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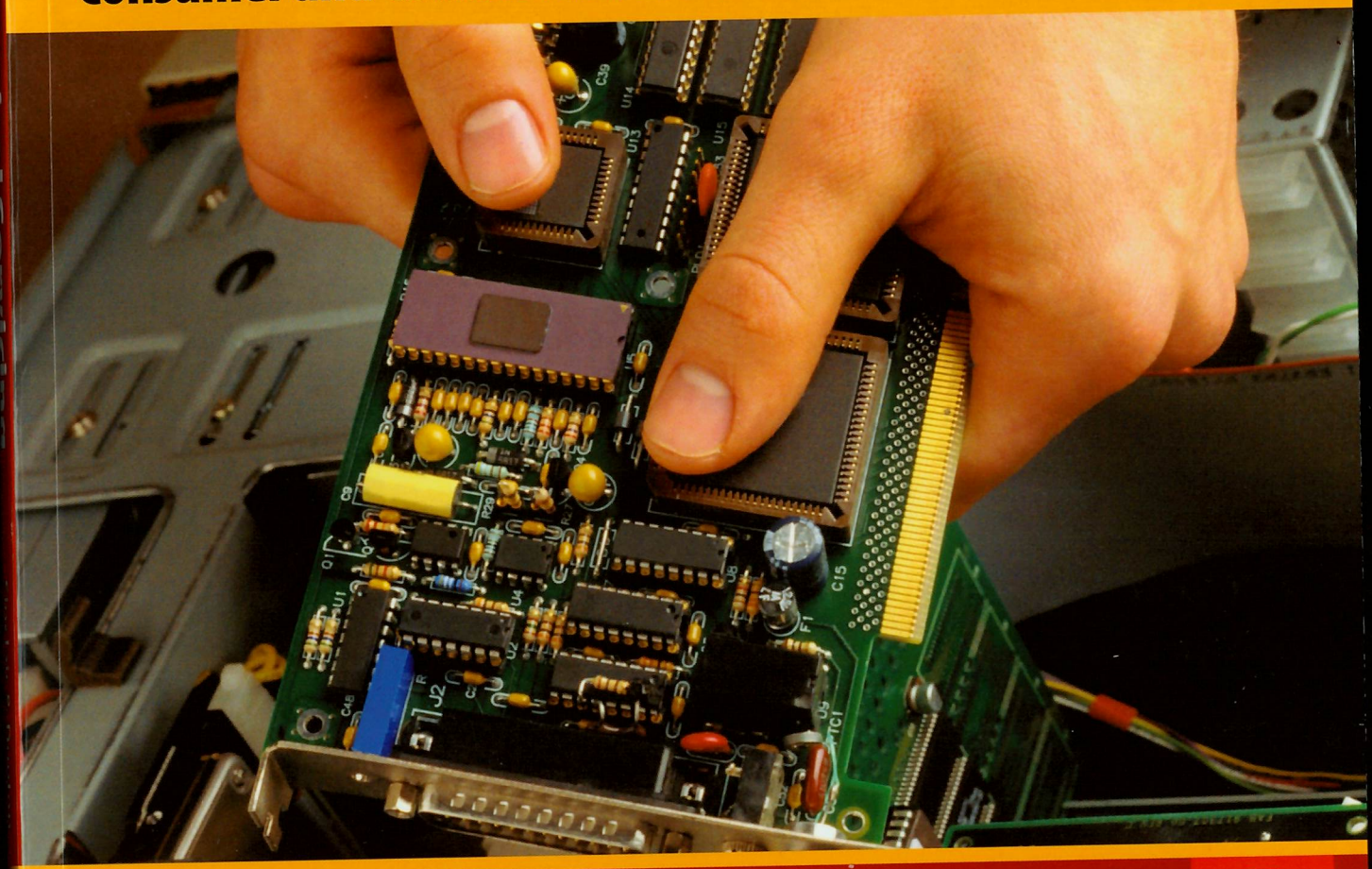
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Electronic and Electrical Servicing

Consumer and Commercial Electronics



Ian Sinclair & John Dunton

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Electronic and Electrical Servicing

Consumer and commercial electronics

Second Edition

Ian Sinclair

and

John Dunton



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1 Direct current technology

Electric current consists of the flow of small particles called electrons in a circuit. Its rate of flow is measured in units called **amperes**, abbreviated either to 'amps' or 'A'. One ampere is the amount of electric charge, in units called coulombs, that passes a given point in a circuit per second. The coulomb has a value of about 6.289×10^{18} electrons (10^{18} means a 1 followed by 18 zeros). The measurement of current is done, not by actually counting these millions of millions of millions of electric charges, but by measuring the amount of force that is exerted between a magnet and the wire carrying the current that is being measured. Current can flow in any material that allows electrons to move, but in such materials there is always some resistance to the flow of current (except for materials called *superconductors*). Resistance is measured in units called ohms, symbol Ω (the Green letter omega).

Electric current can be direct current (d.c.) or alternating current (a.c.) or a mixture of both

Direct current is a steady flow of current, the type that occurs in a circuit fed by a battery. This type of current is used to operate most types of electronic circuit. Alternating current is not a steady flow; it is a current that rises to a peak in one direction, reverses and reaches a peak in the opposite direction and reverses again. This means that at times the current becomes zero and at other times it can be flowing in either direction.

Electronics makes use of a.c. with much smaller times for one cycle, and we usually prefer to refer to the number of cycles in a second, a quantity called **frequency**, rather than the time of one cycle. The unit of frequency is one complete cycle per second, called 1 hertz, abbreviation Hz. Looked at this way, the mains frequency is 50 Hz. The frequencies used for radio broadcasting are measured in millions of hertz, MHz. Computers typically work with thousands of millions of hertz, gigahertz, abbreviation GHz. In following chapters we'll look at how a.c. behaves in circuits and the differences between a.c. and d.c.

In the same way as a pressure is needed to cause a flow of water through a pipe, so an electrical 'pressure' called **electromotive force** or **voltage** is needed to push a current through a resistance. Electromotive force (emf) is measured in units of volts, symbol V. A voltage is always present when a current is flowing through a resistance, and the three quantities of volts, amps and ohms (the unit of resistance) are related. Like current, voltage can be direct or alternating.

