CHAPTER 31

Designing Practical Electronic Circuits

31.1 INTRODUCTION

In Chapters 23 and 24 we looked at the behaviour of basic components in electronics as well as simple systems that could be produced with them. In this chapter we will examine, in more detail, practical applications of electronics, especially using integrated circuit systems. We will look at circuit examples that you might like to try building as the basis of a hobby project. You might become interested enough to purchase and build one of the many hundreds of electronics constructor kits that are commercially available.

Most electronics today is based on combinations of integrated circuits, especially digital ICs, and these are quite easy to use. Always keep in mind the safety aspect of electricity and only deal with kits or projects that involve battery power supplies or use mains plug pack transformers, as described later in this chapter.

31.2 RLC RESONANCE AND TUNING CIRCUITS

Radio waves transmitted from sources such as AM and FM radio stations, television channels and CB or short wave transmitters all involve different frequency electromagnetic signals or voltages. In order to learn how to detect these signals with electronic circuits, we need to examine the AC behaviour of capacitor and inductor components.

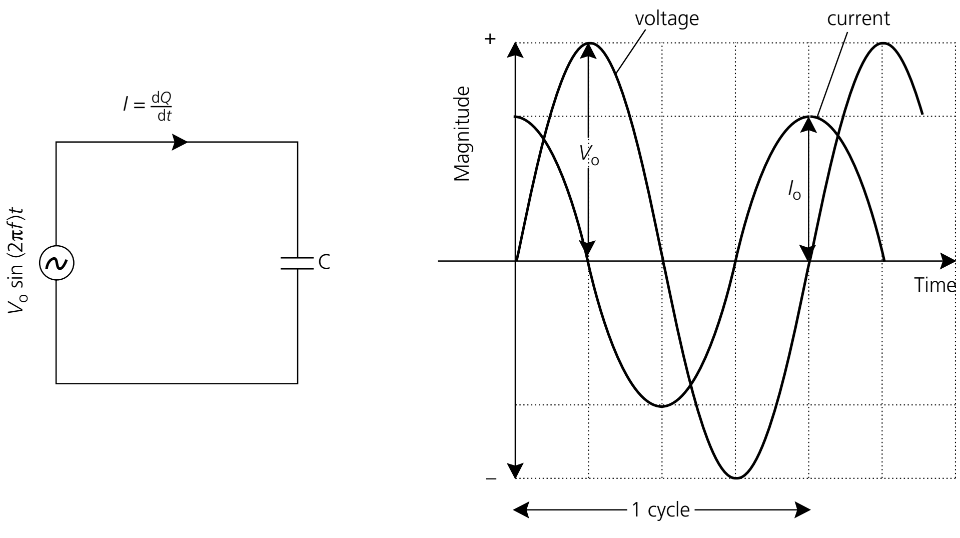


Figure 31.1
Capacitors and AC voltage.

Recall the DC timing constant property of a charging capacitor in an RC circuit. Let's see what occurs when an AC voltage is placed across any capacitor, as in Figure 31.1. The capacitor will charge instantly, with the voltage across it at any time being equal to the supply voltage. A sinusoidally varying AC voltage (sine wave) of frequency f will be given by the equation:

$$V = V_o \sin \omega t = V_o \sin (2\pi f)t$$

(where V_o is the voltage peak amplitude).

and this voltage will at any instant of time be equal to the voltage as defined by the capacitance, namely:

$$V = \frac{Q}{C} = V_o \sin (2\pi f)t$$

or

$$Q = V_o \,.\, C \,.\, \sin (2\pi f)t$$

but the current, I, flowing to the capacitor at any time will be given by:

$$I = \frac{dQ}{dt} \text{ (rate of change of charge with time)}$$

Hence, current flow in any capacitor connected to an AC voltage supply will be:

$$I = \frac{dQ}{dt} = \frac{d(V_o C \sin (2\pi f)t)}{dt}$$

$$I = V_o C\, 2\pi f \cos (2\pi f)t$$

$$I = I_o \cos (2\pi f)t \quad \text{where} \quad I_o = V_o\, 2\pi f C$$

(where I_o is the current peak amplitude).

Note that because the sine curve and a cosine curve are out of phase, the current peak, I_o, leads the voltage peak, V_o, by 90°. This is called a phase shift or **phase angle**. Also notice that the link between I_o and V_o for a capacitor can be written as:

$$V_o = I_o \frac{1}{2\pi f C} = I_o X_C$$

which is similar to Ohm's law and introduces a property of frequency-dependent resistance or **reactance** for a capacitor.

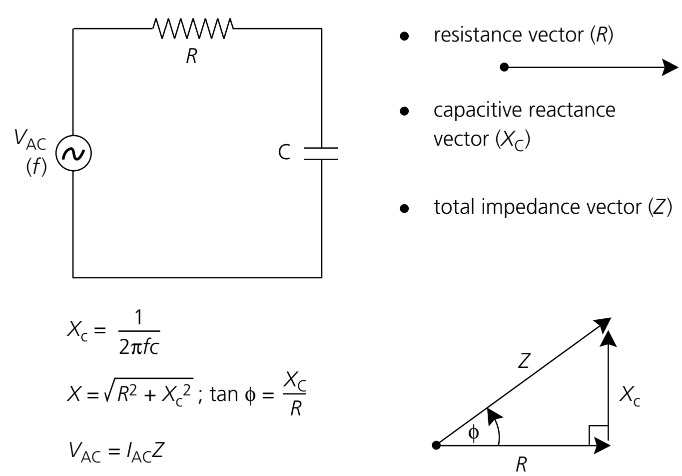


Figure 31.2
RC circuit and impedance.

The **capacitive reactance**, $X_C = \frac{1}{2\pi fC}$, becomes a phasor quantity (similar to a vector quantity) with both magnitude in ohms and a phase angle in degrees. In the RC series circuit of Figure 31.2, the vectors are drawn representing pure resistance, R, in which current and voltage are in phase, and capacitive reactance, X_C, in which the current leads the voltage by 90°. The total AC resistance to the flow of alternating current (AC) from the supply is called the circuit **impedance**, Z, and is calculated by vector addition processes.

In a simple series RC circuit the total impedance:

$$Z = \sqrt{R^2 + X_C^2}$$

and the phase angle (ϕ) is given by:

$$\tan \phi = \frac{X_C}{R}$$

The impedance, Z, is measured in ohms. Ohm's law equivalent for this AC series RC circuit becomes:

$$V = I \,.\, Z$$

Example

In the circuit of Figure 31.2, the AC voltage was 12 V RMS and the supply frequency is 50 Hz, the capacitor has a value of 0.33 μF and the resistance is 10 kΩ. Find:

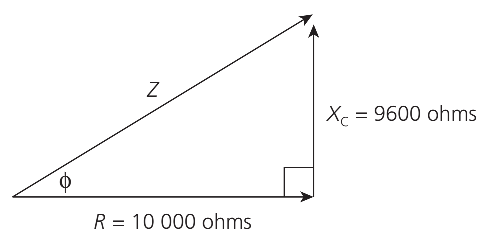
(a) the capacitive reactance X_C;
(b) the total circuit impedance Z;
(c) the AC circuit current (RMS);
(d) the phase angle between voltage and current.

Solution

(a) At f = 50 Hz:

$$X_C = \frac{1}{2\pi fC} = \frac{1}{2\pi \times 50 \times 0.33 \times 10^{-6}}$$
$$X_C = 9600\ \Omega$$

(b) Completing a vector diagram for impedance Z:



$$Z = \sqrt{(9600)^2 + (10\ 000)^2} = 13\ 900\ \Omega$$

(c) Hence, AC current, I_{RMS}, can be calculated using $V = IZ$.

$$12 = I_{RMS} \times 13\ 900$$
$$I_{RMS} = 0.86\ \text{mA}$$

(d) Phase angle is given by:

$$\tan \phi = \frac{X_C}{R} = \frac{9600}{10\ 000} = 0.96 \quad \therefore \text{ angle } \phi = 44°$$

Thus, in this circuit, the current sine wave reaches a maximum 44° before the voltage sine wave reaches its maximum. This would be best shown graphically.

A similar analysis to that above can be applied to a simple inductor coil connected to an AC voltage source. (Refer to Figure 31.3.) The result is that an inductor provides an opposition to the flow of alternating current in a circuit that is frequency-dependent and is called **inductive reactance** (X_L), where $X_L = 2\pi fL$.

Notice that an inductor is a low resistance to low frequency AC and provides high resistance to high frequency AC. This reactance is again measured in ohms. For any inductor coil, the AC current flow lags the AC voltage across the coil by a 90° phase shift and thus the inductive reactance vector can be drawn pointing downward.

