An electronic system allows us to control electrical information and usually allows several stages of electrical energy conversions to take place. Thus, an electronic system consists of a defined set of blocks of circuitry, as shown in Figure 24.1. This is called a schematic or an electronic **block diagram**.

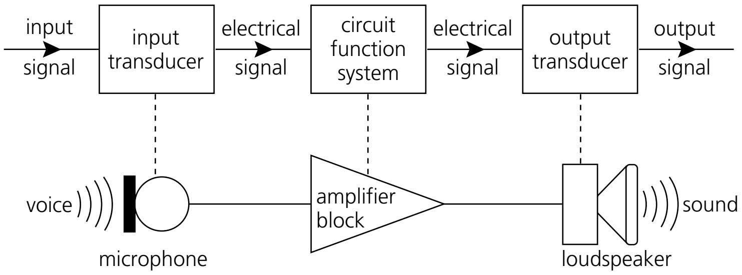


Figure 24.1
Block diagram of an electronic system.

Table 24.1 TRANSDUCERS IN ELECTRONICS

INPUT TRANSDUCERS	OUTPUT TRANSDUCERS
Microphone	loudspeaker
Antenna	light bulb
Thermocouple	LED and display
Photocell	relay coil
LDR	electric motor
Thermistor	cathode ray tube
Laser diode	audio–video heads

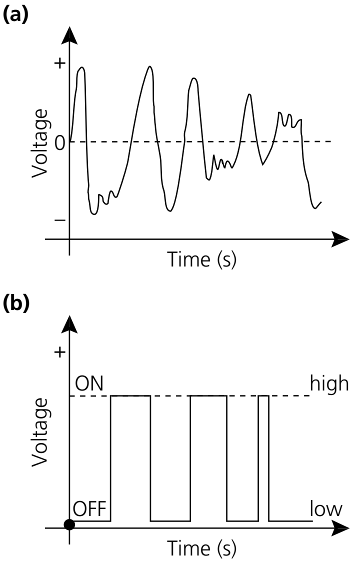
Transducers are devices that convert energy from one form to another in electronic systems, usually involving electrical energy. Table 24.1 lists commonly used input and output transducers in electronics. Occasionally an input transducer can be the same as an output transducer. For example, in some simple intercom systems the loudspeaker can be both the input microphone as well as the output speaker, although, of course, not at the same time. For instance, the two functions may be controlled by a push-to-talk switch.

Analog to digital conversion (ADC)

Electronics is concerned with the control of electrical signals that carry information to devices that interpret the signals and perform a particular function. Block diagrams are often used to get an overall picture of the various functions performed within the system as a result of the electrical signals being interpreted. Two types of electrical signals are commonly found in modern electronic systems. These are **analog** or continuously varying electrical voltage signals, and **digital** or electrical voltage signals that are either ON or OFF. If a digital signal is ON it means that the voltage level is high or equal to the circuit supply voltage whereas if a digital signal is OFF then the voltage level is low or at zero volts.

Figure 24.2 illustrates the nature of these two different types of signals graphically.

Figure 24.2
Electrical signals: analog **(a)**; digital **(b)**.



Analog signals are widely used in audio, video and television systems, while digital signals are used in computers and microprocessor- or microcontroller-based consumer devices. Digital electronics is a well-established field, with many older analog devices now phased out and replaced by digital processing; examples include the digital DVD and audio CD revolution, and mobile phone technology. Underlying these processes is a technique called 'analog to digital conversion' or **ADC**. The reverse process, digital to analog conversion or DAC, is equally important.

The input to an ADC consists of a voltage that varies among a theoretically infinite number of values. Examples are sine waves, the waveforms representing human speech, and the signals from a conventional television camera. The output of the ADC has defined levels or states. The number of states is almost always a power of two — that is, 2, 4, 8, 16, etc. The simplest digital signals have only two states and are called **binary**. All whole numbers can be represented in binary form as strings of ones and zeros.

Information is stored in a computer as groups of bits. A **bit** stands for a binary digit, 0 or 1. The only practical way of representing these two states in an electronic circuit such as a computer is to use two-state logic, or ON and OFF. 'OFF' represents logic 0, and 'ON' represents logic 1. In electrical terms, for most digital logic circuits, 0 volts represents logic 0 and 5 volts represents logic 1. Due to the ever-decreasing power consumption and increasing speed of modern digital circuits, the logic 1 voltage is decreasing to around 3 volts. In general, microprocessors use bits in groups of eight, which are called **bytes**. Groups of four bits are also used, and these are called **nibbles**. There are two nibbles in a byte.

The maximum number that a single byte can hold equals 255, and there are 256 different combinations of binary numbers, including zero, that can be represented. In the binary system, each binary digit or bit represents a power of 2. In the decimal number system, each digit represents a power of 10.

Example. 0 0 0 0 1 1 0 1 in binary (from right to left) represents;

$1 \times 2^0 = 1 \times 1 = 1$

$0 \times 2^1 = 0 \times 2 = 0$

$1 \times 2^2 = 1 \times 4 = 4$

$1 \times 2^3 = 1 \times 8 = 8$

Add these up to get a decimal equivalent $1 + 0 + 4 + 8 = 13$.

In the hexadecimal system, which is used in coding or programming computers, each digit represents a power of 16. There are no numbers past the digit 9, so the letters A to F are used to represent the digits 10 to 15.

Example: 0 1 2 3 4 5 6 7 8 9 A B C D E F These hex digits fit very nicely into a nibble.

0 = 0000 = 0 decimal
1 = 0001 = 1 decimal
2 = 0010 = 2 decimal, etc.
down to the hexadecimal value
F = 1111 = 15 decimal.

As two nibbles fit into a byte, there are also two hexadecimal numbers that fit into a byte. It becomes easy to break down large binary numbers into more something more manageable by splitting them into nibbles and into hexadecimal numbers.

Let's take a quick look at the process of ADC. Refer back to the section of Chapter 16 on modern sound technology (Section 16.10) for audio digital devices that make use of ADC.

In analog technology a simple waveform is recorded and used in its original form. For example, in a cassette tape recorder the varying voltage wave output from a microphone is applied directly through the magnetic recording head onto the magnetic tape. (Refer to Section 25.4.) The pickup head takes the analog signal back off the tape and sends it to the amplifier and speakers. Typical audio frequencies range from about 20 Hz up to about 20 kHz, which represents the music fidelity.

NOVEL CHALLENGE

'It is said that there are 10 types of people in the world: those who understand binary and those who don't.' Explain.

In digital technology a process of sampling the analog wave at a fixed interval is used. The amplitude of the sampled wave section produces a voltage that is converted into a number that is stored in the digital device such as a music or data CD. The sampling rate used in normal music CD recorders is 44.1 kHz or 44 100 numbers per second of music, while that used in DVD audio discs is 192 kHz. When an ADC sampling recording is made, engineers have control over two factors (Refer to Figure 24.3.):

- the **sampling rate** — how many samples are taken per unit time
- the **sampling precision** — the number of different gradations in amplitude that are used when sampling.

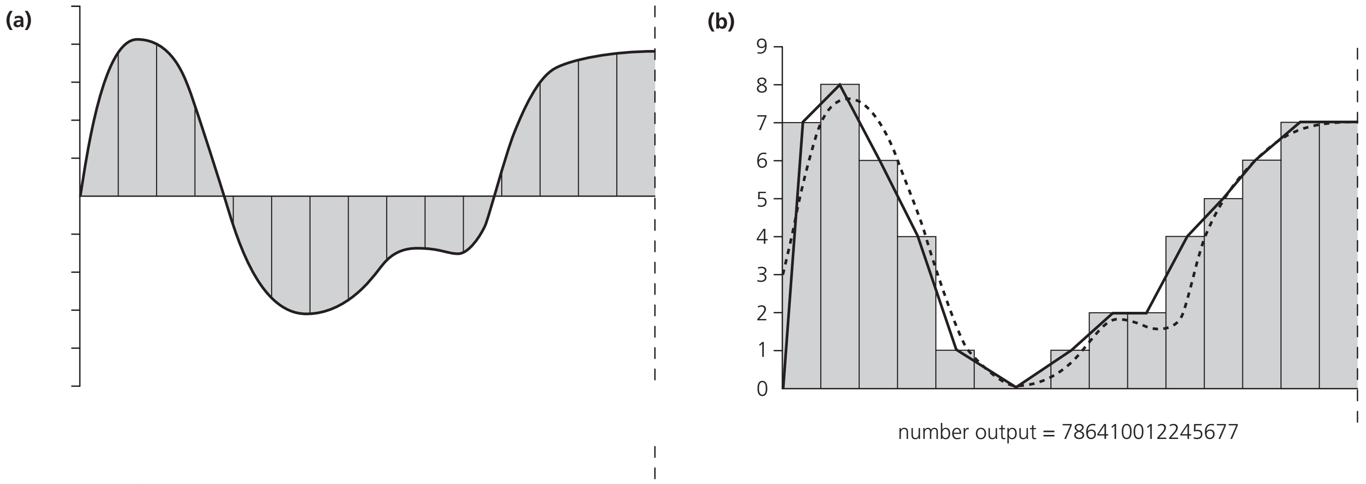


Figure 24.3
Analog to digital conversion (ADC): **(a)** original analog waveform; **(b)** sampled digital waveform.