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The ampere is a fairly large unit, and for most electronics purposes the smaller units milliamp (one-thousandth of an ampere) and microamp (one-millionth of an ampere) are more generally used. The abbreviations for these qualities are mA and μA, respectively. All electrical units can use the same set of smaller units **(submultiples)** and larger units (**multiples**), and some of the most common are listed in Table 1.1. The abbreviation list is of **SI prefixes**, the standard letters used to indicate the multiple or submultiple.

Table 1.1 Multiples and submultiples

Number	*Power*	*Written as*	*Abbreviation*
0.000 000 000 001	10^{-12}	pico-	p
0.000 000 001	10^{-9}	nano-	n
0.000 001	10^{-6}	micro-	μ
0.000 01	10^{-3}	milli-	m
1000	10^{3}	kilo-	k
1 000 000	10^{6}	mega-	M

Two simple examples will help to show how the system works. A current flow of 0.015 amperes can be more simply written as 15 mA (milliamps), which is 15×10^{-3} A. A resistance of 56 000 ohms, which is equal to 56×10^{3} ohms, is written as 56 k (**k** for kilohms). The ohm sign Ω is often left out.

Do not use K for kilo, because the K abbreviation is used for temperatures measured in kelvin. You may see the K in some circuit diagrams that were drawn before agreement was reached on how to represent kilohms.

There are two other important electrical units, of **energy** and of **power**. The energy unit is called the **joule**, abbreviation J, and it measures the amount of work that an electrical current can do, such as in an electric motor or a heater. The power unit measures the rate of doing work, which is the amount of work per second, and its unit is the **watt**, symbol W. Both the units can also make use of the multiples and submultiples in Table 1.1.

Circuits and current

An electric **circuit** is a closed path made from conducting material. When the path is not closed, it is an **open circuit**, and no current can flow. In a circuit that contains a battery and a lamp, for example, the lamp will light when the circuit is closed, and we take the direction of the conventional flow of current as from the positive (+) pole of the battery to the negative (−). This convention was agreed centuries ago, and we now know that the movement of electrons is in the opposite direction, from negative to positive. For most purposes, we stay with the old convention, but for some purposes in electronics we need to know the direction of the electron flow.

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An electrical circuit such as the lamp and battery can be shown in two ways. One is to draw the battery and the bulb as they would appear to the eye. The other is to draw the shape of the circuit, representing items such as the battery and the lamp, the components of the circuit, as symbols, and the conductor as a line. We draw these **circuit diagrams** to show the path that the current takes, because this is more important than the appearance of the components. To avoid confusion, there are some rules (conventions) about drawing these circuits.

- A line represents a conductor
- Where lines cross, the conductors are NOT joined
- Where two lines meet in a T junction, with or without a dot, conductors are connected.

Figure 1.1 shows some symbols that are used for common components. Most of these use two connections only, but a few use three or more. These symbols are UK [British Standard (BS)] and European standards, but circuit diagrams from the USA and Japan may use the alternative symbols for resistors and capacitors.

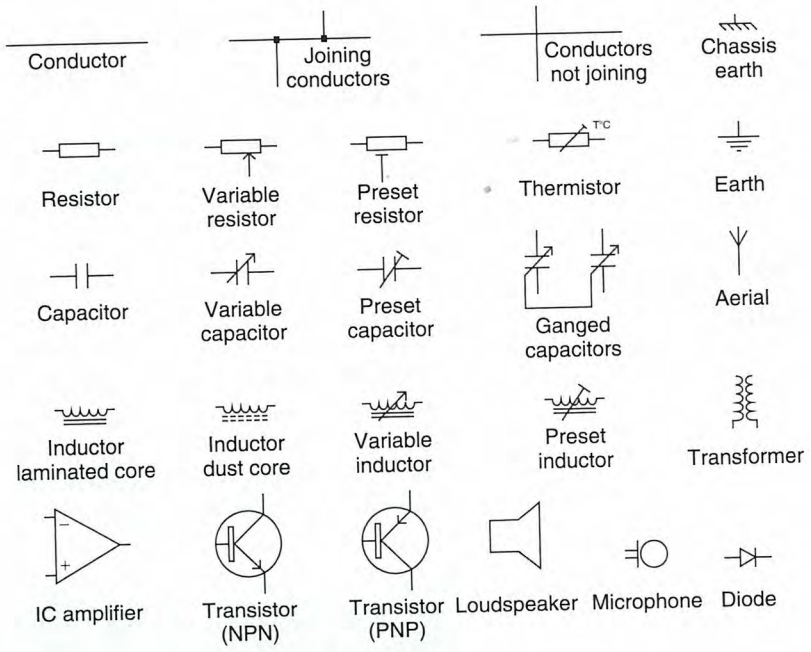


Figure 1.1 Some symbols used in UK circuit diagrams

Circuit diagrams are important because they are one of the main pieces of information about a circuit, whether it is a circuit for the wiring of a house or the circuit for a television receiver. For servicing purposes you must be able to read a circuit diagram and work out the path of currents.

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Effects of current

Electric current causes three main effects, which have been known for several hundred years.

- **Heating effect**: when a current flows through a conductor, heat is generated so that the temperature of the conductor rises.
- **Magnetic effect**: when a current flows through a conductor it causes the conductor to become a magnet.
- **Chemical effect**: when a current flows through a chemical solution it can cause chemical separation (in addition to heating and magnetism).

All of these effects can be either useful or undesirable. We use the heating effect in electric fires and cookers, but we try to minimize the loss of energy from transmission cables by using high voltages with low current for transmission. The heating effect is the same whether the current is d.c. or a.c. The magnetic effect is used in electric motors, relays and solenoids (meaning magnets that can be switched on and off). Less desirable effects include the unwanted interference that comes from the magnetic fields created around wires. One notable wanted chemical effect is that of chemical energy being converted to electrical energy in a cell or battery. Some other chemical effects are, however, undesirable. A current that is passed through a solution of a salty material dissolved in water will cause a chemical change in the solution which can release corrosive substances. This is the effect that causes electrolytic corrosion, particularly on electrical equipment that is used in ships.

All of these effects have been used at one time or another to measure electric current. We now use the magnetic effect in the older type of instruments, but the modern digital meters work on quite different principles.

Working with numbers

We can write any denary number as a number between 1 and 10 multiplied by a **power** of 10. For example, the number 100 is a denary number, equal to 10 tens, and we count in multiples (powers) of 10, using 1000 ($10 \times 10 \times 10$), 10 000, 100 000 and so on. The number 89 is a denary number, equal to eight tens plus nine units. The number 0.2 is also a denary number equal to 2/10, a decimal fraction. The number 255 can be written as 2.55×100 (or 2.55×10^2) and this is often useful in calculations because it avoids the need to work with numbers that contain a large set of zeros.