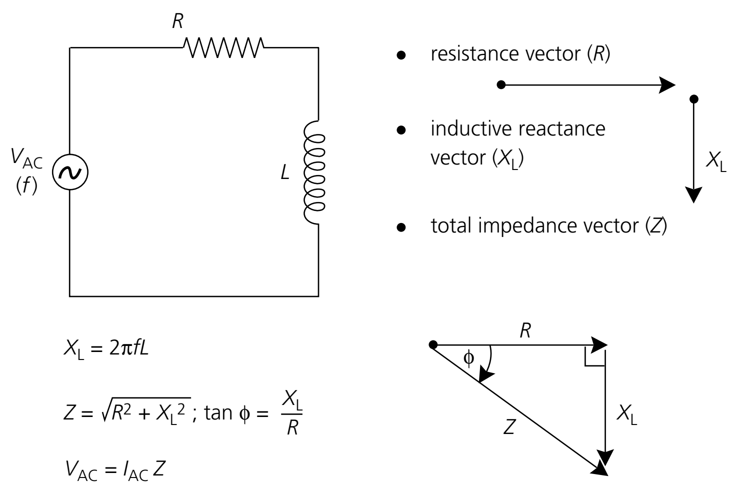


Figure 31.3
RL circuit and impedance.

To calculate total circuit impedance in an RL series circuit, vector processes are again required.

$$Z = \sqrt{R^2 + X_L^2}$$

Series RLC resonance

Consider the circuit of Figure 31.4 showing an RLC series connection to an AC voltage source. In this circuit the inductive reactance will tend to balance the capacitive reactance because of the opposite direction of the vectors. At one particular AC frequency $X_L = X_C$ and a maximum value of current will flow, only restricted by the pure resistance R. At this particular frequency the series RLC circuit is said to **resonate**. An RLC series circuit will resonate at a frequency calculated by equating the reactances, hence:

$$2\pi fL = \frac{1}{2\pi fC} \quad \text{or} \quad f_R = \frac{1}{2\pi\sqrt{LC}}$$

where f_R = resonant frequency.

It is important to realise that in this circuit the total impedance at resonance will be equal to the circuit resistance, R. Figure 31.4 also illustrates graphically the impedance and current flow as a function of frequency.

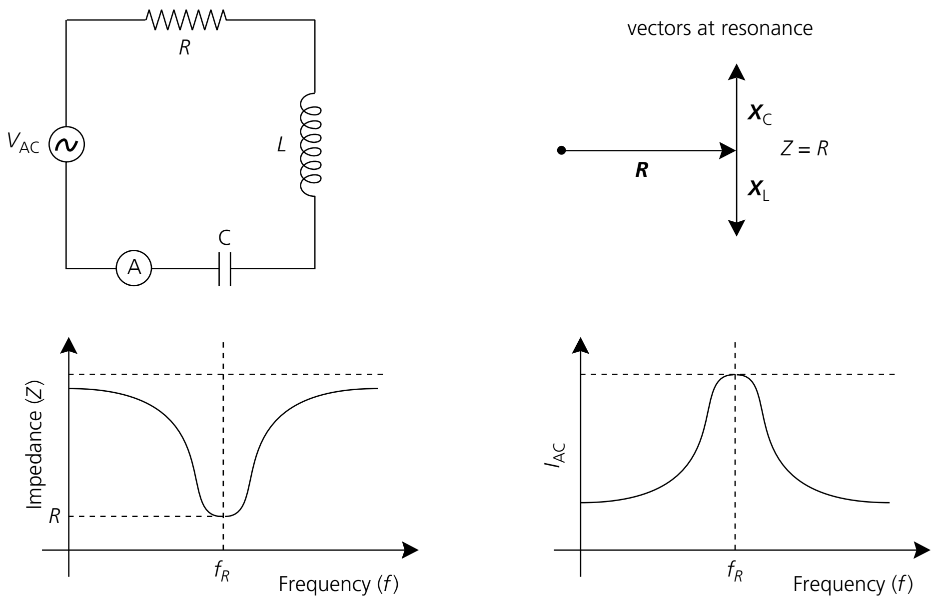


Figure 31.4
RLC series resonance.

In any series circuit at resonance, the voltage across the capacitor and the inductor individually may be many times more than the supply voltage. This is true even if the total voltage across the combination of *L* and *C* together is zero because of the effect of opposite phase angles. This is a danger to anyone who may touch capacitors or inductors in any high voltage AC circuits, as shown in the following example.

Example

An RLC circuit is connected to a variable frequency AC generator whose effective voltage output is 48 V_{RMS}. If the circuit elements have values $L = 100$ mH, $C = 0.02$ μF, $R = 50\ \Omega$, find:

(a) the resonant frequency of the circuit;
(b) the circuit AC current at resonance;
(c) the voltages across each component R, L and C at this resonant frequency.

Solution

(a) The resonant frequency:

$$f_R = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{100 \times 10^{-3} \times 0.02 \times 10^{-6}}}$$

$$f_R = 3.6 \times 10^3 \text{ Hz}$$

(b) At resonance:

$$I_{AC} = \frac{V_{AC}}{R} = \frac{48}{50} = 0.96 \text{ A}$$

(c) Voltage drops across each component:

$$V_C = IX_C = I \times 1/2\pi fC = 0.96/2\pi \times 3.6 \times 10^3 \times 0.2 \times 10^{-6}$$
$$V_C = 2.1 \times 10^2 \text{ V}$$
$$V_L = IX_L = I \times 2\pi fL = 0.96 \times 2\pi \times 3.6 \times 10^3 \times 100 \times 10^{-3}$$
$$V_L = 2.2 \times 10^3 \text{ V}$$
$$V_R = I.R = 0.96 \times 50 = 48 \text{ V}$$

Notice the high voltages individually across L and C, which are considerably greater than the AC values of the EMF in the circuit.

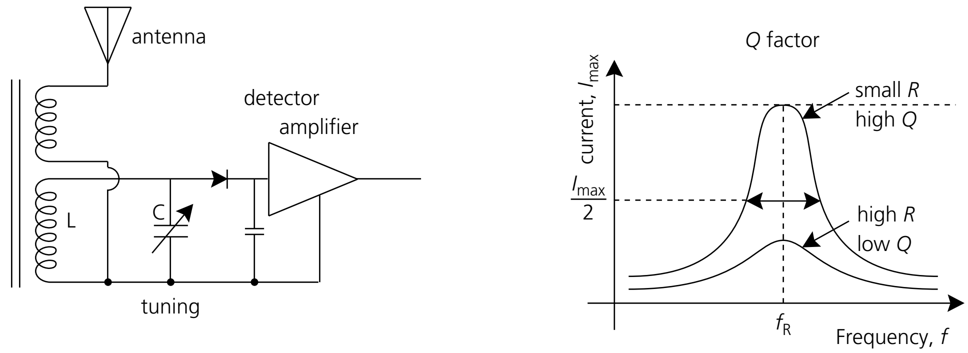
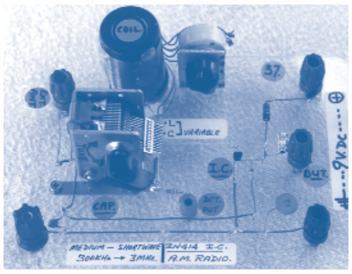


Figure 31.5
Radio tuning circuits.

Photo 31.1
Tuning module.



PHYSICS UPDATE

In 2002 the engineers at Motorola's Semiconductor Products Sector in Austin, Texas developed a set of silicon chips that apply sophisticated digital processing to standard analog signals, enabling software code rather than analog circuitry to do the tuning. Called 'Symphony Digital Radio', the system relies on algorithms running at the rate of 1500 million instructions per second on Symphony's 24-bit semiconductor chip set. The device converts any incoming tuned AM or FM signal into an intermediate frequency that can be filtered and conditioned by DSPs (digital signal processors). The result can be almost CD-quality sound from analog radios, given a sufficiently strong signal. The Motorola system represents an early example in a new class of what the electronics industry calls software or software-defined radios, a technology that derives tremendous flexibility by using digital code in place of fixed hardware to accomplish functional tasks.

One of the most useful applications in electronic circuits for the property of resonance is in **tuning circuits**, as used in radio and television receivers. (See Figure 31.5.) Resonance is used to select a desired frequency or radio channel from the multitude of frequencies arriving at the receiver antenna from all available broadcasting stations. A variable tuning capacitor is used in an RLC circuit, known as a **tank oscillator**, to select a resonant frequency equal to the carrier wave or broadcast frequency of the channel selected. For example, the carrier frequency of radio station Brisbane B105 FM is 105.4 MHz. At the resonant frequency, the EMF induced in the antenna by the incident waves causes a large current in the antenna circuit, which can then produce a modulated audio or video signal. Other channels or stations that have carrier frequencies not in resonance with the antenna circuit will produce negligibly small currents. The quality factor or ***Q* factor** of a resonant circuit is defined as the ratio of the voltage across the capacitor to that of the voltage across the resistor at resonance:

$$Q = \frac{V_C}{V_R} = \frac{1}{R}\sqrt{\frac{L}{C}}$$

The larger the Q factor of a circuit, the sharper will be the resonance curve and therefore the more selective will be the tuning ability. This means that the radio receiver will be better able to tune one individual radio station without at the same time receiving another station that happens to be in a close position on the broadcasting frequency band. Have you ever listened at night to your transistor radio and heard more than one station at the same time; it can get rather confusing, can't it? This effect is often due to poor selectivity and it increases at night when reception of weaker strength radio signals is often enhanced.