You can see that in this diagram the horizontal time base might represent blocks at every one-thousandth of a second with an amplitude precision of 10 units. The shaded rectangles represent samples, with the ADC looking at the wave and assigning a closest decimal number value of between 1 and 9. These decimal numbers are converted to binary form. The ADC thus outputs a string of numbers in succession (a digital word) and produces a digital waveform with an obvious sampling error compared to the original analog waveform. However, as the sampling rate and precision increases (the number of shaded rectangles increases dramatically), the difference between the digital and analog waveforms reduces to nothing. In fact digital waveforms at high sampling rates are at a much higher fidelity.

The actual binary output from the ADC chip can be produced by a variety of electronic methods. The successive-approximation ADC is one of the most commonly used designs. This requires only a single comparator but will be only as good as the DAC used in the circuit.

Figure 24.4
ADC chip block diagram.

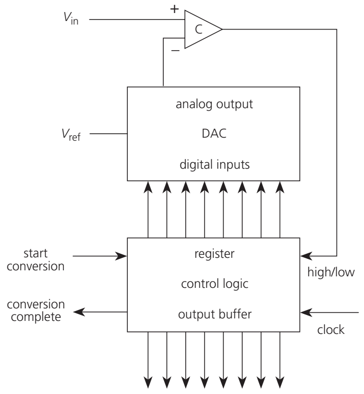


Figure 24.4 is the block diagram of an 8-bit successive-approximation ADC. The analog output of a high-speed DAC is compared against the analog input signal. The digital result of the comparison is used to control the contents of a digital buffer that both drives the DAC and provides the digital output word. As examples in 8-bit binary the decimal 7 = 00000111, 5 = 0000101, 2 = 0000010. You might like to check some websites that show you how to convert between decimal and binary. Note that modern digital ADC and DAC chips can have resolutions up to 18 bits and sampling rates up to 1.5 GHz.

High sampling rates and precisions produce large amounts of digital data in the form of number strings. On a CD, digital numbers are stored by the ADC as word bytes and it takes 2 bytes to represent 65 536 amplitude precision gradations or sample. On a normal stereo (2-channel) music CD which may hold up to 74 minutes of music data there will be about 780 megabytes of digital number storage. You should test this by doing the calculations — 2 bytes per sample at 44.1 kHz for 74 minutes!

The surface of a CD contains one long spiral track of data, which may be up to 5.0 km long. This track is made up of flat laser-light-reflective areas representing digital binary 1, as well as non-reflective bumps representing digital binary 0. This pattern of 1s and 0s is read by the scanning laser head and back-converted by the DAC, first into the digital waveform representing the original precision graduations at the sampling rate, and finally into the analog waveform.

One of the best advantages of digital recording is that the quality does not deteriorate over time like magnetic analog recordings. As long as the laser head can read the number string the information can be decoded. Today error correction techniques as well as number group compression techniques have allowed a tremendous amount of material to be recorded onto a disc. This is evident in multi-layer DVDs which can contain many hours of compressed audio and video information using MPEG technology. Many channels of digital audio are possible to give a finely tuned sound field from multiple speaker systems. Again refer to Section 16.10.

Let us now look at the basic electronic devices that underlie both analog and digital electronic processing systems. After all, to begin to understand complex systems, we need to be able to break them down into their component parts.

24.3 TRANSISTORS

The transistor is one of the most useful devices in electronics. The transistor, just like diodes, can change the form of electrical signals it receives and is therefore called an **active device**. The first transistor was developed by William Shockley, John Bardeen and Walter Brattain at the American Bell laboratories in New Jersey in 1947. This solid state device 'transferred' a current across a high-resistance material, so they called it a 'transfer-resistor' or transistor for short. This first point-contact transistor device had several limitations, including noisy amplification, low power handling capability and limited applicability because of its delicacy. William Shockley had also conceived the idea of the junction transistor, which was free of many of these defects and limitations. Today, most transistors are made of the junction type. Although they are being replaced in circuitry blocks by integrated circuits, the transistor is still essential in many applications and is manufactured in a wide variety of shapes and sizes.

Photo 24.1
Various transistors.

Transistor structure

A **bipolar junction transistor** consists of two PN junctions joined together, as shown in Figure 24.5. This is a bit like two diodes placed back to back. You might like to refer back to Chapter 23 for revision of semiconductor diodes. Two basic types are possible and illustrated as PNP or NPN, together with their symbols showing the direction of conventional current flow through the device. The transistor is called a bipolar device because current flows through the transistor using two different modes. In N-type silicon, current flows as mostly electrons, while in P-type silicon, current flows as holes. The three layers of the transistor are:

- **collector** (C), which in the case of an NPN-type is constructed as a lightly doped N-type silicon layer
- **base** (B), which is a very thin layer of lightly doped P-type silicon
- **emitter** (E), which is a heavily doped N-type silicon layer.

Notice the difference in the thickness of these layers from those of standard diodes. The transistor device is called bipolar because both majority and minority charge carriers are used during conduction. In general, the analysis of an NPN transistor in terms of current flow and bias voltage conditions can be reversed for a similar analysis of a PNP transistor. It is common in analysing the operation of a transistor to discuss a flow of electron current through the device; however, this is always precisely opposite to normal conventional current flow, which is used in most diagrams. Figure 24.6 shows the typical structure of an actual transistor constructed using a crystal of silicon on which layers are formed in a process called the planar epitaxial technique. The centre layer of a transistor, called the base, is always thinner than the outer emitter and collector layers. This is essential for the correct operation of the transistor and is the reason why two simple PN diodes cannot be used back to back to produce the same effect as a transistor in circuits.

In any practical transistor package, the very small piece of semiconductor is usually protected in an epoxy plastic housing and three connecting wire 'pigtails' or pins are attached to the three terminals, C, B and E. Manufacturers provide transistor pin-out diagrams to enable electrical connections to be correctly made to different types of transistor packages such as the common TO-92 pack, TO-220 pack and the TO-3 pack. It is important that correct pin connections are made in transistor circuits, as damage can easily occur if the power supply connections are reversed, for instance. You can refer to various electronics component catalogues for examples of these pin-out diagrams.

Transistors are used in electronic circuits in three ways, basically:

- as direct current (DC) amplifiers
- as fast acting electronic switches
- as AC voltage amplifiers.

We will now examine the first two of these ways, together with some practical circuit applications; the AC voltage amplifier will be left to Chapter 31.

Figure 24.5
Transistors: NPN **(a)**; PNP **(b)**.

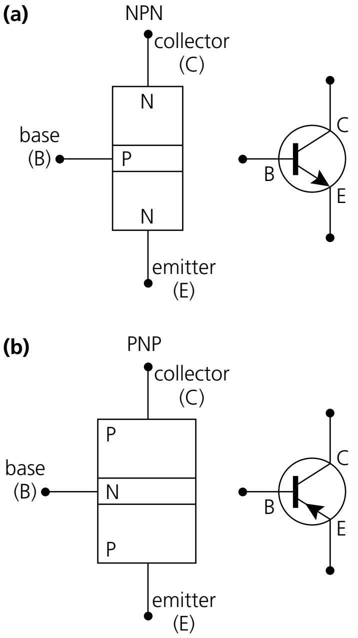
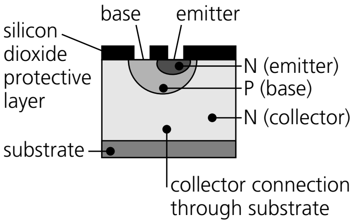


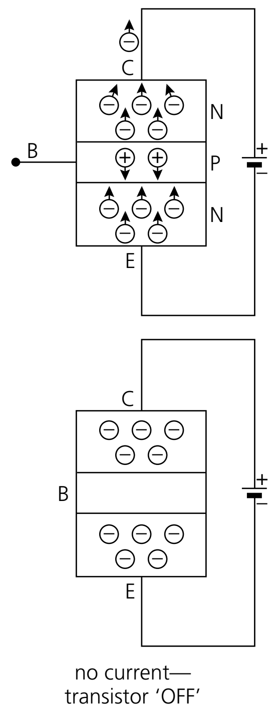
Figure 24.6
Transistor construction in cross-section.



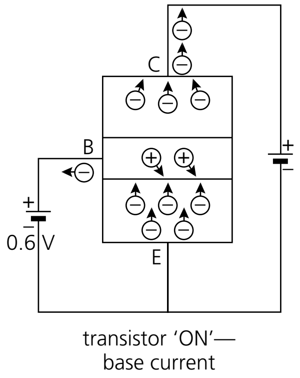
Direct current (DC) amplifiers

Figure 24.7
Transistor current amplifier: at switch-on and equilibrium **(a)**; using base bias **(b)**.

(a) At switch-on and equilibrium



(b) Using base bias



Let us consider what happens when an NPN transistor is connected into a circuit, such as in Figure 24.7**(a)**. When the voltage is applied free electrons in the N regions will tend to move from emitter to collector and free holes in the P region will move towards the emitter. These few holes moving against the electrons will be filled in by electrons in a short time and will cease to exist. This produces an effective potential barrier at the base layer and will stop any further current flow. In order to allow electron current to continue to flow from emitter to collector, the base layer requires a positive voltage. (See Figure 24.7**(b)**.) When this positive base voltage rises above 0.6 V, majority charge carriers begin to cross the emitter–base junction. Because the base is only lightly doped while the emitter is heavily doped, there will be many more electrons coming from the emitter than there will be holes coming from the base. Also, because the base region is very thin and lightly doped, most of the electrons avoid falling into holes in the base region. A continuous flow of electrons through the device is established by maintaining a positive voltage of 0.6 V at the base. Thus, electrons are 'emitted' from the emitter layer and 'collected' by the collector layer. Typically, only about 1% of the emitted electrons will fall into holes generated by the positive base and constitute the base current, I_B, while the remaining 99% of electrons pass from the emitter to the collector to form the collector current, I_C. Thus, the collector current is 99 times the base current and the transistor has produced direct **current amplification**.