A **denary** number is one that is either greater than unity, such as 2, 50 or 350, or a fraction such as 1/10, 3/40 or 7/120 that is made up of digits 0–9 only.

Denary numbers can be added, subtracted, multiplied and divided digit by digit, starting with the least significant figures (the units of a whole number, or the figure farthest to the right of the decimal point of a fraction), and then working left towards the most significant figures.

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Decimals are denary numbers that are fractions of 10, so that the number we write as 0.2 means 2/10, and the number we write as 3.414 is 3 + 414/1000. The advantage of using decimals is that we can add, subtract, multiply and divide with them using the same methods as for whole numbers. Even the simplest of calculators can work with decimal numbers.

The numbers 0.047, 47 and 47 000 are all denary numbers. Each of them consists of the two figures 4 and 7, along with a power of 10 which is shown by zeros put in either before or after the decimal point (or where a decimal point would be). The number 0.047 is the fraction 47/1000, and 47 000 is 47×1000. The figures 4 and 7 are called the significant figures of all these numbers, because the zeros before or after them simply indicate a power of 10. Zero can be a significant figure if it lies between two other significant figures as, for example, in the numbers 407 and 0.407. The zeros in a number are not significant if they follow the significant figures, as in 370 000, or if they lie between the decimal point and the significant figures, as in 0.000 23.

Powers of 10 are always written in this index form, as shown in Table 1.2. A positive index means that the number is greater than one (unity), and a negative index means that the number is less than unity; for instance, the number $1.2 \times 10^3 = 1200$, the number $47 \times 10^{-2} = 0.047$, and so on.

Table 1.2 Powers of 10 in index form

Number	*Power*	*Written as*
1/1 000 000 or 0.000 001	−6	10^{-6}
1/100 000 or 0.000 01	−5	10^{-5}
1/10 000 or 0.0001	−4	10^{-4}
1/1000 or 0.001	−3	10^{-3}
1/100 or 0.01	−2	10^{-2}
1/10 or 0.1	−1	10^{-1}
1	0	10^{0}
10	1	10^{1}
100	2	10^{2}
1000	3	10^{3}
10 000	4	10^{4}
100 000	5	10^{5}
1 000 000	6	10^{6}

The British Standard (BS) system of marking values of resistance (BS1852/1977) uses the standard prefix letters such as k and M, but with a few changes. The main difference is that the ohm sign (Ω) and the decimal point are **never** used. This avoids making mistakes caused by an unclear decimal point, or by a spot mark mistaken for a decimal point, or the Ω sign mistaken for a zero. This is particularly important for circuit diagrams that are likely to be used in workshop conditions. In this BS system, all values in ohms are indicated by the letter R, all values in kilohms by the letter k, and all values in megohms by M. These letters are then placed where the decimal point would normally be found, and the point is not used. Thus R47 = 0.47

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ohms; 5k6 = 5.6 kilohms; 2M2 = 2.2 megohms, and so on. The BS system is illustrated throughout this book. In this system there is no space between the number and the letter. The BS value system is used also for capacitance values and for some voltage values such as the stabilized value of a Zener diode.

Relationships between units

The electrical units of volts, amps and ohms are related, and the relationship is commonly known (not quite correctly) as Ohm's law, which as an equation is written as $V = R \times I$. In words, it means that the voltage measured across a given resistor (in volts) is equal to the value of the resistance (in ohms) multiplied by the amount of current flowing (in amperes). Any equation like this can be rearranged, using a simple rule:

> An equation is unaltered if the quantities on each side of the equals sign are multiplied or divided by the same amount.

For example, the Ohm's law equation can be rearranged, as illustrated in Figure 1.2, as either $R = V/I$ (resistance equals volts divided by current) or $I = V/R$ (current equals volts divided by resistance). We get the first of these by taking $V = R \times I$ and dividing both sides by I to get $V/I = (R \times I)/I$. Because I/I must be 1, this boils down to $V/I = R$ (the same as $R = V/I$). Now try for yourself the effect on $V = R \times I$ of dividing each side by R.

These equations are the most fundamentally important ones you will meet in all your work on electricity and electronics. In electrical circuits the units in which the law has been quoted (volts, amperes, ohms) should normally always be used; but in electronic circuits it is in practice much easier to measure resistance in k and current in mA. Ohm's law can be used in any of its forms when both R and I are expressed in these latter units, but the unit of voltage in these other expressions always remains the volt.

There are, therefore, two different combinations of units with which you can use Ohm's law as it stands: either VOLTS AMPERES OHMS or VOLTS MILLIAMPERES KILOHMS. Never mix the two sets of units. Do not use milliamperes with ohms, or amperes with kilohms. If in doubt, convert your quantities to volts, amps and ohms before using Ohm's law.

Example: What is the resistance of a resistor when a current of 0.1 A causes a voltage of 2.5 V to be measured across the resistor?

Solution: Express Ohm's law in the form in which the unknown quantity R is isolated: $R = V/I$. Substitute the data in units of volts and amperes.

$$R = 2.5/0\ 1 = 25\ \Omega$$

Example: What value of resistance is present when a current of 1.4 mA causes a voltage drop of 7.5 V?

Solution: The current is measured in milliamps, so the answer will appear in kilohms. $R = VI = 7.5/1.4 = 5.36$ kilohms, or about 5k4.

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Example: What current flows when a 6k8 resistor has a voltage of 1.2 V across its terminals?

Solution: The data is already in workable units, so substitute in $I = V/R$. Then $I = 1.2/6.8\,\text{A} = 0.176\,\text{A}$, or 176 mA.

Example: What current flows when a 4k7 resistor has a voltage of 9 V across its terminals?

Solution: With the value of the resistor quoted in kilohms, the answer will appear in milliamps. So substitute in $I = V/R$, and $I = 9/4.7 = 0.001\,915\,\text{A} = 1.915\,\text{mA}$.

The importance of Ohm's law lies in the fact that if only two of the three quantities current, voltage and resistance are known, the third of them can always be calculated by using the formula. The important thing is to remember which way up Ohm's law reads. Draw the triangle illustrated in Figure 1.2. Put V at its Vertex, and I and R down below and you will never forget it. The formula follows from this arrangement automatically using a 'cover-up' procedure. Place a finger over I and V/R is left, thus $I = V/R$. The other ratios can be found in a similar way.