VOLTAGE REGULATORS AND POWER SUPPLIES 31.3

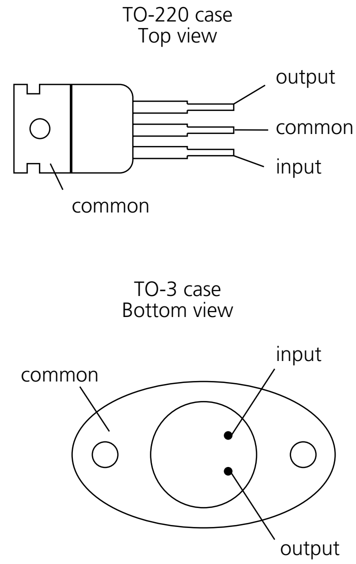
Recall in Chapter 23, when referring to rectification, it was stated that simple DC power supply circuits suffer from a lack of voltage regulation. The solution offered was to use a zener diode to maintain constant voltage conditions. In more advanced DC power supply designs a better choice is a three terminal linear IC called a **voltage regulator** or a **three terminal regulator**. These devices are one of the most useful IC components in modern electronics simply because they do away with the need for complex voltage regulation circuits when designing the power supply section for consumer items, such as small transistor radios or cassette players. In fact, highly regulated DC voltage supplies are vital for most digital circuits such as computers and audio–video control circuits.

The term regulated power supply means that active devices such as transistors and Op-Amps are used to electronically filter or eliminate variations in output voltage and sometimes current. The stabilised voltage output of a regulated supply allows a circuit to operate more precisely. Three terminal regulator ICs provide very high general regulation characteristics as well as other advantages such as current limiting, thermal overload protection against over-heating, and the ICs are available as either positive, negative or variable output voltage types.

Three-terminal regulators have three-pin connections called input, output and common, as shown in Figure 31.6, which illustrates the common 7800 series of positive regulators in a TO-3 or TO-220 IC case design. For example, a 7805 voltage regulator has an output voltage of exactly +5.0 V. The last two digits of the series generally refer to the regulator's output voltage. Similarly, the 7900 series is a negative voltage regulator family providing similar features to the positive types but with a different pin configuration. As usual, it is always wise to check the manufacturer's pin diagrams before connecting these regulator chips into the circuit. Both of these regulator families provide output currents up to 1.5 A maximum if the chip is adequately mounted onto an aluminium **heat sink** to dissipate the heat produced as the IC chip operates.

Figure 31.7 illustrates a common circuit used in voltage regulator power supply design. The transformer and diode bridge provide a rectified input to the device and the output is maintained at a very constant positive 5.0 V at 1.0 A maximum current capability. Notice that, as with all regulators, the input voltage has to be at least 2 V higher than the desired output, preferably even higher, in order to maintain regulation and eliminate ripple voltage passing across from the rectifier. As well, capacitors are usually connected between the common terminal and both the input and output terminals, as close as possible to the regulator chip itself.

Figure 31.6
Three-terminal regulators — 7800 series pin diagrams.



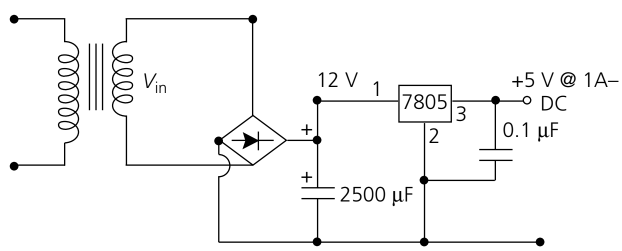


Figure 31.7
Voltage regulator.

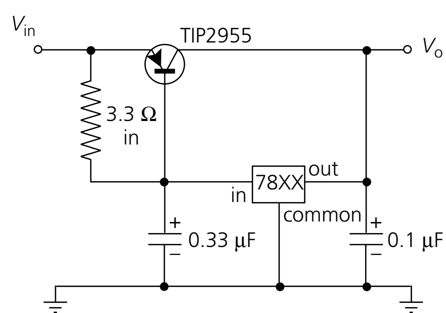


Figure 31.8
Current pass transistor with a voltage regulator.

If a power supply circuit design calls for a high current capability as well as voltage regulation properties, then a **current bypass** power transistor can be used, as shown in Figure 31.8. In this circuit a PNP power transistor, such as a TIP2955, is used to allow for an output voltage of 12 V at a maximum current of 4.0 A. The input to this circuit again would be any rectified and filtered DC voltage greater than about 15 V.

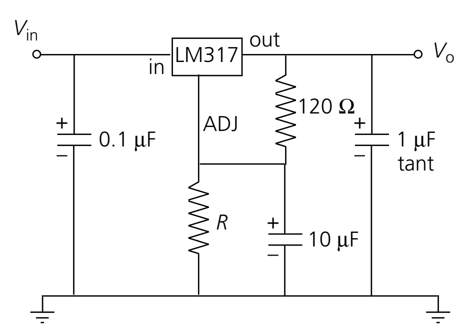
Sometimes the most versatile power supply designs are those that provide variable output voltages all at the same maximum current capability. The LM317 or LM350 series regulators allow this type of function with a circuit as shown in Figure 31.9. In this circuit design the value of resistor R is given by:

$$R = (96V_o) - 120$$

where V_o is output voltage required.

Of course, if R is made a variable resistor or potentiometer, then the circuit is fully variable and not just adjustable. Again, V_{in} should be at least 2.5 V higher than the required V_o and the capacitor voltage ratings must match the required input and output voltages.

Figure 31.9
LM317 adjustable voltage regulator.



With these circuits it is easy to see that simple power supply design is within reach of most constructors. One final integrated circuit regulator chip that is very versatile is the 723 voltage regulator, which is intended for both positive and negative supply design. Its output voltage is adjustable between 2 and 37 volts. Its own internal transistor can supply currents up to 150 mA, but output current capability can be increased with the appropriate external bypass transistor.

NEI Activity 31.1 DESIGNING A POWER SUPPLY

Obtain copies of the data sections from electronics supplier catalogues, such as can be obtained from Dick Smith Electronics or Tandy electronics stores. Research the full range of three terminal regulators available together with their respective costs and operating characteristics. You might like to see what it would cost to build a complete DC power supply designed to operate from a plug-pack AC transformer. Aim for a variable supply from 3 volts to 9 volts output capable of supplying up to 1.0 amp of current.

Questions

1 In a series RC circuit operating at an AC frequency of 1.0 kHz and voltage 10 V_{RMS}, R = 2700 Ω, C = 0.1 μF. Calculate **(a)** capacitive reactance; **(b)** total circuit impedance; **(c)** the alternating current flow in the circuit; **(d)** the phase angle between voltage and current.

2 An RLC series circuit is connected to an AC generator of voltage 50 V_{RMS}. In the circuit L = 100 mH, C = 2.0 μF, R = 150 Ω.
- **(a)** What is the resonant frequency?
- **(b)** What is the effective current at resonance?
- **(c)** What are the voltage drops across each component at resonance?
- **(d)** What power is delivered to the circuit at resonance?
- **(e)** What is the circuit Q factor?

3 Using the circuit of Figure 31.9, calculate the value of the adjust resistor needed to supply an output voltage of 7.2 V. What would be an appropriate input voltage for this circuit?

TRANSISTORS AS AC VOLTAGE AMPLIFIERS 31.4

Recall that, in Chapter 24, a transistor was described as an active semiconductor three terminal device that could be biased to act either as a direct current amplifier or as an electronic switch. One of the most practical uses of transistors in electronic circuit design is as an amplifier for small AC voltages. Such small voltages are produced, for instance, as the output of a microphone. AC **voltage amplifiers** based on either discrete transistors or integrated circuits (Op-Amps) form the heart of many electronic systems and are one of the building blocks of modern electronic technology. Let's look now into their principles of operation and design.

It has been seen that a small base current (DC) flowing into a transistor will control a much larger collector current. If this base current is made to change in a periodic fashion by a small AC voltage signal connected to the transistor's base, then a corresponding amplified AC voltage will appear across the transistor output or collector resistance. The transistor needs to be biased correctly to avoid various types of output voltage distortion. The voltage across the collector resistor depends on both the size of the collector current and the value of the collector resistance. Remember that for any given base current the size of the collector current depends on the transistor gain, β, hence a transistor AC voltage gain depends on its own current gain and also on the value of the collector resistor used.

The available transistor output AC voltage is usually taken via a capacitor connected directly (coupled) to the collector terminal of the transistor. Let us now look at how to design a practical transistor amplifier circuit that could be used to amplify the very small AC voltage produced by a microphone. The circuit is shown in Figure 31.10 and is correctly called a linear class A common emitter NPN transistor amplifier. Transistors suitable for this type of circuit are often called general purpose small signal amplifier transistors or GPSS types. Common examples are designated as BC108, BC548 or 2N3566, but hundreds of different types are manufactured.