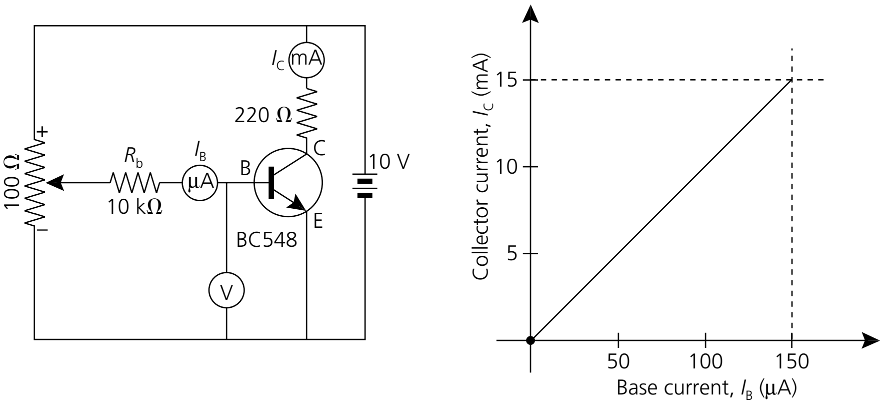
The ratio of the collector current to the base current is known as the current amplification factor or **current gain** of the transistor and is denoted by the symbol β (Greek letter beta) or h_{fe}. It varies for different transistors but usually lies in the range between 20 and 800.

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

Since small variations in base current are controlling larger variations in collector current, the transistor circuit involving base and emitter is often called the '**control circuit**' and the collector–emitter circuit is called the '**working circuit**'. If the base–emitter junction is forward biased, current will pass through both control and working circuits as long as the collector is positive with respect to the emitter. Small changes in the base current can produce large changes in the working current (NPN current amplification).

Figure 24.8 illustrates an actual test circuit that may be used to show current amplification by measuring I_B and I_C. Note that a voltage divider potentiometer is used to control base–emitter forward bias. The graph of output data I_C versus I_B can be used to derive the current gain, β, of the device being tested. Note also that a collector resistor is used in the circuit, which limits the maximum size of the collector current in order not to overheat and destroy the transistor.

Figure 24.8
Testing current gain, β.



A special type of transistor designed for high power levels and high current gain is called the **darlington**. It is essentially two bipolar transistors back to back on the same piece of silicon. The darlington pair has a switch-on voltage of about double that of a normal transistor, a DC gain value of about 1000, and if necessary can be made to handle up to about 5 A of current.

Example

Consider the circuit and graph of Figure 24.8.

(a) What voltage should register on the base–emitter voltmeter when a small collector current I_C begins to be measured?

(b) Use the graph of data supplied to calculate the current gain of the BC548 transistor in this circuit.

Solution

(a) Milliammeter, I_C, will not show any working current until V_{BE} reads at least 0.6 V as this is the switch-on voltage for the transistor.

(b)
$$\beta = \frac{I_C}{I_B} = \frac{15\ \text{mA}}{150\ \mu\text{A}} = 100$$

The current gain has a value of 100.

Transistor switches

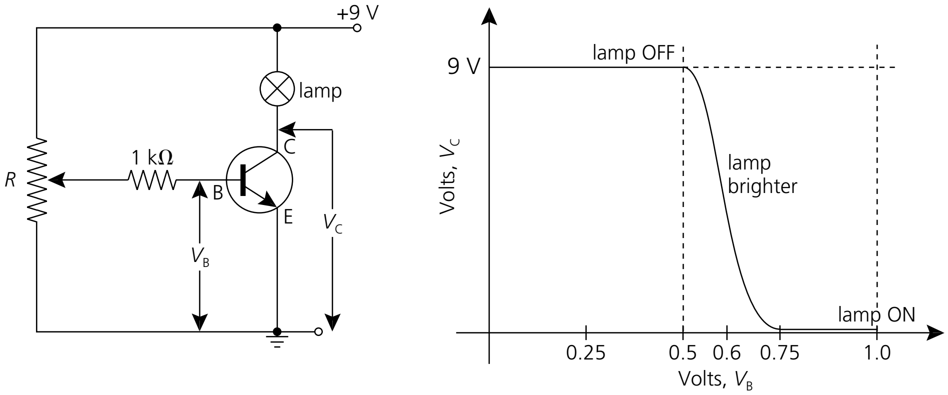


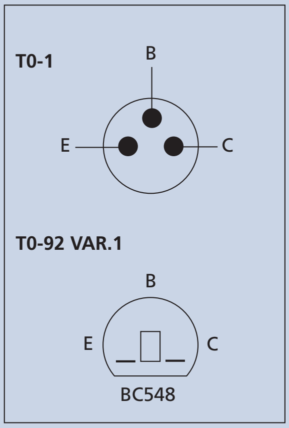
Figure 24.9
Transistor switch action.

The switching action of a transistor is produced by varying the voltage applied to the base so that the transistor is either turned ON (large collector–emitter current flowing) or turned OFF (no collector–emitter current flowing). Consider the circuit of Figure 24.9, showing a lamp in the working circuit. A potentiometer voltage divider is used to control and vary the voltage applied to the transistor's base. V_B and V_C are the voltages as measured at the base and collector with respect to the earth. The graph shows how the lamp's brightness is controlled as the potentiometer is varied. The analysis is as follows.

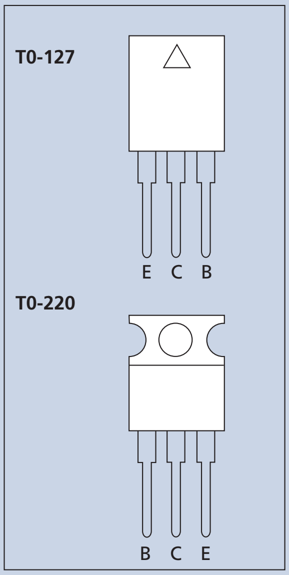
As the base voltage rises from zero, the lamp remains off, because the collector voltage is at 9 V so there is no potential difference across the lamp. The transistor is said to be turned OFF. It acts like an open switch (collector–emitter path). When the base voltage reaches 0.6 V (for a silicon transistor), the base current turns the transistor ON and it starts conducting. It takes only a small rise in base voltage, to about 0.75 V, until the transistor is fully ON or fully conducting. The transistor has a very low collector–emitter path resistance and it acts like a closed switch. The transistor's collector is now at a very low voltage, hence the full 9 V is applied across the lamp. It is turned ON and produces full brightness. Lowering the base voltage to below 0.6 V will turn the lamp off again.

Let's look at three more practical circuits making use of switching action.

TRANSISTOR OUTLINES BOTTOM VIEW

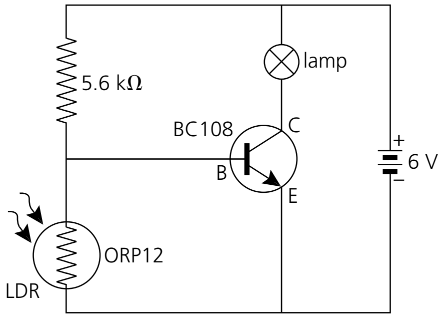


TRANSISTOR OUTLINES FRONT VIEW



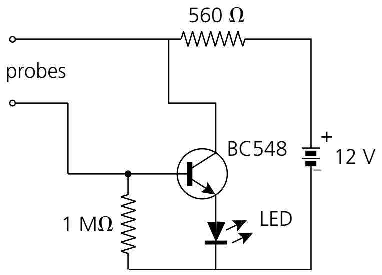
- Figure 24.10 shows an LDR or **light dependent resistor** controlling the base voltage. In bright light conditions the LDR has a low resistance, which means that the base voltage is held low, the transistor is OFF, its collector voltage is high and the lamp is turned off. In dark conditions the LDR has a high resistance, which means that the base voltage is held high, the transistor is ON and conducts, causing the collector voltage to go low and the large potential difference across the lamp causes it to switch on.

Figure 24.10
LDR switching circuit — automatic light switch.



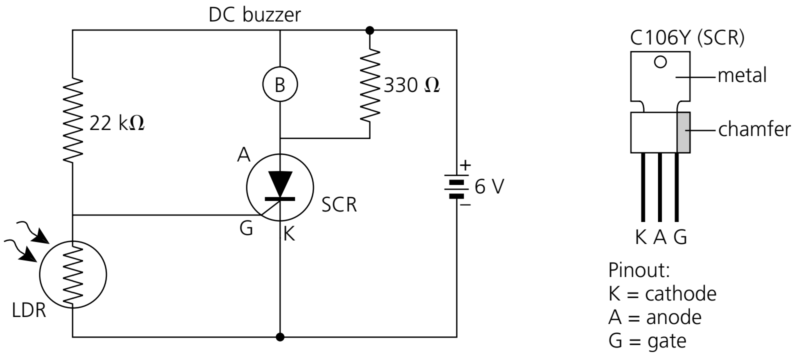
- Figure 24.11 shows a transistor switching an LED as a result of two circuit points being connected together with a resistance such as human skin. If a small base current is produced by holding the probes with opposite hands, the transistor is correctly biased and it switches on. This allows a collector–emitter current to flow through the LED and it illuminates. The LED will turn off again if the touch probes are released, because of the open circuit or very high resistance between collector and base.