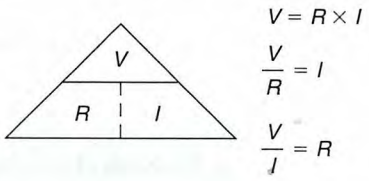


Figure 1.2 The *V R I* triangle

Work, power and energy

The related quantities of work, energy and power are often confused. Mechanical **work** is done whenever a force F causes movement in the same direction as the force through a distance d. The force is measured in units of newtons (N) and 1 N is the force necessary to accelerate a mass of 1 kilogram by 1 metre per second per second (1 m/s^2). Work is therefore the product of $F \times d$ (measured in newton metres), and this unit is called the **joule**. Work is also directly related to the **torque** or turning moment applied to a rotating shaft. The joule is also the unit of work that is used in electrical measurements.

Power is the rate at which work is done and is measured in **watts** (which are joules of work per second). Work also generates heat and this is also measured in watts. Electric motors were often specified by their work loading in horse power or brake horse power (HP or BHP) on the rating plate, where 1 HP is equivalent to 746 W. Therefore, a 1/2 HP a.c. motor would draw just over 1.5 A from the nominal 240 V supply mains.

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Energy is the capacity to do work and, because it is easier to measure power, energy is often calculated as the product of power and time. Thus, 1 J is equal to 1 watt-second (**not** one watt per second but watts multiplied by seconds). This means that 1 kWh = 3600 kilojoules (kJ) or 3.6 megajoules (MJ).

When a current flows through a resistor, electrical energy is converted into heat energy, and this heat is passed on to the air around the resistor, and dissipated, spread around. The rate at which heat is dissipated, which is the rate of working, is **power**, and is measured in units of watts.

The amount of power dissipated can be calculated from any two of the quantities V (in volts), I (in amps) and R (in ohms), as follows:

- Using V and I — Power = $V \times I$ watts
- Using V and R — Power = V^2/R watts
- Using I and R — Power = I^2R watts

Most electronic circuits use small currents measured in mA, and large values of resistance measured in k, and we seldom know both volts and current. The power dissipated by a resistor is therefore often more conveniently measured in milliwatts using volts and k or using milliamps and k. Expressing the units V in volts, I in milliamps and W in milliwatts, the equations to remember become:

The milliwatts dissipated = V^2/R (using volts and k)
= I^2R (using milliamps and k)

Example: How much power is dissipated when: (a) 6 V passes a current of 1.4 A, (b) 8 V is placed across 4 ohms, (c) 0.1 A flows through 15 R?

Solutions: (a) Using $V \times I$, Power = $6 \times 1.4 = 8.4$ W, (b) using V^2/R, Power = $8^2/4 = 64/4 = 16$ W, (c) using I^2R, Power = $0.1^2 \times 15 = 0.01 \times 15 = 0.15$ W.

Example: How much power is dissipated when (a) 9 V passes a current of 50 mA, (b) 20 V is across a 6k8 resistor, (c) 8 mA flows through a 1k5 resistor?

Solutions: (a) Using $V \times I$, Power = $9 \times 50 = 450$ mW, (b) using V^2/R, Power = $20^2/6.8 = 400/6.8 = 58.8$ mW, (c) using I^2R, Power = $8^2 \times 1.5 = 64 \times 1.5 = 96$ mW.

The amount of energy that is dissipated as heat is measured in joules. The watt is a rate of dissipation equal to the energy loss of one joule per second, so that joules = watts × seconds or watts = joules/second. The energy is found by multiplying the value of power dissipation by the amount of time

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during which the dissipation continues. The resulting equations are: Energy dissipated = $V \times I \times t$ joules or V^2t/R joules or I^2Rt joules, where t is the time during which power dissipation continues, measured in seconds. In electronics you seldom need to make use of joules except in heating problems, or in calculating the stored energy of a capacitor.

Electrical components and appliances are rated according to the power that they dissipate or convert. A 3W resistor, for example, will dissipate 3J of energy per second; a 3kW motor will convert 3000J of energy per second into motion (if it is 100% efficient). As a general rule, the greater the power dissipation required, the larger the component needs to be.

Calculations

At one time tables of values were used to help in solving complicated calculations, or calculations that used numbers containing many **significant figures**. Significant figures are the digits that need to be used in calculations, so that zeros ahead of or following other digits are not significant, but zeros between other digits are. For example, the zeros in 12000 or 0.0053 are not significant because it is only the other digits, the 1 and 2 or 5 and 3, that we really need to work with. When you multiply 12000 by 3, you don't need to start by thinking 'three times zero is zero, three times zero is zero' and so on. You simply think 'three times 12 (thousand) is 36 (thousand)'. Zeros in 26005 **are** significant because they are part of the number.

Nowadays we use electronic calculators in place of tables, but a calculator is useful only if you know how to use it correctly. Calculators can be simple types that can carry out addition, subtraction, multiplication and division only, and these can be useful for most of your calculations.

To solve some of the other types of calculations you will meet in the course of electronics servicing, a scientific calculator is more useful. A good scientific calculator, such as the Casio, need not be expensive and it will be able to cope with any of the calculations that will need to be made throughout this course. You should learn from the manual for your calculator how to carry out calculations involving squares, square roots and powers, angle functions (particularly sines and cosines), and the use of brackets.

The **square** of a number means that number multiplied by itself. For example, 2 squared (written as 2^2) is $2 \times 2 = 4$. Five squared is 25. It is simple enough for whole numbers, but when it comes to numbers with fractions, like 6.75^2 (equal to 45.5625), then you need a calculator.

Many of the quantities used in electronics measurements are **ratios**, such as the ratio of the current flowing in the collector circuit of a transistor (I_c) to the current flowing in its base circuit (I_b). A ratio consists of one number divided by another, and can be expressed in several different ways:

- as a common fraction, such as 2/25
- as a decimal fraction, such as 0.47; this is the most common method
- as a percentage, such as 12% (which is another way of writing the fraction 12/100).

To convert a decimal fraction into a common fraction, first write the figures of the decimal, but not the point. For example, write 0.47 as 47. Now draw a fraction bar under this number (called the **numerator**) and under it

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write a power of 10 with as many zeros as there are figures above. In this example, you would use 100, with two zeros because there are two digits in 47. This makes the fraction 47/100.