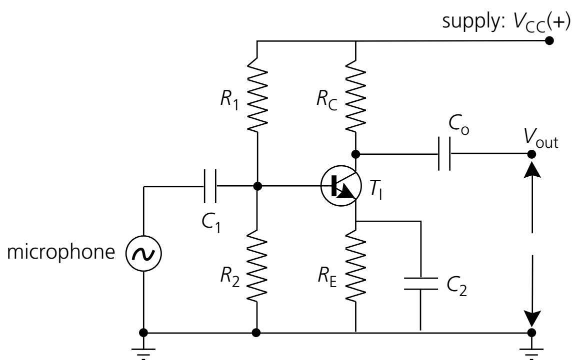


Figure 31.10
Common emitter class A small signal amplifier.

Linear amplifiers should fulfil these basic principles of design:

- The output signal voltage should be an exact replica of the input, but much larger in amplitude.
- The amplifier's input impedance must be as close as possible in value to that of the output of the voltage transducer driving it.
- No unwanted AC signals or DC voltages should enter the amplifier input.
- The amplifier's output impedance must match the load into which it is driving.
- The amplifier should introduce minimum distortion or change of wave shape at the output.

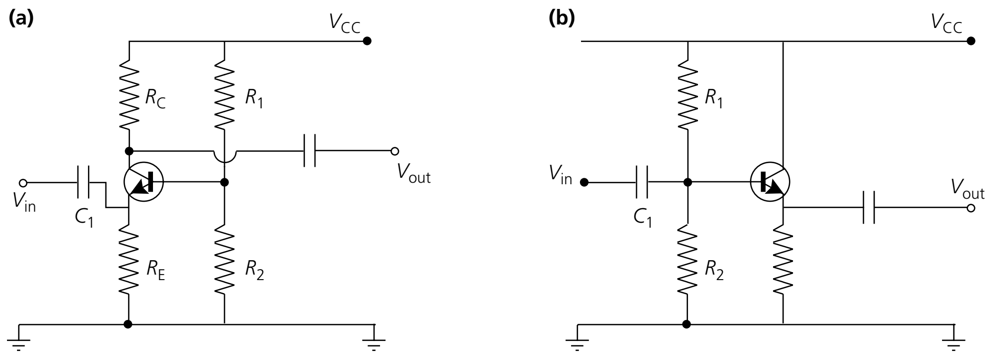
In a **class A amplifier**, such as we are designing, the transistor conducts during the complete input signal cycle, that is, for 360°. In class B and class C amplifiers, transistor conduction is not for the full input cycle and while this is often more efficient for higher voltage and power levels, they are more difficult to design and will not be considered here. The transistor in Figure 31.10 is connected in **common emitter** mode because the transistor emitter terminal forms part of the current loop for both input and output circuits. Other methods of transistor connection are called common base and common collector or emitter follower and are shown in Figure 31.11. These are less often used in general purpose amplifier circuits and are restricted to special applications.

INVESTIGATING

The symbol for the power supply in these circuits is V_{CC}. Find out what the 'CC' means.

NPN bipolar transistors will be used in our amplifier design because these devices have a high β gain, which can produce large voltage gains in the output circuit comprising resistor R_C in parallel with the output terminal load device. Manufacturers provide β gain values on data sheets, both an AC and a DC value, but because our designs assume only small input signal voltages, we will take these as equivalent. **Biasing** is the name given to the fixed DC voltage connected between transistor emitter and base, which causes a steady current to flow in the base–emitter circuit when no input voltage signal is applied through capacitor C_1. The

Figure 31.11
Other amplifier modes: **(a)** common base; **(b)** emitter follower.



(a) Common base (b) Emitter follower

biasing network consists of voltage divider R_1 and R_2 and the emitter resistor R_E. Biasing is necessary to provide the correct operating DC conditions for our amplifier, specifically:

- to provide a conduction voltage of more than 0.7 V for silicon transistors
- to avoid output distortion due to the rectifying properties of the base–emitter junction
- to prevent thermal runaway occurring as a result of amplified leakage current being temperature-dependent and adding to the base current — this could cause thermal breakdown of the semiconductor
- to provide for a variation of characteristics among manufactured transistors. This means the bias network has to cope with the fact that no two transistors, even of the same type, are identical and so if one device has to be replaced by another, the overall circuit does not have to be redesigned. One characteristic that varies widely from one transistor to another is the current gain factor, β. For example, BC108 transistors can vary from a value of 100 to a value of 800 in this factor.

The amplifier of Figure 31.10 uses **voltage divider bias** because the base bias voltage is determined by the resistors acting as a voltage divider to the supply voltage. Let us look at a typical set of steps for designing a transistor amplifier of this type. We will assume a transistor has been selected that has a maximum DC collector current of 5 mA and we are using a power supply V_{CC} of 12 V.

Step 1 Calculate value of R_E

It is appropriate to drop about 10% of the supply voltage across R_E. Hence, 10% of 12 V = 1.2 V. For class A operation, the quiescent or steady state collector current should be about half the maximum allowed, that is, in this circuit, a value of 2.5 mA, which is the same as I_E. Hence:

$$R_E = \frac{V_{RE}}{I_E} = \frac{1.2\ \text{V}}{2.5\ \text{mA}} = 480\ \Omega$$

Step 2 Calculate value of R_C

For a class A amplifier, R_C, the collector resistor, should have a value such that half the supply voltage appears across the transistor's collector–emitter terminals, with the quiescent collector current flowing. In our amplifier, at an I_C value of 2.5 mA:

$$V_{CE} = \frac{V_{CC}}{2} = \frac{12}{2} = 6\ \text{V}$$

Now the remaining 6 V drop will appear across R_C and R_E. From Step 1 and Ohm's law:

$$6\ \text{V} = 2.5\ \text{mA}\ (R_C + 480)$$
$$R_C = 1920\ \Omega\ \text{(value of 2 k}\Omega\text{ is close)}$$

Step 3 Calculate the voltage at the transistor's base, V_B

Assuming a silicon transistor, $V_{BE} = 0.7$ V, hence the voltage at the base $V_B = V_{BE} + V_{RE}$, $V_B = (0.7 + 1.2)\text{ V} = 1.9$ V.

Step 4 Calculate maximum base current, I_B

A small signal voltage amplifier transistor will have a worst case β value of, say, 200.

Hence $I_B = \frac{I_C}{\beta} = \frac{2.5\text{ mA}}{200} = 0.013$ mA, which will represent the maximum value of base current required. This figure allows a calculation of both R_1 and R_2 values.

Step 5 Calculate R_1 and R_2 divider values

The current drawn into the transistor's base is supplied by the voltage divider $R_1 : R_2$. If the voltage at the base is to remain constant irrespective of the current value, I_B, it is necessary to make the current flow through the divider $R_1 : R_2$ much larger than I_B — about 10 times, in fact, as a rule of thumb.
Hence:

$$\text{current through } R_2 = 10 \times 0.013\text{ mA} = 0.13\text{ mA}$$

Given that the voltage required at the base, $V_B = 1.9$ V, the value of:

$$R_2 = \frac{1.9\text{ V}}{0.13\text{ mA}} = 14.6\text{ k}\Omega = 15\text{ k}\Omega\text{ closest}$$

Also: the voltage drop across resistor $R_1 = 12 - 1.9 = 10.1$ V, and the value of the current through $R_1 = 0.13$ mA. Thus, the value of:

$$R_1 = \frac{10.1\text{ V}}{0.13\text{ mA}} = 77.7\text{ k}\Omega = 82\text{ k}\Omega\text{ closest}$$

Step 6 Calculate values of capacitors

These capacitors are the least critical in practical amplifier design. The input and output **coupling capacitors** are usually chosen to be in the range of 1.0–10 μF. The **emitter bypass capacitor**, C_2, is necessary to obtain maximum voltage amplification from this type of circuit. A portion of the output signal voltage appearing at the collector can find its way into the resistor R_E. This leads to a decrease in overall gain and in order to prevent this happening, resistor R_E has to ignore any voltage at the signal AC frequency. It has to become an AC short circuit path to ground at signal frequencies. If a capacitor is placed in parallel with R_E, so that its X_C reactance at signal frequencies is very low, then this short circuit path is produced and the possible decrease in amplifier gain is prevented. In most practical audio amplifier circuits, such as those used to amplify small microphone voltage signals, a typical emitter bypass capacitor value is from 20 μF to 50 μF.