Figure 24.11
Transistor touch switch.



- Figure 24.12 is a light-controlled high current switch, which might be used as a burglar alarm. The circuit contains both an LDR and a **silicon controlled rectifier** (SCR) device or **thyristor**, which differs from a transistor in that it not only can carry larger currents but once switched ON cannot be turned OFF by removing the voltage at the base terminal or gate, G. This circuit would operate as an alarm by ensuring that a bright light beam is shone onto the LDR, which would provide a low voltage at the SCR gate to keep it turned OFF. This keeps the buzzer turned OFF because the SCR anode is held high. If a burglar breaks the light beam, the LDR now has a high resistance, causing the gate to trigger, or turn ON, the SCR, and the buzzer would sound. The action of the SCR will keep the buzzer turned ON until such time as the power supply is disconnected.

Figure 24.12
Light controlled high current switch (SCR).



Activity 24.1 CHANGING THE CIRCUITS

Consider how to modify the circuits already presented to do slightly different jobs. For instance, how would you modify the following circuits?

1. Modify the circuit of Figure 24.10 to trigger when a light is turned ON rather than OFF, as, for example, in a circuit to automatically turn on the garage lights when the car is driven in at night.
2. Modify the circuit of Figure 24.12 to act as a fire alarm buzzer, using a thermistor sensor.

Before leaving the various transistor circuits to look at other semiconductor devices, let's consider the special type of transistor called a **field effect transistor** or FET. Remember that in a junction transistor the base current is needed to remove excess electrons in the base region to allow a larger working current to flow from collector to emitter. In some circuits even this small base current can provide difficulties. Consider Figure 24.13. In the FET device a current flowing from the 'drain' (collector) through the channel to the source (emitter) is controlled by an electric field produced by charges present on the gate (base). Only an extremely small electric field strength is necessary, provided by a very small gate current and this produces an extremely high effective input resistance for the device. FETs are used in amplifier circuits where large voltages are controlled by extremely small voltages at the gate. Such a situation might arise when trying to amplify the very weak electrical signals produced by the human body during muscle or nerve activity in medical diagnostic equipment such as an electrocardiograph.

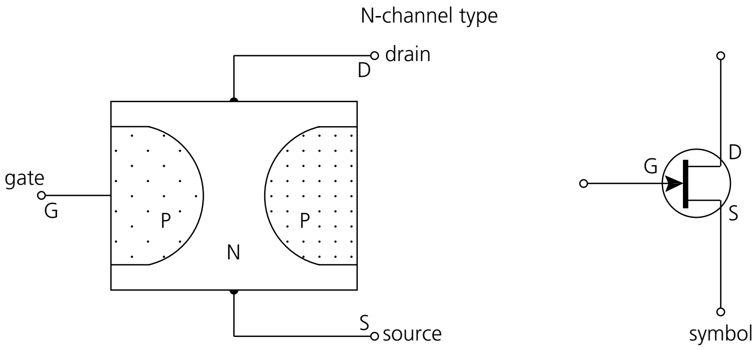


Figure 24.13 Field effect transistor (FET) — N-channel type.

Activity 24.2 SPECIAL TRANSISTORS

Transistor design has come a long way since the first bipolar junction type. Some further types of transistor you might like to research and present a report on are listed below. Find a common application circuit for each type:

1. Junction field effect transistor JFET.
2. MOSFET.
3. Power MOSFET.
4. Phototransistor MEL-12.

Questions

1 What is the difference between electronic analog and digital voltage signals? Give an example of electronic systems that interpret voltages of both types.

2 Explain what is meant by each of the following terms: **(a)** P-type semiconductor; **(b)** NPN transistor emitter; **(c)** NPN transistor base; **(d)** PNP transistor collector; **(e)** current value I_B.

3 An operating transistor has the following parameters: $\beta = 200$, $I_B = 15\ \mu A$. What are the values of I_C and I_E?

4 Figure 24.14 shows the schematic diagram for an NPN transistor in normal operation.

(a) Redraw this diagram showing a normal symbol for the transistor. Label E, B and C.

(b) Add the voltages X and Y, showing correct polarity.

(c) Show how the voltages X and Y can be obtained in practice from a single supply voltage V_{CC}.

Figure 24.14
For question 4.

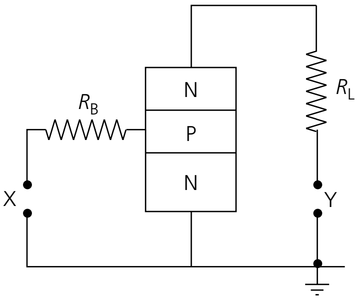
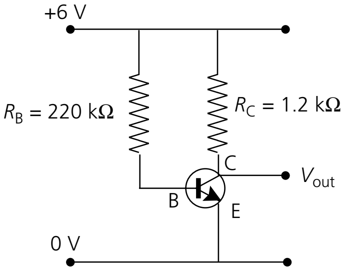


Figure 24.15
For question 6.

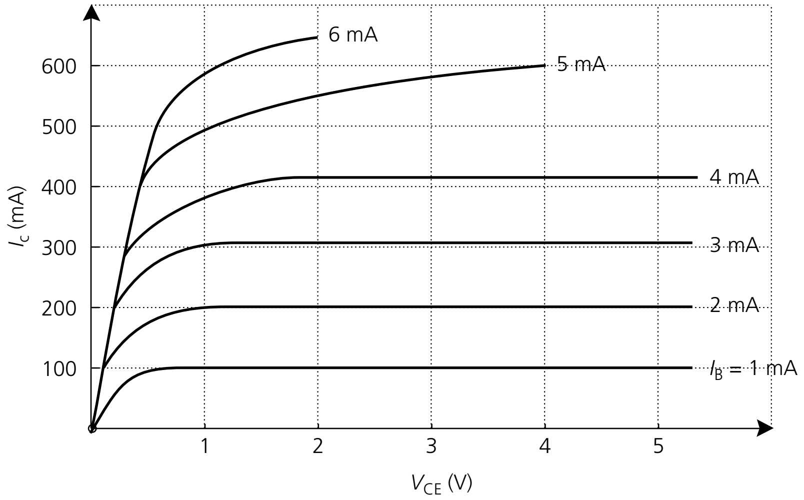


5 Explain the operating conditions that are necessary to make a transistor function as a switch.

6 In the circuit of Figure 24.15, the current gain of the transistor is 150. Calculate the value of the base current and the output DC voltage at the collector. Use the value $V_{BE} = 0.7$ V.

7 Figure 24.16 shows graphically the collector characteristics I_C/V_{CE} for a particular transistor. Calculate the transistor's current gain, β, when the base current is 2.5 mA and the collector–emitter voltage is 3.0 V.

Figure 24.16
For question 7.



Collector characteristics

24.4 INTEGRATED CIRCUITS

During the 1960s and 1970s advancements in semiconductor technology made it possible to combine larger numbers of active devices like transistors and diodes, as well as other passive components, onto a silicon chip. It has become possible to produce complete functional system circuits, involving both analog and digital processes, within a single integrated circuit package. The original integrated circuit concept was presented to engineers at an Institute of Radio Engineers symposium in Washington DC on 5 May 1952 in a paper by G. W. Drummer entitled 'Electronic components in Great Britain'. In this paper he stated:

> At this stage, I would like to take a peep into the future. With the advent of the transistor and the work into semiconductors generally, it seems now possible to envisage electronic equipment in a solid block with no connecting wires. The block may consist of layers of insulating, conducting, rectifying and amplifying materials, the electrical functions being connected directly by cutting out areas of the various layers.

The first microelectronics integrated circuit patent was filed on 6 February 1959 to a J. S. Kilby as US Patent No. 3,138,743, with the following statement:

> It is therefore, a principal object of this invention to provide a novel miniaturised electronic circuit fabricated from the body of semiconductor material containing a diffused P–N junction wherein all components of the electronic circuit are completely integrated into the body of semiconductor material.

Such integrated circuit (IC) packages represent the miniaturisation of electronics with consequent increase in speed and reliability of operation, as well as an overall massive reduction in costs of manufacture. An integrated circuit package may contain the equivalent of thousands of transistors and the most common method of construction is similar to the silicon planar method described for transistors. The IC fabrication technique is very complex and expensive as it involves etching layers of semiconductor, multiple photographic exposure through light-resistive masks and numerous steps of subsequent metallic vacuum deposition to form the transistor blocks and conducting pathways. It is important to realise that integrated circuits have been the single most important factor in the development of modern electronic systems.

Integrated circuits are mass-produced with variations in the type of basic transistor building elements within the chip design itself. These types are commonly referred to as **integrated circuit series**, such as the 74 series TTL chips and the 74LS series low power Schottky chips, both requiring power supply voltages of 5 V. More versatile are the 74C series CMOS chips (3–15 V), the 74HC series high speed CMOS chips (2–6 V) and the 4000 series CMOS chips (3–15 V). All these CMOS chips involve metal oxide semiconductor material and use field effect transistor (FET) construction. A disadvantage of all CMOS type ICs is that they are easily damaged by stray electrostatic charge and therefore must usually be handled taking special precautions.

The only component that cannot be integrated onto a silicon chip IC package is the electromagnet coil or inductor. Inductors need to be added externally to the chip in circuit construction, although it is possible to simulate their behaviour with a combination of passive capacitors and other active devices.