To convert a common fraction into a decimal, do the division using a calculator. For example, the fraction 2/27 uses the 2, division and 27 keys and comes out as 0.074 074, which you would round to 0.074.

To convert a decimal ratio into a percentage, shift the decimal point two places to the right, so that 0.47 becomes 47%. If there are empty places, fill them with zeros, so that 0.4 becomes 40%.

To convert a percentage to a decimal ratio, imagine a decimal point where the % sign was, and then shift this point two places to the left, so that 12% becomes 0.12. Once again, empty places are filled with zeros, so that 8% becomes 0.08.

Averages

The **average value** of a set of numbers is found by adding up all the numbers in the set and then dividing by the number of items in the set. Suppose that a set of resistors has the following values: one 7R, two 8R, three 9R, four 10R, four 11R, three 12R and two 13R. This is a set of 19 values, and the average value of the set is found as follows:

$$\frac{\begin{bmatrix}7+8+8+9+9+9+10+10+10+10+\\11+11+11+11+12+12+12+13+13\end{bmatrix}}{19} = \frac{196}{19}$$

This divides out to 10.32 (using two places of decimals), so that the average value of the set is 10.32 ohms or 10R32.

An average value like this is often not 'real', in the sense that there is no actual resistor in the set that has the average value of 10.32R. It is like saying that the average family size in the UK today is 2.2 children. This may be a perfectly truthful average value statement, but you will seldom meet a family containing two children and 0.2 of a third one.

Chemical cells

Cells convert chemical energy into d.c. electrical energy without any intermediate stage of conversion to heat. Only a few chemical reactions can at present be harnessed in this way, although work on fuel cells has enabled electricity to be generated directly without any fuel having to be burned to provide heat. Cells and batteries, however, although important as a source of electrical energy for electronic devices, represent only a tiny (and expensive) fraction of the total electrical energy that is generated.

A cell converts chemical energy directly into electrical energy. A collection of cells is called a **battery**, but we often refer to a single cell as a 'battery'. Cells may be connected in **series** to increase the voltage available or in **parallel** to increase the current capacity, but parallel connection is usually undesirable because it can lead to the rapid discharge of all cells if one becomes faulty and the others pass current into the faulty cell.

Cells may be either primary or secondary cells. A **primary cell** is one that is ready to operate as soon as the chemicals composing it are put together.

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Once the chemical reaction is finished, the cell is exhausted and can only be thrown away. A **secondary cell** generally needs to be charged by connecting it to a voltage higher than the output voltage of the cell before it can be used. Its chemical reaction takes place in one direction during charging, and in the other direction during discharge (use) of the cell. The cell can then be recharged.

Cells are classed according to their open-circuit voltage (usually 1.2–1.6 V, except for lithium cells) and their capacity. **Open circuit** means that nothing is connected to the cell that could allow current to flow. The **capacity** of a cell is its stored energy, measured in mA-hours. In principle, a cell rated at 500 mA-hours could supply 1 mA for 500 hours, 2 mA for 250 hours, 10 mA for 50 hours, and so on. In practice, the figure of energy capacity applies for small discharge currents and is lower when large currents are delivered.

Cells also have **internal resistance**, the resistance of the current-carrying chemicals and conducting metals in the cell. This limits the amount of current that the cell can deliver to a load, because even if the cell is short-circuited the internal resistance will limit the amount of current. Rechargeable cells usually have lower values of internal resistance than the non-rechargeable type.

Most primary cells are of the zinc/carbon (Leclanché) type, of which a cross-section is shown in Figure 1.3. The zinc case is sometimes steel coated to give extra protection. The ammonium chloride paste is an acidic material which gradually dissolves the zinc. This chemical action provides the energy from which the electrical voltage is obtained, with the zinc the negative pole.

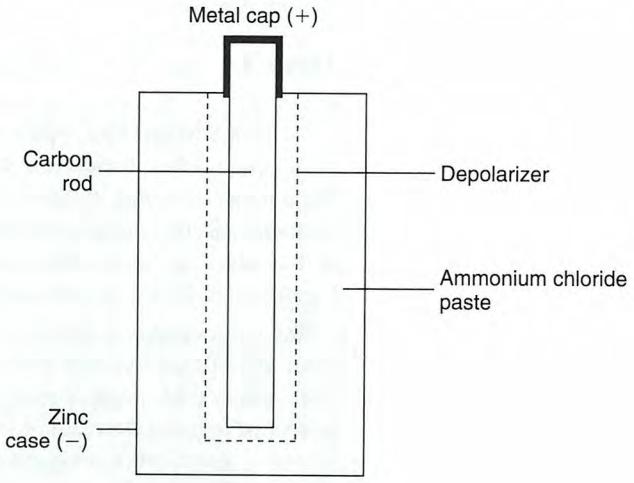


Figure 1.3 A typical (Leclanché) dry cell construction

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The purpose of the manganese dioxide *depolarizer* mixture that surrounds the carbon rod is to absorb hydrogen gas, a by-product of the chemical reaction. The hydrogen would otherwise gather on the carbon, insulating it so that no current could flow. The zinc/carbon cell is suitable for most purposes for which batteries are used, having a reasonable shelf-life and yielding a fairly steady voltage throughout a good working life.

Other types of cell such as alkaline manganese, mercury or silver oxide and lithium types are used in more specialized applications that need high working currents, very steady voltage or very long life at low current drains. However, mercury-based cells are not considered environmentally friendly when discarded unless they can be returned to the manufacturer. The use of a depolarizer is needed only if the chemical action of the cell has generated hydrogen, and some cell types do not.

Practical 1.1

Connect the circuit of Figure 1.4(a) using a 9 V transistor radio battery. Draw up a table on to which readings of output voltage V and current I can be entered.

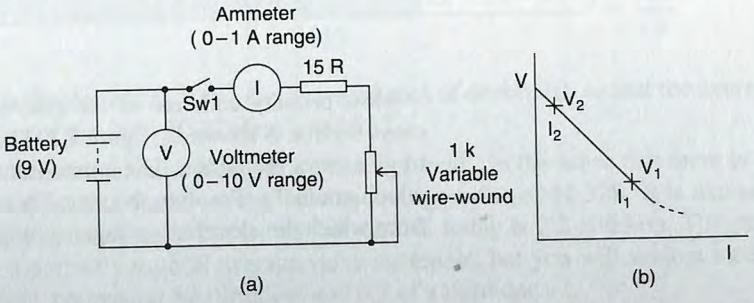


Figure 1.4 (a) Circuit for Practical 1.1, and (b) graph

With the switch Sw1 open, note the voltmeter reading (using the 10 V scale). Mark the current column 'zero' for this voltage reading. Then close Sw1 and adjust the variable resistor until the current flow recorded on the current meter is 50 mA. Note the voltage reading V at this level of current flow, and record both readings on the table. Open switch Sw1 again as soon as the readings have been taken.