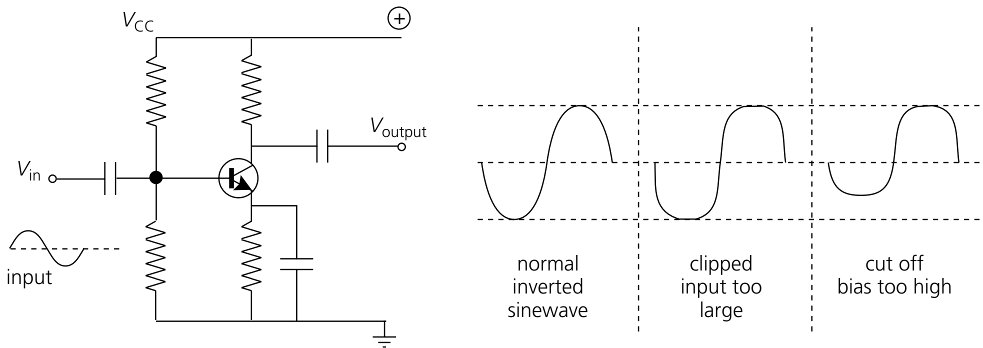
Our finished practical amplifier of Figure 31.10 has the following components and will act as a reliable small signal voltage amplifier:

T_1 = BC108 NPN	V_{CC} supply = 12 V DC
R_1 = 82 kΩ	$C_1 = C_{out}$ = 1 μF
R_2 = 15 kΩ	C_2 = 47 μF
R_C = 2 kΩ	R_E = 480 Ω

If this amplifier circuit is constructed it is usually found that values close to those calculated will still make the circuit work quite satisfactorily. This is an advantage of the voltage divider bias conditions. If the bias conditions for a transistor amplifier are not correct, then various forms of **distortion** of the output waveform can occur. Distortion, such as saturation and cut-off, can occur with incorrect resistor values, and total signal clipping can occur if the input voltage signal is too large in amplitude. Engineers designing critical amplifiers need to be careful not to introduce these forms of amplifier distortion as they will lead to eventual distortion of the sound output if, for instance, the amplifier is part of an audio system.

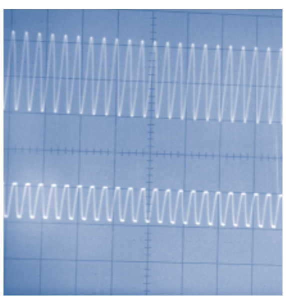
Refer to Figure 31.12. Notice also that the output signal in these common emitter class A amplifiers is always phase inverted. This means that if the input signal is a maximum at a particular time then the consequent output signal will be a minimum.

Figure 31.12
Amplifier output distortion.



The final amplifier design will increase small changes in input voltage to much larger changes in output voltage. This is called **voltage amplification** or voltage gain, A_V, where:

Photo 31.2
Signal amplification.



$$A_V = \frac{V_{out}}{V_{in}} = \frac{R_C}{R_E}$$

In circuits with an emitter bypass capacitor present:

$$A_V = \frac{R_C}{r_e}$$

where r_e is the internal emitter resistance. Its value is usually about 10–20 Ω so that voltage gain values, A_V, of 100–200 times are quite common. The voltage gain of an amplifier circuit is often easily measured with an oscilloscope and is usually quoted at a particular frequency of, say, 1000 Hz. The photo illustrates the voltage amplification of a transistor amplifier on a CRO screen.

Questions

4 Explain the operating conditions necessary to make a transistor function as a voltage amplifier. What bias method is commonly used?

5 You are designing a single transistor amplifier circuit using a device with a maximum collector current of 20 mA, β = 250 and voltage supply of 9 V. Using the design steps, calculate all values of the circuit components needed. Sketch your designed circuit and estimate its maximum voltage gain.

IC APPLICATION CIRCUITS 31.5

Linear IC applications

Let's continue our investigation of Op-Amp integrated circuits applications. Recall that, in Chapter 24, the Op-Amp chip was used in its inverting amplifier mode. This method of operation is similar to the discrete transistor AC voltage amplifier discussed in the previous section, but IC chip amplifiers are much more stable and are easier to use in electronics design. You should also realise that manufacturers often make integrated circuits with multiple operational amplifiers in the one chip package. Good examples are the LM324 Quad GP operational amplifier or the TL074 Quad JFET low noise operational amplifiers, where Quad refers to four amplifiers available in each chip package. Figure 31.13 illustrates the pin configuration of the LM324 Op-Amp chip in a 14 pin DIL package.

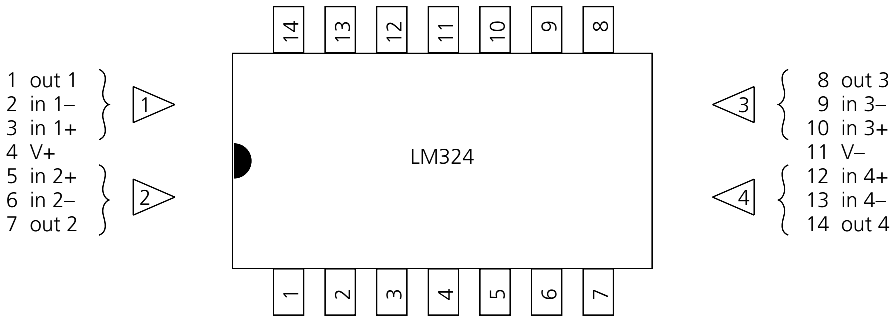


Figure 31.13
Quad Op-Amp LM324 chip.

Further application circuits of the linear operational amplifier IC are found as the wave function generator, adder and comparator as well as the audio amplifier. A brief discussion of each circuit type follows. Notice that quite often the Op-Amp chip requires a dual polarity power supply in these circuits.

Wave function generators

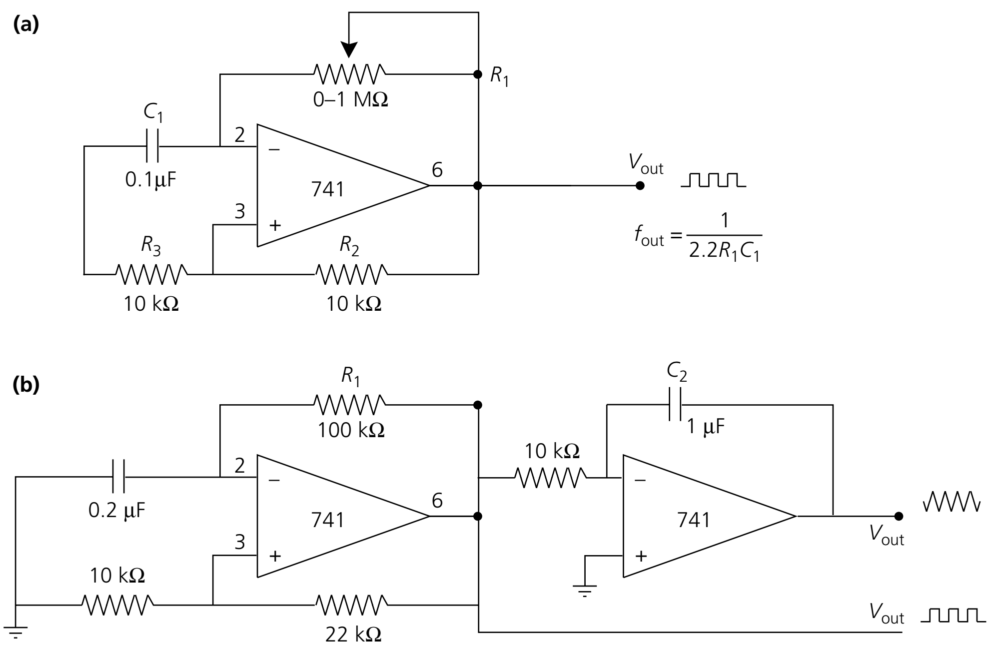


Figure 31.14
Wave function generator circuits.

The circuit of Figure 31.14**(a)** is using the 741 Op-Amp as a free running multivibrator circuit that produces a continuous square wave clock pulse. In circuit **(b)** the output of a similar circuit is connected to the input of a circuit that has a capacitor in place of the feedback resistor and has the function of carrying out an integration operation on the input voltage. This circuit will produce a second triangular wave output at pin 6 of the second 741 Op-Amp. Note the frequency formula for both circuits.

Adders and comparators

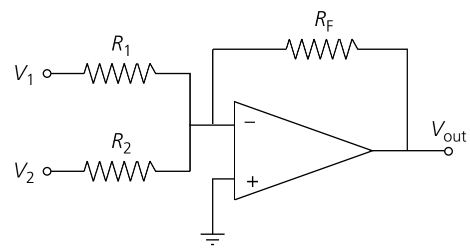


Figure 31.15
Op-Amp adder.

$$V_O = \left(\frac{R_F}{R_1}\right) V_1 + \frac{R_F}{R_2}(V_2)$$

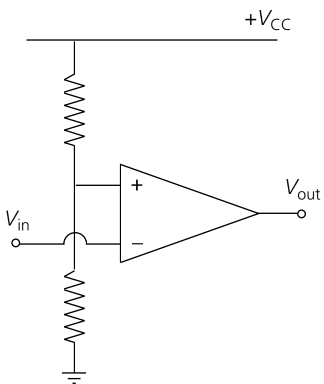


Figure 31.16
Op-Amp comparator.