Integrated circuits generally fall into two categories, analog IC or **linear IC** devices, and **digital IC** devices. Analog ICs are used for processing analog voltage signals by such operations as amplifying, adding, multiplying, filtering and other more complex functions. The input and output voltages of these devices can have any value between the power supply voltages driving the device and there is a direct or linear functional relationship between the input and the output. Digital ICs are used to process **binary signals** where the input and output voltages of the device exist at only two states, called ON and OFF, or HIGH and LOW. Binary voltage states are often represented mathematically as a 1 or a 0: 1 = HIGH (ON); 0 = LOW (OFF).

PHYSICS UPDATE

Ever since 1999 the microchip giant IBM has continually perfected new forms of silicon–germanium chip processing technology. This technology involves the use of a combination of germanium atoms embedded in a silicon substrate, allowing much faster current conduction through the crystal and much smaller chip size. The heart of IBM's SiGe technology is a heterojunction bipolar transistor (HBT) doped with germanium to increase the electron transfer.

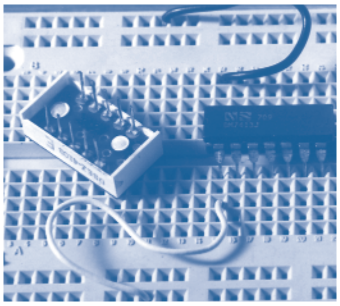
Today's 2 GHz microprocessors could be boosted to 50 GHz or more using the latest silicon–germanium technology. With over 1000 microelectronic patents in 2002 alone, IBM offers a range of industry-standard CMOS, RFCMOS, and silicon–germanium Bi-CMOS process technologies ranging in transistor size from 0.5 μm to 90 nm. Uses for the latest SiGe devices include wireless Bluetooth component chips, wireless LAN and global positioning systems chips, multi-action mobile telephone systems, and optical networking components.

The transistor operation underlying these digital ICs is a rapid switching action as described in the previous section. Digital IC circuits usually require fewer external discrete components than linear IC circuits and are tending in recent times to replace them in a lot of electronic systems. These digital IC application circuits will be discussed in more detail in Chapter 31.

Once the integrated circuit is fabricated, it can be encapsulated into a protective cover and connecting pins added so that it may be connected into a circuit with appropriate external components such as resistors, capacitors, diodes and transistors. A very common IC package is the **dual in line** (DIL) type. It was first fostered by Bryant Rogers as a dual in-line package (DIP) while at Fairchild Semiconductor in 1964. This type uses an epoxy plastic case with the IC chip embedded in it and two sets of parallel pins down each long side of the IC. Usually DIL packages contain 8, 14 or 16 pins. Manufacturers provide detailed drawings (schematics) and IC pin diagrams that show, most importantly, the power supply pins and other input–output pins. The pins on an IC are usually numbered consecutively anticlockwise, starting with pin 1 at the top left-hand corner when viewing from above the top of the IC. Photo 24.2 illustrates the IC package and its pins lying ready to be inserted into a circuit building protoboard.

Linear devices and application circuits

Photo 24.2
An IC ready to be inserted into a protoboard.



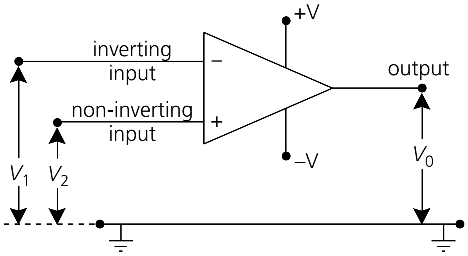
Linear integrated circuits include the voltage regulator IC family, which may form the basis of both positive and negative power supply designs. These are discussed in more detail in Chapter 31. Two other important types of linear integrated circuits are the **operational amplifiers** (Op-Amps), which are used in audio, video and medical electronics applications, and the electronic **timers** used in timing and digital processing circuits. The simplest of these circuits is discussed now, with further examples given in Chapter 31.

Operational amplifier integrated circuits

An Op-Amp is a very high gain (amplification factor) voltage amplifier designed to amplify signals over a wide frequency range. The AC signal frequency range over which an amplifier produces equivalent amplification is called its **bandwidth**. Op-Amps have two input terminals: the inverting input labelled – and the non-inverting input labelled +. The device amplifies the difference in voltage between these two inputs even if one of the inputs is earthed. They usually operate from a dual polarity power supply, which means that the voltages needed to operate the integrated circuit are, for example, +9 V and 0 V, as well as –9 V and 0 V (Figure 24.17). In a lot of circuit diagrams the power supply connections to the integrated circuits are not shown. Note that in this circuit:

- if V_2 is zero, then $V_o = -A_vV_1$, where A_v = voltage gain
- if V_1 is zero, then $V_o = A_vV_2$
- if V_1 is larger than V_2, then the output is negative
- if $V_1 = V_2$, then the output is zero.

Figure 24.17
Operational amplifier.



The voltage gain of the Op-Amp is dependent on the frequency of the signal input. The amplifier gain decreases very quickly as the input frequency rises. An ideal Op-Amp has an infinite voltage gain and an infinite input impedance as well as zero output impedance. The concept of circuit impedance is effectively an AC or frequency dependent resistance.

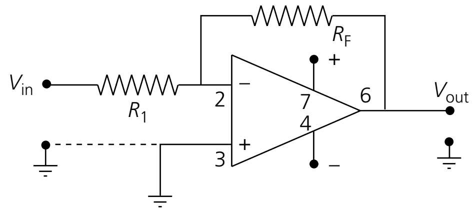
Remember that these integrated circuits work with AC voltage signals and their input and output resistance will vary with the frequency of the signal they are handling. You will come across this concept again in Chapter 31 when dealing with AC behaviour of components and devices.

If the Op-Amp was operated like this in practice, this very high voltage gain, which is referred to as the amplifier's open-loop gain, would be in the order of 10^5–10^6 times. As well, the circuit input impedance would be approximately 10–100 MΩ. This would make the amplifier circuit difficult to control. For this reason, these amplifiers are usually operated with a **feedback resistor**, R_F, from output to input. This has the effect of reducing voltage gain and input impedance to a manageable level (Figure 24.18). In this circuit:

$$\text{input impedance, } Z_{in} = R_1$$

and

$$\text{voltage gain, } A_V = \frac{R_F}{R_1}$$



If $R_1 = 1$ MΩ
$R_F = 10$ MΩ
then $Z_{in} = 1$ MΩ
$A_V = 10$

Figure 24.18
Basic inverting amplifier with feedback.

Operational amplifiers are used to produce circuits whose functions may include waveform generators, filters, amplifiers, adders or mixers, integrators and differentiators. One of the most common Op-Amp devices is the **741 Op-Amp**, which is manufactured either singly as an 8 pin DIL package or as a 14 pin DIL Quad Op-Amp package. It has a power dissipation of 310 mW and a temperature range of 0–70°C. A typical application circuit for this device is the inverting amplifier.

Using an Op-Amp as an inverting amplifier Refer to Figure 24.19. The most common application of the Op-Amp is the inverting amplifier configuration that produces an amplified output 180° out of phase with the input. This means that when the input signal is a maximum amplitude the output signal is a minimum amplitude and vice versa. The closed loop voltage gain for the circuit is given by:

$$A_{Cl} = \frac{V_0}{V_{in}} = \frac{-R_F}{R} = \frac{R_2}{R_1}$$

and the effective input impedance of the circuit is simply R_1, as shown in Table 24.2.

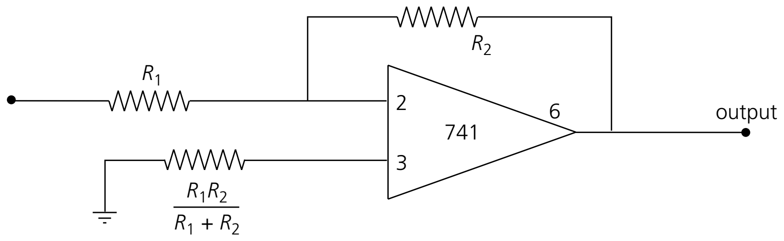
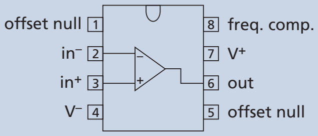


Figure 24.19
Inverting amplifier.

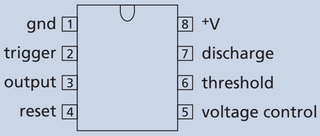
CHIP PINOUT DIAGRAMS

8 pin DIL



top view 741

8 pin DIL



top view 555

Table 24.2

GAIN, A_V	R_1	R_2	BANDWIDTH	R_{in}
1	10 kΩ	10 kΩ	1 MHz	10 kΩ
10	1 kΩ	10 kΩ	100 kHz	1 kΩ
100	1 kΩ	100 kΩ	10 kHz	1 kΩ
1000	100 kΩ	1000 kΩ	1 kHz	100 Ω

Example

In the circuit of Figure 24.19, the operational amplifier circuit is constructed using R_1 = 15 kΩ and R_2 = 500 kΩ. Calculate:

(a) the closed loop voltage gain, A_V;
(b) the input impedance of the circuit;
(c) the optimum value of the input pin 3 resistance to ground.

Solution

(a) Voltage gain $A_V = \dfrac{R_2}{R_1} = \dfrac{500\text{ k}\Omega}{15\text{ k}\Omega} = 33.3$.

(b) Input resistance is simply value of R_1 = 15 kΩ.