Go on to make a series of readings at higher currents (75 mA, 100 mA, etc.) until voltage readings of less than 5 V are being recorded. Take care that for every reading Sw1 remains closed for only as long as is needed to make the reading. Plot the readings you have obtained on a graph of output voltage against current. It should look like the example shown in Figure 1.4(b).

(Continued)

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Practical 1.1 (Continued)

Now pick from the table a pair of voltage readings $V1$ and $V2$, with $V2$ greater than $V1$, together with their corresponding current readings, $I1$ and $I2$, expressed in amperes. Work out the value of the expression shown, left, and you will get the internal resistance of the battery in units of ohms.

Note that false readings can be obtained if a cell passes a large current for more than a fraction of a second. Try to make your readings quickly when you are using currents approaching the maximum, and switch off the current as soon as you have taken a reading.

Most primary cells have an open-circuit voltage (or emf) of around 1.4–1.5 V. The important exception is the lithium cell (see later), which provides around 3.5 V. A lithium cell must **never** be opened, because lithium will burst into flames on exposure to air or water. Lithium cells should not be recharged or put into a fire.

Towards the end of the useful life of a cell or battery, the value of its internal resistance rises. This causes the output voltage at the terminals of the cell or battery to drop below its normal value when current flows through the cell or battery, which is then said to have poor **regulation**. A voltage check with this cell or battery removed from the equipment will show a normal voltage rating, but the cell or battery should nevertheless be replaced.

The only useful check on the state of a cell or battery is a comparison of voltage reading on load (with normal current flowing) with the known on-load voltage of a fresh cell. Simply reading the voltage of a cell that is not connected to a load is pointless.

At one time, the term **secondary cell** meant either the type of lead-acid cell which is familiar as the battery in a car, or the nickel–iron alkaline (NiFe) cell used in such applications as the powering of electric milk floats. In present-day electronics, both types have to some extent been superseded by the nickel–cadmium (NiCd or nicad), nickel–metal-hydride (Ni-MH) and lithium-ion secondary (meaning rechargeable) cells. There is, however, a large difference in the emf of secondary cells. The old lead-acid type has an emf of 2.0 V (2.2 V when fully charged), but the nickel–cadmium and Ni-MH types have a much lower emf of only 1.2 V, and the lithium-ion cell can provide around 3.6 V.

The NiCd cell uses as its active material cadmium (a metal like zinc), in powdered form, that is pressed or sintered into perforated steel plates, which then form the negative pole of the cell. The positive pole is a steel mesh coated with solid nickel hydroxide. The electrolyte is potassium hydroxide (caustic potash), usually in jelly form (Figure 1.5).

Nickel–cadmium (nicad) cells are sealed so that no liquids can be spilled from them, and they have a fairly long working life provided they are correctly used. They can deliver large currents, so they can be used for

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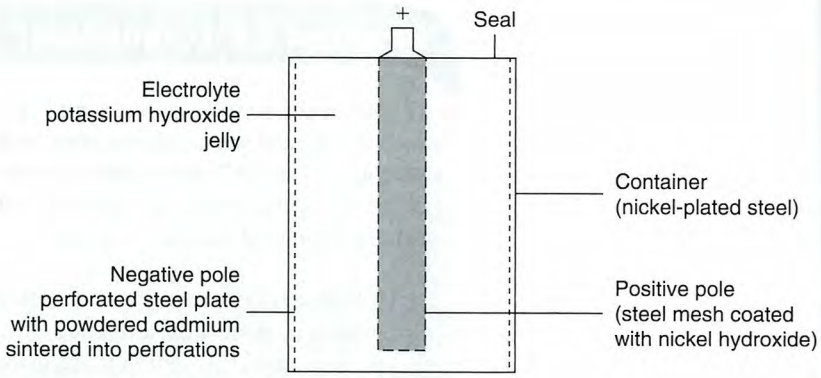


Figure 1.5 The nickel–cadmium cell

equipment that demands higher power than could be supplied by primary cells. They have much longer life than other cells in applications for which they are rapidly discharged at intervals. Long periods of inactivity can cause the cells to fail, although it is often possible to restore their action by successive cycles of discharging and charging. One major problem is the memory effect, a reduction in capacity caused by recharging before the cell is fully discharged. Because of this, it is common practice to use a discharging cycle before charging a nickel–cadmium cell.

More recently, the sealed Ni-MH battery has been introduced. This type has up to 40% higher capacity than its nickel–cadmium counterpart of the same size, and also offers benefits of faster charge and discharge rates, and longer life. The Ni-MH cell contains no cadmium and is therefore more environmentally acceptable. The operating voltage is about the same as that of the NiCd cell. The memory effect can be greatly reduced if the Ni-MH battery is on occasions completely discharged before recharging. The usual recommendation is that this should be done after three to five normal charge–discharge sequences.

Table 1.3 shows the advantages and disadvantages of using batteries as power sources for electronic equipment, as compared to mains supplies.

Table 1.3 Battery-operated equipment

Advantages	*Disadvantages*
Equipment is portable	Limited energy capacity
An ordinary battery is smaller and lighter than is any form of connection to the main supply	Voltage generally low
Safer to use, no high voltages being involved	Batteries deteriorate during storage
Equipment requires no trailing leads	Batteries for high voltage or high current operation are heavier and more bulky than the equivalent mains equipment

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Lithium-ion rechargeable cell

The lithium-ion rechargeable (Li-ion) cell avoids the direct use of the metal lithium because it oxidizes too readily. A lithium-ion cell must never be broken open. The carbon anode is formed from a mixture of compounds at about 1100°C and then electrochemically treated with a lithium compound. The cathode is formed from a mixture of the compounds of lithium, cobalt, nickel and manganese. A mixture of chemicals, avoiding the use of water, is used for the electrolyte. This cell is nominally rated at 3.6 V and has a long self-discharge period, typically falling by 30% after 6 months. The recharge period is typically about 3 hours and the cell can withstand at least 1200 charge–recharge cycles.