Refer to Figure 31.15 which illustrates the Op-Amp used as an adder. It is simply an inverting amplifier with more than one input resistor. Resistors R1 and R2 control the amount of each voltage input that will appear added together at the circuit output. The comparator circuit of Figure 31.16 is used as a switch, which changes when a certain threshold voltage is reached, determined by the voltage divider resistors present at the non-inverting input of the Op-Amp. Voltage comparators drive the familiar bar graph LED displays in stereo amplifiers that indicate volume or recording level changes and contain a series of illuminating level indicators.

Audio amplifiers

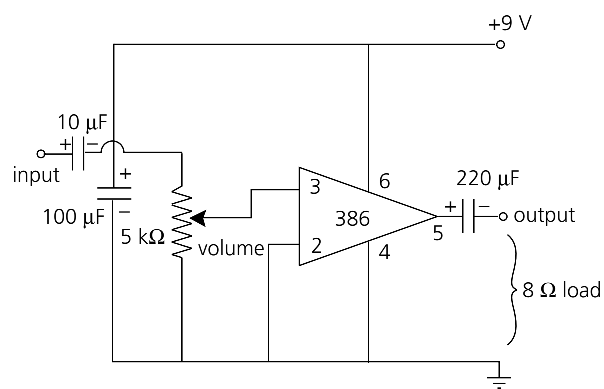


Figure 31.17
Linear LM386 audio amplifier.

Before leaving linear IC circuit applications let's look at a very practical IC, the LM386, which is a low voltage audio amplifier that could be used as the basis of a construction project, say, as an amplifier to drive a small set of speakers from the headphone output socket of your portable stereo Walkman. Of course, a separate circuit would be needed for each channel of the available stereo output (Figure 31.17). The 5 kΩ potentiometer is used to control the volume because it subdivides the voltage from the input and applies the appropriate proportion to pin 3 of the chip. The internal gain of the LM386 chip is set to a value of 20. The circuit operates quite well from a simple 9 V DC power supply. The LM386 power amplifier is a very versatile integrated circuit that can supply about 400 mW of power into a typical 4 Ω speaker load impedance using the 9 V supply.

In the same category but able to supply higher power ratings, especially if properly connected to thermal sinks to dissipate heat generated, is the LM380 2.5 W amplifier IC and the LM1875 20 W amplifier IC. Usually these devices are driven from a properly designed regulated power supply. Again, pin configuration diagrams for these chips are very easy to obtain and the chips are relatively inexpensive to purchase.

Digital devices and application circuits

Integrated circuits are used to perform a wide variety of functions in systems such as telephones, calculators and computers. Two basic classes of circuit types exist in digital electronics. Firstly, there are the **logic circuits**, which act as directional switches, latches and counters, and secondly, the **multivibrators**, which perform memory and timing functions. Both of these circuit classes can be represented by various **digital ICs**. Most of the digital ICs discussed in this section are manufactured in multiple unit packages in the form of 14 pin DIL chips. The series 4000 CMOS logic family are commonly used in circuit applications

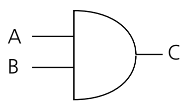
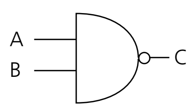
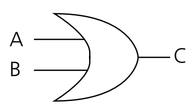
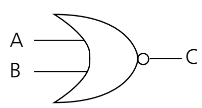
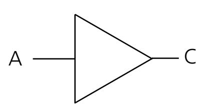
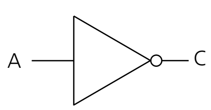
Logic gate	Circuit symbol	Truth table			Typical IC chip CMOS
		Input A	Input B	Output	
AND		0 0 1 1	0 1 0 1	0 0 0 1	4081 quad buffered 2-input
NAND		0 0 1 1	0 1 0 1	1 1 1 0	4011 quad 2-input
OR		0 1 0 1	0 0 1 1	0 1 1 1	4071 quad 2-input
NOR		0 1 0 1	0 0 1 1	1 0 0 0	4001 quad 2-input
Buffer		0 1		0 1	4050 Hex-non inverting
Inverter (NOT)		0 1		1 0	4049 Hex-inverting

Figure 31.18
Digital gates.

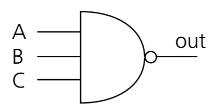
with both quad (4) or hex (6) multiples available in the one IC package. Manufacturers make available IC pin configuration diagrams that describe the necessary input, output and power supply pin connections.

No matter how complicated, all digital ICs are made from simple building blocks called logic gates or just gates, which are the equivalent of electronic switches. The circuits are called logic gates because they make logical decisions with the output state being dependent on the input states. Let's look at the basic set of logic gates, their input–output characteristics or **truth tables**, and typical IC packages that contain them. (See Figure 31.18.) Remember that 1 = digital ON or HIGH and 0 = digital OFF or LOW. In actual voltage terms, a digital high represents the chip supply voltage and a digital low represents ground or zero volts. Refer back to Chapter 24 (Section 24.2) for discussion of ADC.

Logic gates may have more than two inputs, which increases the decision-making power of the gates. Multiple input gates can increase the number of ways that the logic functions can be interconnected to form advanced digital logic circuit blocks. For example, Figure 31.19 shows the truth table for a 3 input NAND gate.

Figure 31.19
Three-input NAND gate.

Symbol

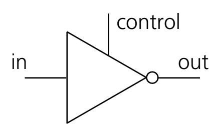


Truth table

A	B	C	Out
0	0	0	1
0	0	1	1
0	1	0	1
0	1	1	1
1	0	0	1
1	0	1	1
1	1	0	1
1	1	1	0

Figure 31.20
Three-state inverter.

Symbol



Truth table

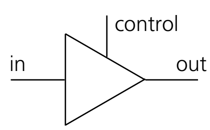
Control	In	Out
0	0	1
0	1	0
1	X	Hi-Z

X means either 1 or 0

Often the single input inverter designed to reverse the output from another gate can have an extra control input, in which case it is called a three-state inverter (Figure 31.20). Also, the buffer gate, which is a circuit that isolates gates from each other electrically or provides outputs that are capable of driving higher resistance loads, can have a control input as well. This gate is called a three-state buffer (Figure 31.21). Three-state buffers and inverters have an output that can be electronically disconnected from the rest of the circuitry. The output then is neither high nor low, but 'floats' and appears as a very high resistance.

Figure 31.21
Three-state buffer.

Symbol



Truth table

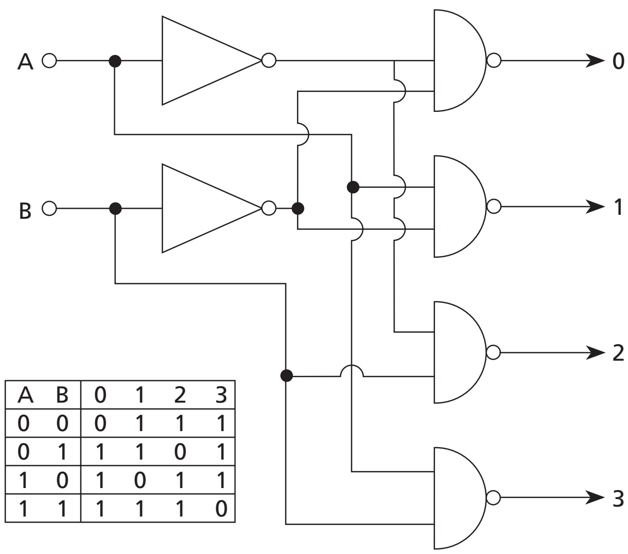
Control	In	Out
0	0	0
0	1	1
1	X	Hi-Z

X means either 1 or 0

Logic gates can be interconnected in a network of gates referred to as logic circuits. The methods of logic circuit connections can either be combinational or sequential.

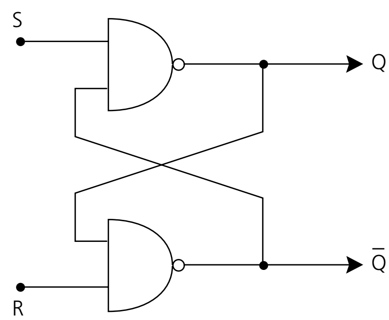
Combinational logic circuits respond to incoming data pulses immediately and their decisions do not depend on a series of previous logic events. Any combinational circuit can be constructed using the basic NAND and NOR logic gates. For example, the combinational logic circuit of Figure 31.22 and its truth table illustrate the process of converting a two-bit binary number to its decimal equivalent. Advanced combinational networks are often available as separate digital ICs; for example, data selectors (multiplexers) and digital encoders–decoders, such as the 74HC154 CMOS 4 to 16 decoder/demultiplexer chip.

Sequential logic circuit outputs are determined by the previous states of the circuit's inputs. That is, data bits move through the circuits step-by-step. Often a separate clock pulse



A	B	0	1	2	3
0	0	0	1	1	1
0	1	1	1	0	1
1	0	1	0	1	1
1	1	1	1	1	0

Figure 31.22
Binary to decimal decoder (BCD).



S	R	Q $\bar{Q}$
0	0	Disallowed
0	1	1 0
1	0	0 1
1	1	No change

Figure 31.23
RS Flip-flop (latch).