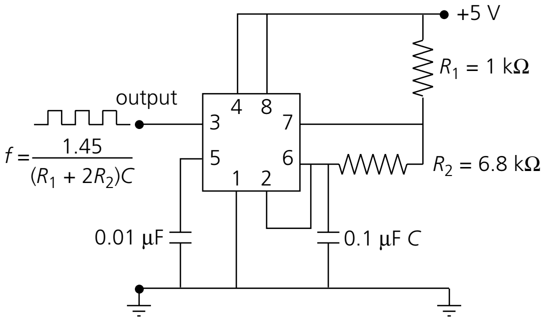
(c) Optimum value of resistance $= \dfrac{R_1 \times R_2}{R_1 + R_2} = \dfrac{15\text{ k}\Omega \times 500\text{ k}\Omega}{515\text{ k}\Omega}$ = 14.6 kΩ, or its nearest preferred value of 15 kΩ.

Other applications of the Op-Amp include circuits that act as waveform generators, adders and comparators, and simple integrators. These are further discussed in Chapter 31.

Timer integrated circuits

The **555 timer**, produced by several manufacturers, is specifically designed for precision timing circuits. It can also be used in digital multivibrator modes and as a Schmitt trigger. The Schmitt trigger is a circuit that has the function of converting an analog frequency signal to a digital frequency signal or restoring an electrically noisy digital signal to a very stable and well formed noiseless digital signal. The 555 timer is also made in single or Quad DIL packages. It can operate with supply voltages from 4.5 V to 16 V and can directly drive loads such as relays, LEDs, low power amplifiers and high impedance speakers. Accurate timing periods variable from a few microseconds to several hundred seconds can be produced by using a square wave output controlled by external R–C networks. Timing periods can be started by a trigger signal and stopped using a reset signal. When used as a signal frequency generator (astable mode) the device output can be varied simply using external capacitors and resistors.

Figure 24.20
555 square wave generator.



The circuit of Figure 24.20 is a simple square wave generator circuit, which could be used as a circuit providing stable timing pulses. This circuit is often called a **square wave clock**. The 555 timer is being used in its astable or free running multivibrator mode because it will continue to produce a series of wave pulses as long as the power supply voltage is connected to the chip. With the values shown in the figure, the frequency of the output is about 1.0 kHz. However, the output frequency is adjustable with either R_1, R_2 or C and is given by:

$$f = \frac{1.45}{(R_1 + 2R_2)\cdot C}$$

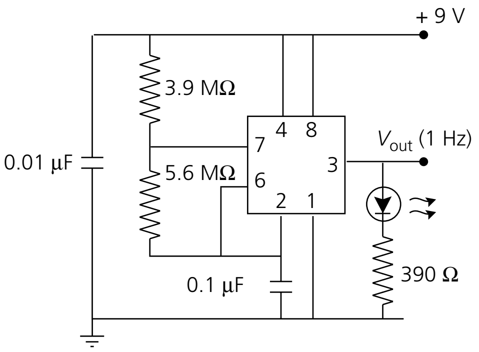


Figure 24.21
555 second interval clock.

The circuit of Figure 24.21 is a similar clock using the 555 timer, but its output frequency is only 1.0 Hz and thus it acts as a second counter. Again, the circuit is a free running or **astable multivibrator**.

Questions

8 List the advantages of modern integrated circuit chips. Do they have any disadvantages?

9 What is the circuit symbol for Op-Amp? Sketch the full circuit diagram for an inverting amplifier whose voltage gain is 200, if an input resistor of 10 kΩ is used. What is the circuit's effective input impedance?

10 Explain the difference between linear and digital ICs. Give two examples of linear ICs.

11 Draw a diagram representing the output waveform of a 555 timer IC chip connected into its astable mode of operation. How would you describe the waveform?

12 Sketch the input and output waveforms on a common set of axes for an Op-Amp of gain 10 and input signal of 1 kHz. Consider an inverting mode of operation.

13 What is meant by the digital term binary levels? How do these binary levels correspond to voltage levels in a digital IC circuit?

14 What is the difference in circuit usage between TTL, 74LS and CMOS digital IC chips?

15 What is the output frequency of a 555 timer IC circuit if the chip is connected as in Figure 24.20 and components R_1 = 15 kΩ, R_2 = 28 kΩ, and C = 0.1 μF?

EI Activity 24.3 LET'S BUILD CIRCUITS

If you have access to circuit building boards especially designed for ICs, such as the SK40 protoboards, then your teacher may supply you with some integrated circuits as described in this chapter so that you can actually build some of the circuits. The simplest circuit to build and get working is the 741 Op-Amp in its inverting mode. Remember to always connect power supply voltages to the correct pins of the IC and connect the power supply last of all.

MICROCONTROLLERS AND ROBOTICS

One of the most important types of integrated circuits today is the **microcontroller**. In simple terms a microcontroller is a specialist digital computer chip embedded inside a device or product. The best examples of modern consumer devices that contain these chips are vehicle engine controllers, TVs, VCRs and DVD players, digital cameras and mobile phones, refrigerators, cooking ranges and washing machines. In fact any modern device that requires some sort of input from its user is most likely to contain an embedded microcontroller chip somewhere in its internal circuitry. These IC chips contain a CPU (central processing unit) and are usually programmed to perform a small range of tasks, or may even be dedicated to perform only one prescribed task.

Typical microcontroller chips that you may encounter in your electronics course at school include the PIC family from 'Microchip', the AVR family from 'Atmel', the BASIC STAMP controllers by 'Parallax'(which actually contain a PIC chip and are made to allow programming with the BASIC language). You may also encounter the RCX Hitachi controller used in the Lego-Mindstorms robotics kits. Each of these devices will have one or more of the following features:

- a specific program set of tasks stored in ROM memory
- programs that can be changed through programmable CMOS Flash and EEPROM memory
- a dedicated set of input–output (I/O) structures that limit the need for external components
- very low power consumption, typically 50 mW
- are housed inside rugged multipin DIP packages that allow for a wide variety of physical operating conditions such as high temperature or acidic environments.

It is the dedicated I/O structure that is most the important feature of any microcontroller. In the case of the television receiver controller, input signals via infrared beams are received from the remote handset, and the microcontroller sends signals to its outputs which in turn control processes such as picture quality, channel selection and speaker amplifier volume. Outputs are also displayed on LCD panels which respond to inputs from an operator touchpad. This type of microcontroller operation is commonplace in the kitchen or laundry. The proper operation of a modern motor vehicle engine or its peripheral systems, such as ABS brakes or air-bag safety, could not be done without complex microcontroller operation.

The actual microprocessor used in microcontroller chips can vary widely, but most are based on similar processors that once formed the heart of personal computers, such as Z80, 80386, 80586 and Pentium processors. Let's now take a look at some of the types mentioned above.

AVR 8-Bit RISC chips

Atmel's **AVR** microcontrollers have a RISC core running single-cycle instructions and a well-defined I/O structure that limits the need for external components. Internal oscillators, timers, UART, SPI, pull-up resistors, pulse width modulation, ADC, analog comparator and watch-dog timers are some of the features you will find in AVR devices. AVR instructions are tuned to decrease the size of the program whether the code is written in C or Assembly. With on-chip in-system programmable Flash and EEPROM, the AVR is a perfect choice in order to optimise cost and get products marketed quickly. The Atmel® AVR is an 8-bit MCU with up to 128K of programmable Flash and EEPROM.

Table 24.3 ATMEL AVRs

AVR 8-BIT RISC MICROCONTROLLERS		MEMORY CONFIGURATIONS (BYTES)		
Processor	Package	Flash	EEPROM	RAM
tiny AVR	8-32 pin	1-2K	up to 128	up to 128
low power AVR	8-44 pin	1-8K	up to 512	up to 1K
megaAVR	32-64 pin	8-128K	up to 4K	up to 4K

Parallax BASIC Stamps

Named because of their size similarity to a postage stamp, these microcontrollers are made in two forms, BS-1 and BS-2. They usually come on a small development board that is powered from a 9 volt battery and can be connected to one of the ports on a PC so that it can be programmed easily in BASIC. They are most often used in prototyping circuit and program designs.

Table 24.4 BASIC STAMPS

	BS-1	BS-2
RAM	14 bytes	26 bytes
EEPROM	256 bytes	2000 bytes
Max program length	75 instructions	600 instructions
I/O pin number	8	16
Execution speed	2000 lines/s	4000 lines/s

The power of any microcontroller lies within the programming language used to drive the embedded program. In all cases a high-level language such as BASIC, PASCAL, C, a symbolic icon-based language such as Lego RoboLAB or even JAVA can be used. The instructions sequence (program) is then compiled into a form that the microcontroller will understand by further computer software. This also allows it to be downloaded as machine code directly to memory addresses in the microcontroller chip flash memory by way of the computer's parallel communications port, either by direct cable or by infrared beam. Several well-known compilers and microcontroller programmer software are freely available on the Internet for a range of chips. The following listing shows some of the commands in the instruction set that is available for the BASIC STAMP.

Standard BASIC commands:
for...next — normal looping statements
if...then — normal decision making
let — optional assignment
goto — go to a normal label in the program
gosub — go to a subroutine

I/O instructions:
high — set an I/O pin to its high value (1)
output — set the direction of an I/O pin to output
pot — read the value of a potentiometer on an I/O pin
pulsin — read the duration of a pulse coming from an input pin.
sound — send a sound of a certain frequency to an output pin.

Instructions specific to BASIC Stamp:
branch — read a branching table
eeprom — download a program to EEPROM
nap — sleep for a specific time
random — pick a random number
read — read a value from EEPROM

NOVEL CHALLENGE

There are many electronics stores, such as Dick Smith, Jaycar or Altonics, that market electronic construction kits using pre-programmed PIC chips. You may also be able to find experimenters' kits that actually allow programming of the chip by connection to your computer. Also **use the Internet** to find Australian companies marketing tutorial software that teaches you about PIC programming. Just like the BASIC Stamps, PICs can also be programmed in the BASIC language, with several free software programs able to do this, such as PICBasic-lite.