In addition to its advantages with holding increased energy, the Li-ion cell tends not to suffer from the memory effect, ensuring a longer life even when poorly treated. Its features include high energy density and high output voltage with good storage and cycle life. Lithium-ion cells are used in desktop personal computers (to back up memory), camcorders, cellular phones and also for portable compact disc (CD) players, laptop computers, personal digital assistants (PDAs) and similar devices. Lithium-ion cells have even been used in an electric sports car (the Venturi Fetish).

The cell operates on the principle that both charging and discharging actions cause lithium ions to transfer between the positive and negative electrodes. Unlike the action of other cells, the anode and cathode materials of the lithium-ion cell remain unchanged through its life.

Charging cells

Lead-acid cells need to be recharged from a constant-voltage supply, so that when the cell is fully charged, its voltage is the same as that of the charger, and no more current passes. By contrast, nickel–cadmium cells must be charged at constant **current**, with the current switched off when the cell voltage reaches its maximum. Constant-current charging is needed so that excessive current cannot pass when the cell voltage is low. Using the wrong charging method can damage cells.

Nickel–metal-hydride cells need a more complicated charger circuit, and one typical method charges at around 10% of the maximum rate, with the charging ended after a set time. A charger suitable for Ni-MH cells can be used also for NiCd, but the opposite is not true. Some types of cell include a temperature sensor that will open-circuit the cell when either charge or discharge currents cause excessive heating. For some applications trickle charging at 0.03% of maximum can be used for an indefinite period.

Lithium-ion cells can be charged at a slow rate using trickle-chargers intended for other cell types, but for rapid charging they require a specialized charger that carries out a cycle of charging according to the manufacturer's instructions.

A completely universal battery charger needs to be microprocessor controlled and is an expensive item, although useful if you use a variety of different cells.

Table 1.4 compares primary and secondary cells.

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Table 1.4 Primary and secondary cells compared

Primary cells	*Secondary cells*
Low cost	Expensive
Small size	Some fairly large
Short life	Comparatively long life
Throw away when exhausted	Rechargeable
Light weight	Generally heavier than equivalent primary cell
Readily available	Specialized products, less easily obtainable

Capacitors with a value of about 1–5 farads (F), which can be charged to 5 V through a high value of resistance, can support a small (backup) discharge current for many hours. Modern construction provides a device of only about 5 mm high with the same diameter, so that these can be used to provide a backup power supply for circuits that need only a small current to maintain operation throughout short duration power failures.

Connecting cells

When a set of cells is connected together, the result is a **battery**. The cells that form a battery could be connected in series, in parallel, or in any of the series–parallel arrangements, but in practice the connection is nearly always in series. The effect of both series and parallel connection can be seen in Figure 1.6. When the cells are connected in series, the open-circuit voltages (emfs) add, and so do the internal resistance values, so that the overall voltage is greater, but the current capability is the same as that of a single cell.

When the cells are connected in parallel, the voltage is as for one cell, but the internal resistance is much lower, because it is the result of several internal resistances in parallel. This allows much larger currents to be drawn, but unless the cells each produce *exactly* the same emf value, there is a risk that current will flow between cells, causing local overheating. For this reason, primary cells are never used connected in parallel, and even secondary cells, which are more able to deliver and to take local charging current, are seldom connected in this way.

Higher currents are therefore obtained by making primary cells in a variety of (physical) sizes, with the larger cells being able to provide more current, and having a longer life because of the greater quantity of essential chemicals. The limit to size is portability, because if a primary cell is not portable it has a limited range of applications. Secondary cells have much

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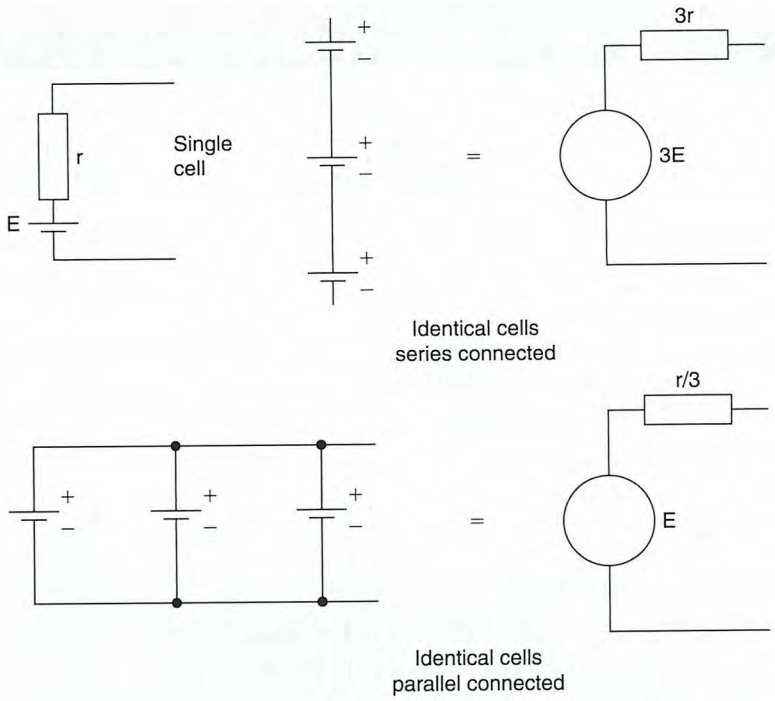


Figure 1.6 Connecting cells in series and in parallel

lower internal resistance values, so that if high current capability is required along with small volume, a secondary cell is always used in preference to a primary cell. One disadvantage of the usual type of nickel–cadmium secondary cell in this respect, however, is a short *shelf-life*, so that if equipment is likely to stand for a long time between periods of use, secondary cells may not be entirely suitable, because they will always need to be recharged just before use.

The important parameters for any type of cell are its open-circuit voltage (the emf), its 'typical' internal resistance value, its shelf-life, active life and energy content. The **internal resistance** is the resistance of the electrolyte and other conductors in the cell, and its value limits the amount of current that a cell can provide because it causes the output voltage of the cell to drop when current flows. The **shelf-life** indicates how long a cell can be stored, usually at a temperature not exceeding 25°C, before the amount of internal chemical action seriously decreases the useful life. The **active life** is less easy to define, because it depends on the current drain, and it is usual to quote several figures of active life for various average current drain values. The **energy content** is defined as emf × current × active life, and will usually be calculated from the most favourable product of current and time. The energy content is affected more by the type of chemical reaction and the weight of the active materials than by details of design.