(square wave) signal is required in order to make the data bits move. The basic building block of sequential logic circuits is the **Flip-flop**. A basic reset-set Flip-flop circuit (RS Flip-flop), also called a **latch**, is shown in Figure 31.23, together with its truth table. The outputs Q and $\bar{Q}$ are always in opposite digital states. Flip-flop circuits can become quite complex and form the basis of counters and registers as used in computer circuits.

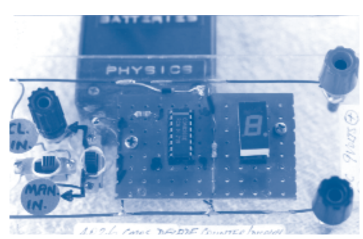
Circuit designers use **Boolean algebra** statements to show the respective outputs of logic gates. This algebra was invented by an English mathematician, George Boole, in the middle of the nineteenth century as a system of analysing logic statements mathematically. (See Figure 31.24.)

- The Boolean operation 'AND' is represented by a dot (●).
- The Boolean operation 'OR' is represented by a plus sign (+).
- The Boolean operation 'NOT' or inversion is represented by a bar over the letter ($\bar{A}$).

Combinations of the Boolean operations are also possible; for example, the NAND gate produces a combination of NOT and AND, whereas the NOR gate produces a combination of NOT and OR.

Figure 31.25 illustrates two circuits that use chips combining both combination and sequential logic circuits. The block diagram shows the simple decimal **counter** system, which is able to count incoming clock pulses from a circuit such as the clock of Figure 31.14. The BCD counter advances one count for each incoming pulse. When the count reaches binary (1001) or decimal (9) the counter recycles to 0000. The decoder activates the appropriate segments of a seven-segment LED display so that the count is obtained. Notice that a single chip can replace the function of both counter and decoder driver. This is the CMOS 4026 chip. Notice that this chip has a carry out (CO) pin that allows counts to other 4026 chips in order to cascade them together so that a total count of hundreds or thousands is possible. (See Photo 31.3.)

Photo 31.3
4026 counter chip.



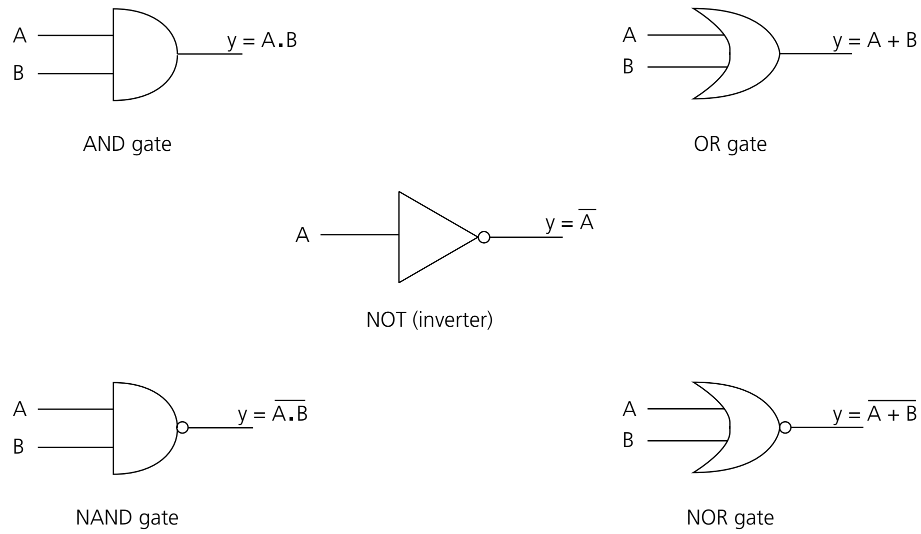


Figure 31.24
Boolean operators.

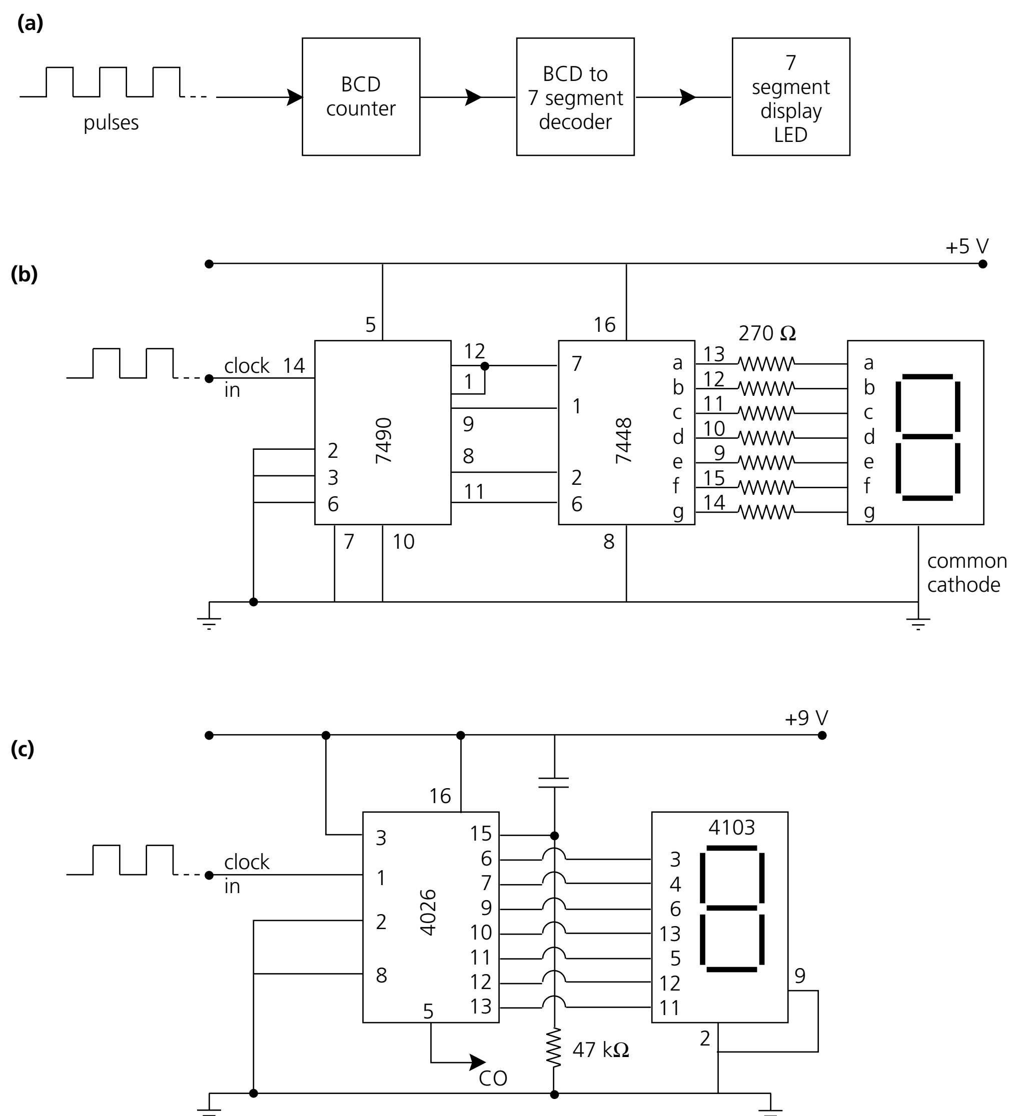


Figure 31.25
Decimal counting system: **(a)** block diagram; **(b)** separate chip circuit, 7490 + 7448; **(c)** single chip circuit, CMOS 4026 decade counter-display driver.

It is great fun to work with these digital counter and display driver chips. Using a protoboard and simple LEDs to indicate output states of gates or logic circuits, much experimentation can be done. Always be careful to observe correct power supply connections to all IC chips and handle them with care, especially if the type you are using is a CMOS design. An important circuit building tip for use with all digital logic circuits is to ensure that the inputs and outputs of unused gates in an IC package are connected to earth. This will avoid spurious noise signals triggering the gates falsely.

Questions

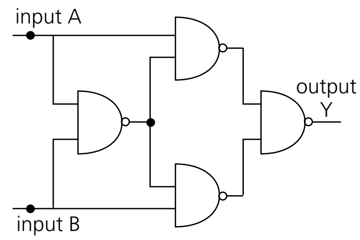
6 Select a simple application for a 741 Op-Amp. Sketch the circuit used including chip power supply and explain the operation of the circuit.

7 Draw the symbols used to represent the following logic gates: **(a)** 2 input AND gate; **(b)** 3 input NAND gate; **(c)** 2 input OR gate; **(d)** 3 state buffer.

8 The output of digital logic gates can be summarised with Boolean algebra statements. Which gates correspond to the following statements in Boolean algebra?
(a) A + B; **(b)** A●B; **(c)** $\overline{A + B}$; **(d)** A●B●C; **(e)** $\overline{A}$.

9 Figure 31.26 illustrates a combination of NAND gates. Deduce the truth table for the combination and decide if it is equivalent to any single logic gate.