Microchip's PIC family

One of the most successful microcontroller chip families belongs to the PIC range — for example the commonly used PIC16F84A device. It is powerful (200 nanosecond instruction execution) yet easy to program (only 35 single-word instructions). CMOS Flash/EEPROM-based 8-bit microcontroller packs Microchip's powerful PIC architecture into an 18-pin package. The same device can be used for prototyping and production and the end application can be easily updated without removing the device from the end product via the ICSP. It is easily adapted for automotive, industrial, appliances, low power remote sensors, electronic locks and security applications.

Program memory: 1792 (bytes), 1024 (words).

Table 24.5 SPECIFICATION CHART

DATA RAM	SPEED MHz	I/O PORTS	TIMERS	BROWN OUT	ICSP
68	20	13	1+WDT	False	True

Additional features:	20 mA source and 25 mA sink per I/O, 64 bytes data EEPROM
Low voltage device option:	PIC16LF84A
Package options	18 PDIP, die-waffle, uncut wafer, 18 SOIC 300mil, 20 SSOP 208mil, wafer-frame

Robotics and the LEGO RCX brick microcontroller

In the early 1980s Seymour Papert, an early pioneer in artificial intelligence at the Massachusetts Institute of Technology, had the idea to include a computer inside a LEGO® block. This idea has been further refined into the 'LEGO Mindstorms invention system'. Photo 24.3 shows a typical LEGO RCX 1.0 brick with attached sensors and used as part of a robot chassis in classroom robotics study. The RCX (Robotic Control X) is an autonomous LEGO microcontroller based on the Hitachi H8 chip. Table 24.6 shows the specifications. The microcontroller has three input ports (1, 2 and 3) for sensors such as touch, light and rotation, and also has three output ports (A , B and C) able to drive motors, lamps etc.

Table 24.6 RCX 1.0 SPECIFICATIONS

SERIES	H8-3297
ROM size	16K internal
SRAM size	512 internal & 32K in brick
Execution speed	16 MHz @ 5 V
Timers	8-bit × 2 & 16-bit × 1
ADC	8-bit × 8
I/O pins	43
Input only pins	8
Serial port	1
10 mA outputs	10
Power supply	6 × 1.5 V alkaline cells or AC plug-pack

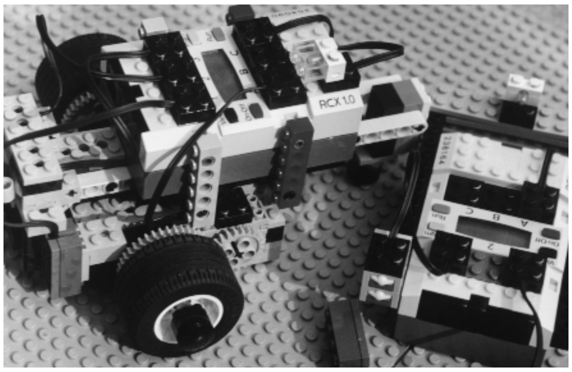


Photo 24.3
Robotics RCX brick.

In the school lab environment, students use the RCX brick as the heart of a course of study in robotics and control systems using PC **RoboLAB** programming software. Sensors are electrically connected to the input ports to take data from the environment, process the data (data-logging) and signal output devices such as motors to rotate. Mobile robots can be built from standard LEGO building pieces that allow the RCX brick and sensors to move about the environment and perform specific tasks or challenges. RoboLAB is the icon-based programming language that comes in a variety of complexity levels: pilot, inventor and investigator. This program is based on National Instruments' 'LabVIEW' virtual instrument software and it can become the basis of powerful experimental investigations. In fact, it was LabVIEW software that NASA used to monitor the Mars sojourner *Rover's* location in 1997.

Programs constructed in RoboLAB are downloaded to the brick using an infrared transmitting tower connected to the USB port of the PC. The RCX brick can also be directly controlled remotely from the computer. An on-chip 16K ROM contains a driver that is run when the brick is first powered up and this driver is extended by downloading firmware to the brick initially. The driver and firmware accept and execute commands from the downloaded student byte code programs which are stored in a 6K region of memory.

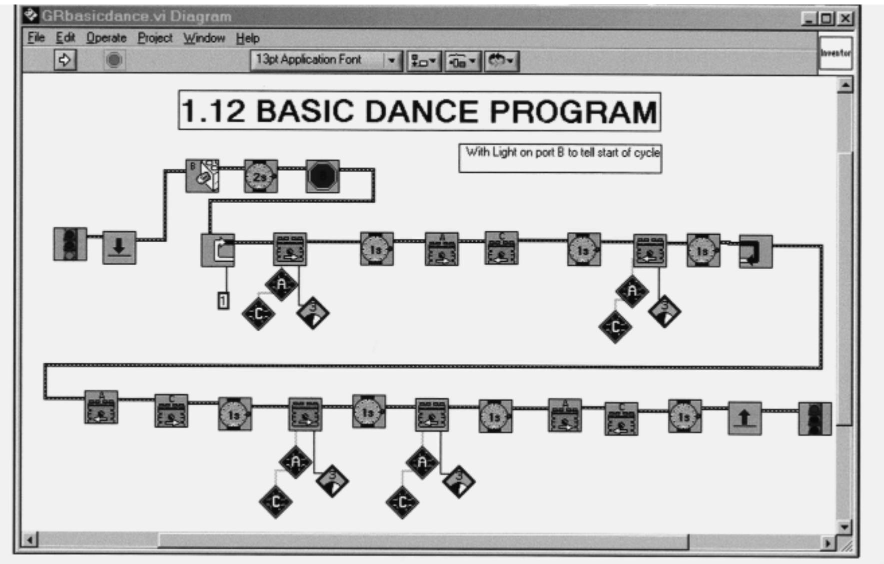
An even higher-level language that is available for the RCX microcontroller brick is the C-language variant called Not-Quite-C or **NQC**, written by Dave Baum. This language allows direct command line programming to the brick through an interface called the BricXCC or Brick X command centre.

Photo 24.4 shows a screen dump of a typical RoboLAB inventor-level program for the RCX brick allowing the robot to perform a series of dance steps under software control.

NOVEL CHALLENGE

If your school has access to the LEGO robotics system discussed above, you might try to investigate the robot construction and subsequent programming necessary to complete the following challenge task.

Design and build a robot that effectively senses and follows a dark or black line drawn in a circle of approximate diameter 2.5 m on the lab floor. On starting the program, the robot must follow the circular line until it comes into contact with a solid block, at which point it turns through 90 degrees, travels in a straight line for 1.0 m and then stops. Present your findings and demonstrate your final robot performing its task.



1.12 BASIC DANCE PROGRAM

With Light on port B to tell start of cycle

Photo 24.4
Sample RoboLAB program.

Practice questions

The relative difficulty of these questions is indicated by the number of stars beside each question number: * = low; ** = medium; *** = high.

Review — applying principles and problem solving

***16** An electronic circuit is to be used to convert light intensity changes to sound. What might be the input and output transducers? Briefly describe the functional blocks that might make up the circuit and illustrate these in a block diagram.

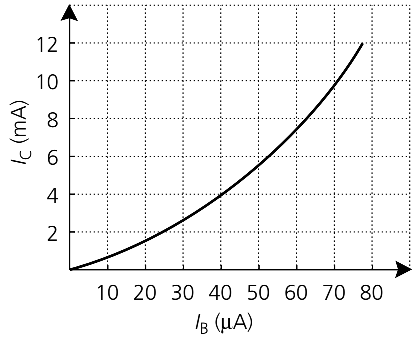
***17** Name the three terminals of a transistor and illustrate these on a symbol used to represent an NPN transistor.

***18** What is the difference between an Op-Amp IC and a timer IC? State a common example of each type of integrated circuit.

****19** Sketch the circuit for a non-inverting amplifier whose voltage gain is 500 and whose input impedance is 20 kΩ. Use a 741 Op-Amp chip and include all power supply connections.

****20** Figure 24.22 shows the graphical current transfer characteristics of a particular transistor. Estimate the current amplification factor, β, at $I_B = 35\ \mu A$ and at $I_B = 60\ \mu A$.

Figure 24.22
For question 20.



****21** A student obtains the following data table from an experiment to measure transistor current gain:

I_B (µA)	20	40	60	80	100	120
I_C (mA)	3.6	7.0	10.8	14.5	17.9	21.5

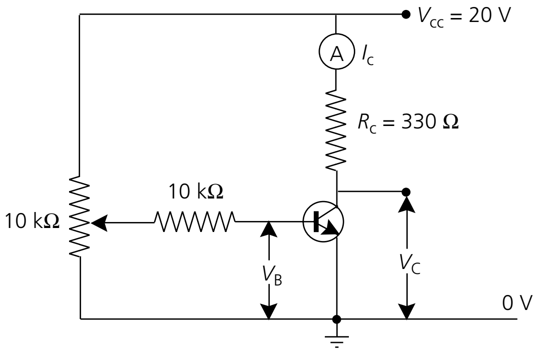
(a) Plot I_C versus I_B values correctly in order to produce a line of best fit and deduce the current gain, β.

(b) Sketch the circuit that the student may have used to obtain this type of data.

****22** The circuit of Figure 24.23 is used to investigate the voltage gain of a transistor. If the supply voltage used is $V_{CC} = 18$ V and the following table gives values of the collector current, I_C, and the base–emitter voltage, V_{BE}, use the fact that voltage gain $A_V = \frac{\Delta V_C}{\Delta V_{BE}}$ to calculate the gain for this circuit. Complete the table for the values of V_C voltage at the collector.

I_C (mA)	V_{BE} (V)	V_C (V)
10.0	0.62	
30.0	0.69	
50.0	0.76	

Figure 24.23
For question 22.



*****23** Figure 24.24 shows an Op-Amp temperature sensing and heater circuit. The resistance of the thermistor decreases with an increase in temperature.

(a) In what mode is the Op-Amp operating in this circuit?

(b) As the temperature drops, explain what happens to the output of the Op-Amp.

(c) What will be the subsequent effect on the transistor collector working current?

(d) Why does the heater then switch on?

(e) What is the function of the set-temp potentiometer in the circuit?

(f) Redraw the circuit correctly, showing the power supply connections to the Op-Amp chip.

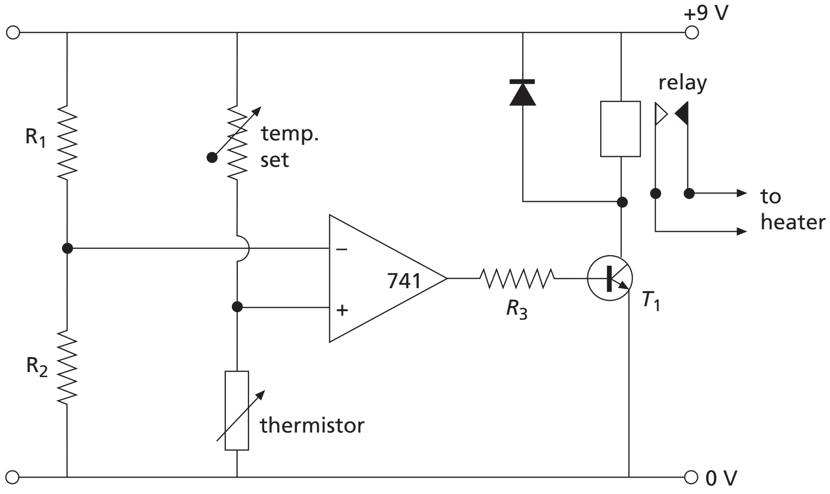
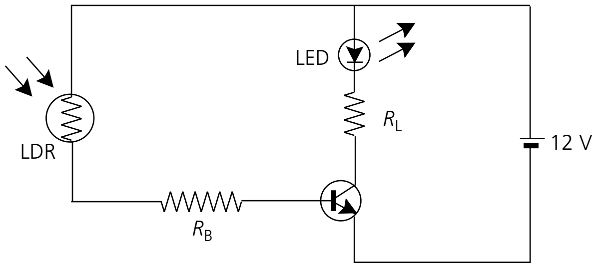


Figure 24.24
For question 23.

Extension — complex, challenging and novel

*****24** In Figure 24.23 explain if the LED would be ON or OFF under the conditions of **(a)** full sunlight on the LDR; **(b)** darkness or no light on the LDR.

Figure 24.25
For question 24.



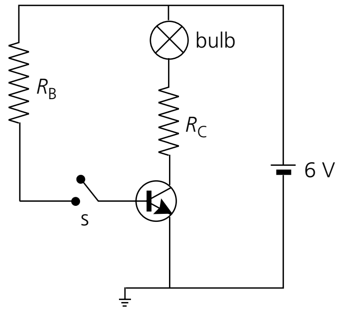
*****25** In Figure 24.26 a transistor is to switch a torch bulb as shown. If the bulb is intended to operate at 3 V and dissipate 0.3 W, calculate:

(a) the collector current, I_C, at proper illumination;

(b) the collector resistor, R_C, value required;

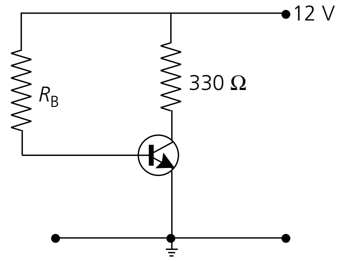
(c) the base resistor, R_B, value if the transistor has $\beta = 100$.

Figure 24.26
For question 25.



*****26** In the circuit of Figure 24.27 the transistor has a current gain value of 500 and I_C = 20 mA. Calculate **(a)** the value of R_B; **(b)** the power dissipated in R_B and R_L; **(c)** voltage V_{CE}; **(d)** voltage V_{BE}.

Figure 24.27
For question 26.

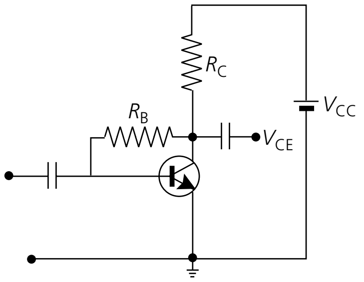


*****27** Figure 24.28 is referred to as a common emitter amplifier with collector feedback. Assuming a silicon transistor, and the values as listed: R_C = 10 kΩ, R_B = 100 kΩ, V_{CC} = 10 V and β = 120,

(a) show that $I_B = \dfrac{(V_{CC} - I_C \times R_C - V_{BE})}{R_B}$;

(b) calculate I_B, I_C and V_{CE} for this circuit.

Figure 24.28
For question 27.



*****28** Figure 24.29 shows a 741 Op-Amp in a single audio frequency mixer circuit with two fader inputs. Consider this circuit and explain:

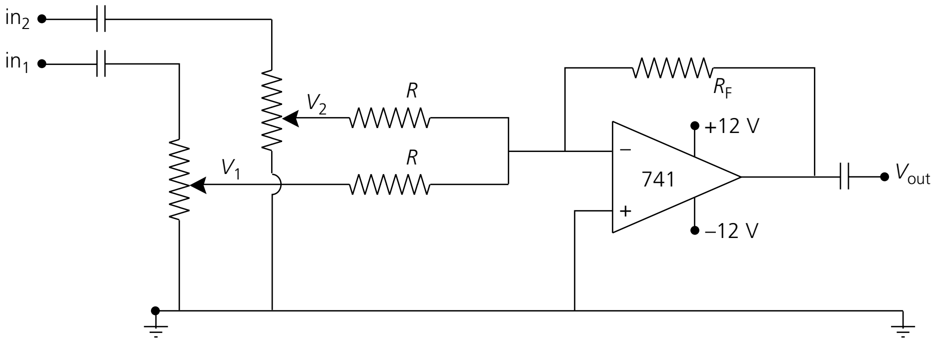
(a) the function of the input potentiometers;

(b) a mathematical equation linking V_{out} to V_1 and V_2;

(c) if $R_F = R$ in this circuit, what is the amplifier gain and give the equation linking the same quantities as in **(b)**;

(d) what would happen to the output voltage if the non-inverting input was connected to a small DC voltage rather than ground.

Figure 24.29
For question 28.



***29 The circuit of Figure 24.30 contains a 555 timer IC chip and is described as a digital signal injector for testing audio circuits. Describe how this circuit works and determine its likely output frequency range. What is the likely function of the circuit components VR_1 and VR_2? How could the circuit be used as a piece of test equipment in an audio laboratory?

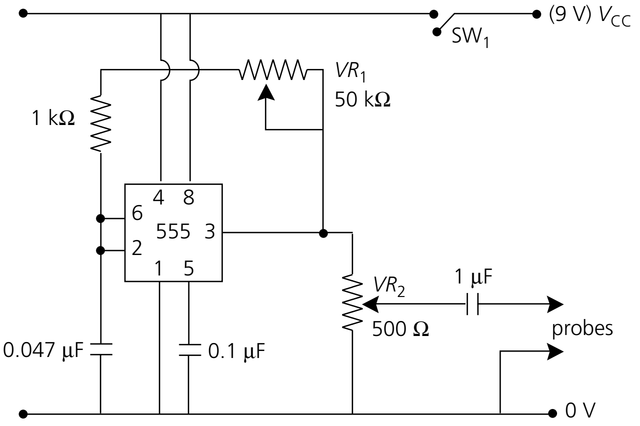


Figure 24.30
For question 29.

The following circuit provides a 2.5 W amplifier based on the LM380 chip suitable for general purpose audio applications:

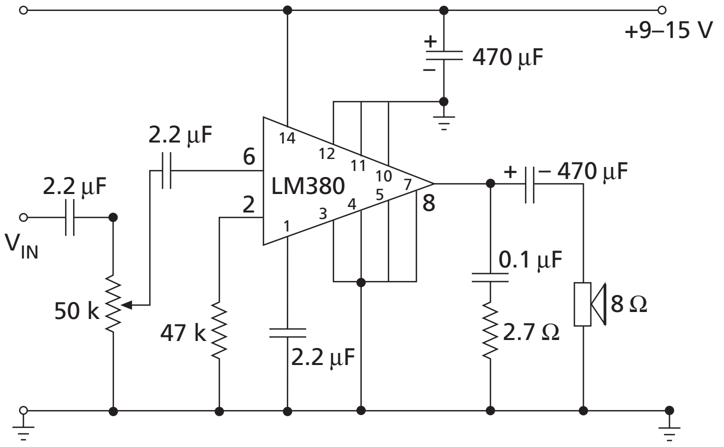


Figure 24.31

Make a list of components in this circuit, and use an electronics supplier catalogue (e.g. Dick Smith) to work out a total price if you wanted to build the circuit.