Figure 31.26
For question 9.



EI Activity 31.2 BUILDING WITH ICs

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 text so that you can actually build some of the circuits. Remember to always connect power supply voltages to the correct pins of the IC and connect the power supply last of all. If you are using multiple gate digital chips always connect unused gate inputs and outputs low to avoid false triggering.

Practice questions

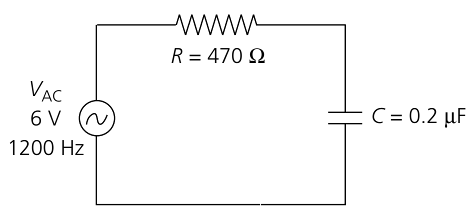
The relative difficulty of these questions is indicated by the number of stars beside each question number: * = low; ** = medium; *** = high.

Review — applying principles and problem solving

***10** Explain the differences in AC circuits between resistance, capacitive and inductive reactance. How are these concepts linked to impedance?

***11** For the circuit of Figure 31.27, calculate **(a)** capacitive reactance, X_C; **(b)** total circuit impedance, Z; **(c)** the RMS current flowing; **(d)** the phase angle between current and voltage.

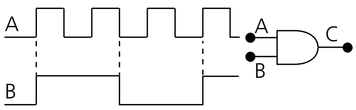
Figure 31.27
For question 11.



****12** Explain the function of each of the resistors used in a voltage divider common emitter class A transistor amplifier. Draw the common circuit diagram for this amplifier, marking all necessary connections including power supply.

****13** Calculate all necessary circuit component values in the design of a single transistor amplifier if it is to operate with the following parameters: V_{CC} = 12 V, β = 280 and I_C (max) = 18 mA. Sketch your designed circuit and estimate its voltage gain.

Figure 31.28
For question 14.



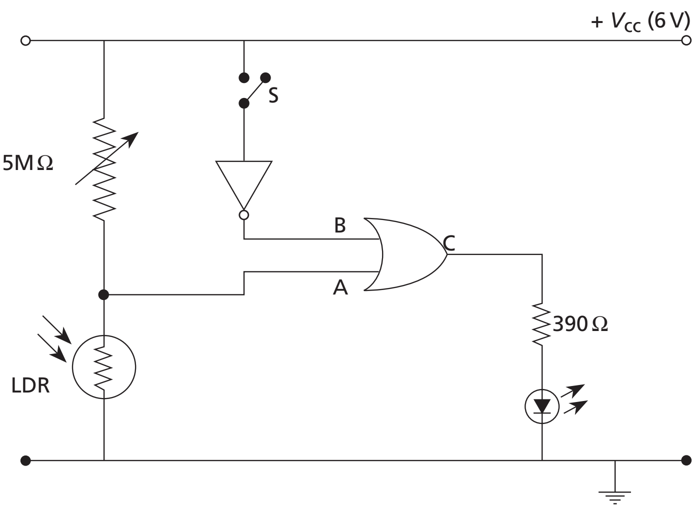
***14** Figure 31.28 illustrates the input waveforms applied to an AND gate. Correctly draw, at the same scale, the output waveform of this gate.

****15** An AC source (f = 100 Hz) is connected in series with a resistor of 1000 Ω.
(a) Draw a circuit diagram.
(b) If the peak voltage is 12 V, plot a curve (V–t) for three cycles of the waveform. What is the peak current value?

****16** Suppose you wish to build an AC powered battery replacement circuit for your portable Walkman player so that it can be used at your study desk. Draw a circuit that would provide the necessary 9 V output. Your circuit must be capable of supplying about 120 mA of smooth output current.

****17** Figure 31.29 illustrates a circuit that could be used as an automatic night light switch. The circuit automatically switches on the LED when darkness falls or when the sensor is covered.
(a) Identify each electronic component used in this circuit and make a listing.
(b) When it is dark how does the resistance of the LDR alter?
(c) Explain how the circuit works!
(d) What is the purpose of the potentiometer at the input A of the circuit?
(e) What is the function of the switch in the input B of the circuit?

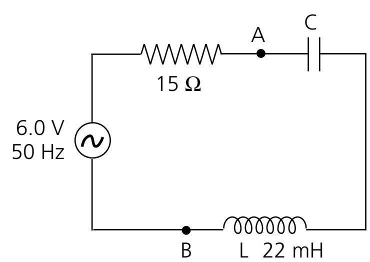
Figure 31.29
For question 17.



Extension — complex, challenging and novel

*****18** The circuit of Figure 31.30 contains an AC source of 50 Hz, 6.0 V. If the capacitor has a value of 65 µF:
(a) what is the total impedance, Z_{AB};
(b) what is the total circuit impedance if the source internal impedance is 5 ohms;
(c) what is the RMS current flowing in the circuit;
(d) what is the value of RMS voltage between points A and B?

Figure 31.30
For question 18.



*****19** Consider Figure 31.31. Recall that a magnet moved inside a coil of wire will generate a small AC voltage. Look at the circuit diagrams supplied and analyse them to answer these questions:

(a) How is the simple rectifier power supply working?

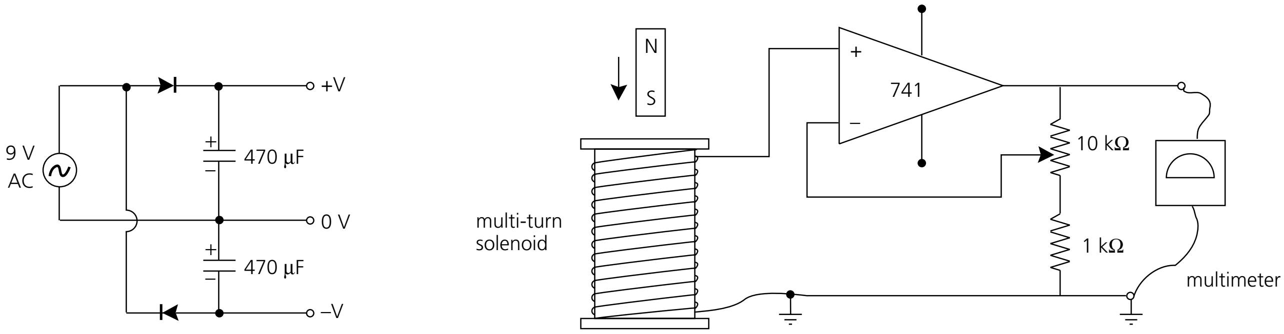
(b) Why is it needed in this circuit application, and how is it connected?

(c) How is the Op-Amp modifying the signal produced when the magnet is moved into the multi-turn coil?

(d) What will occur when the circuit variable resistor is adjusted?

(e) To what range would the multimeter need to be set?

Figure 31.31
For question 19.



****20** In Boolean algebra, an exclusive OR (XOR) function is represented by the plus symbol inside a circle (⊕). An XOR gate produces a digital high (1) output only when one of its inputs is high (1). If both inputs are either high or low then the output is low. Draw a logic gate circuit diagram that would represent the following Boolean algebra statements:

(a) $Y = \bar{A} + \bar{B} + \bar{C}$

(b) $Y = \bar{A} \oplus \overline{B\ \bullet}$

(c) $Y = \bar{A} \oplus \bar{B}$

*****21** Consider Figure 31.32, showing the circuit of a Quad NAND gate CMOS IC, the 4011 operating from a 9 V DC supply. The circuit is one method of testing the truth table for the NAND logic gate. Analyse the circuit given and answer these questions:

(a) Would the 9 V DC supply need to be regulated?

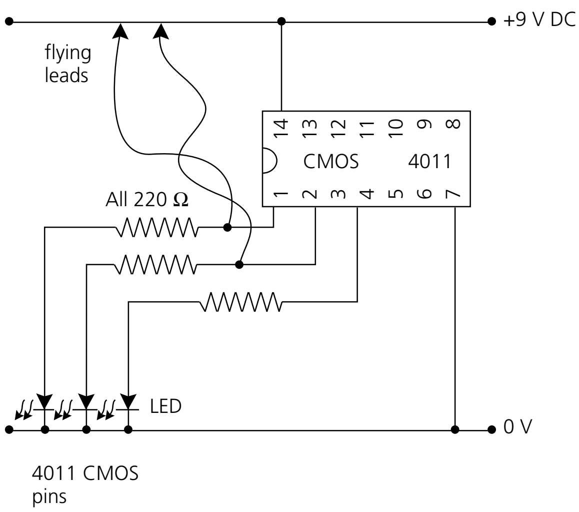
(b) How many different gates could be tested?

(c) What is the purpose of the flying leads?

(d) Why are the resistors needed?

(e) Explain how the three LEDs display the input and output combinations of the gate. Draw a truth table.

(f) Could this circuit be used to test other gate types? Explain.



1	in A1	8	in B3
2	in B1	9	in A3
3	out 1	10	out 3
4	out 2	11	out 4
5	in A2	12	in B4
6	in B2	13	in A4
7	V_{SS} (0 V)	14	V_{DD}

Figure 31.32
For question 21.