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Multiple-choice revision questions

1.1 The quantity 'voltage' measures:
- (a) flow of electric current
- (b) quantity of electric current
- (c) driving force of electric current
- (d) stored electric current.

1.2 In the number 537, the digit 7 is:
- (a) a binary digit
- (b) the least significant digit
- (c) the most significant digit
- (d) a decimal fraction.

1.3 The prefix M means:
- (a) one hundred
- (b) one thousand
- (c) ten thousand
- (d) one million.

1.4 When a potential difference of 6 V exists across a 1k0 resistor, the current flowing will be:
- (a) 6 mA
- (b) 3 A
- (c) 0.16 A
- (d) 1/6 mA.

1.5 A cell or a battery converts:
- (a) heat energy into electrical energy
- (b) electrical energy into light energy
- (c) electrical energy into chemical energy
- (d) chemical energy into electrical energy.

1.6 A nickel–cadmium (NiCd) cell must be recharged:
- (a) from a source of constant current
- (b) from a low-impedance source
- (c) from a source of constant voltage
- (d) from a high-impedance source.

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2 Conductors, insulators, semiconductors and wiring

Conductors and insulators

Conductors are materials that allow a steady electric current to flow easily through them, and which can therefore form part of a circuit in which a current flows. All metals are good conductors. Gases at low pressure (as in neon tubes) and solutions of salts, acids or alkalis in water will also conduct electric current well.

Insulators are materials that do not allow a steady electric current to flow through them and they are therefore used to prevent such a flow. Most of the insulators that we use are solid materials that are not metals. Natural insulators, such as sulphur and pitch, are no longer used, and plastic materials such as polystyrene and polythene have taken their place. Pure water is an insulator, but any trace of impurity will allow water to conduct some current, so that this provides one way of measuring water purity.

Semiconductors are materials whose ability to conduct current can be enormously changed by adding microscopic amounts of chemical elements. In a pure state, a semiconductor is an insulator, although light or high temperature will greatly lower the resistance.

A good example of the contrasting uses of insulators and conductors is provided by printed circuit boards. The boards are made of an insulator, typically stiff bonded paper called SRBP (synthetic-resin bonded paper), which is impregnated with a plastic resin; but the conducting tracks on the boards are made of conducting copper or from metallic inks. Boards made from fibreglass are used for more demanding purposes.

Both *insulation and conduction* are relative terms. A conductor that can pass very small currents may not conduct nearly well enough to be used with large currents. An insulator that is sufficient for the low voltage of a torch cell could be dangerously unsafe if it were used for the voltage of the mains (line) supply.

Resistance

The amount of conduction or insulation of materials is measured by their **resistance**. A very low resistance means that the material is a conductor; a very high resistance means that the material is an insulator. The resistance of any sample of a substance measures the amount of opposition it presents to the flow of an electric current. A long strip of the material has more resistance than a short strip of the same material. A wide sample has less resistance than a narrow sample of the same length and same material. These effects are illustrated in Figure 2.1.

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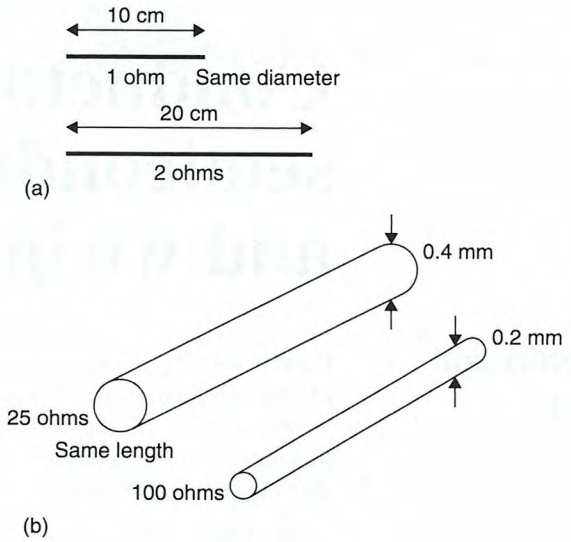


Figure 2.1 Both wire length (a) and wire diameter (b) affect resistance

The resistance of a sample of a given substance therefore depends both on its dimensions and on the material itself. As a formula, this is

$$R \propto L/A$$

where L represents the length of the sample and A its area of cross-section. The sign $\propto$ means 'is proportional to'. The formula therefore reads in full as: 'Resistance is proportional to sample length divided by the sample's area of cross-section'. This assumes that the area of cross-section is constant, as is normal for a wire. Resistance is measured in units called **ohms** (symbol Ω, the Greek letter omega), which will be defined shortly.

We can use the formula at present by using proportion. To illustrate this, look at two examples.

Example: A 2 m long sample of wire has a resistance of 5 ohms. What resistance value would you expect for a length of 1.5 m of the same wire?

Solution: If a 2 m sample has a resistance of 5 ohms, the resistance of a 1 m sample must be $5/2 = 2.5$ ohms. A 1.5 m length will therefore have a resistance of $2.5 \times 1.5 = 3.75$ ohms.

Example: A sample of wire of radius 0.2 mm has a resistance of 12 ohms. What would be the resistance of a sample of the same material of the same length but with radius 0.3 mm?

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Solution: The area of a cross-section is proportional to the *square* of the radius. Therefore Resistance $A \times$ (Radius of $A)^2$ = Resistance $B \times$ (Radius of $B)^2$. Substitute the data, and simplify to get $12 \times 0.2^2 = R = 0.3^2$ so that $R = 5.33$ ohms.

The resistance value of a sample of material does not depend only on its dimensions, however, because every material has a different value of resistance per standard sample. This resistance per standard sample is called the **resistivity** of the material in question. It is measured in units called ohm-metres (ohms multiplied by metres, written as Ωm). The resistance of a sample of any material is then given by the formula:

$$R = \rho l/A$$

where ρ (the Greek letter called 'rho') represents the resistivity of the material, L is the length, and A is the area of cross-section.

Example: Copper has value of resistivity equal to $1.7 \times 10^{-8}\,\Omega$m. What is the resistance of 12 m of copper wire of 0.3 mm radius?

Solution: Substitute the data in the equation $R = \rho L/A$, putting all lengths into metres and remembering that $A = \pi r^2$, then:

$$R = \frac{1.7 \times 10^{-8} \times 12}{\pi \times (0.0003)^2} = \frac{20.4 \times 10^{-8}}{2.83 \times 10^{-7}} = 0.72 \text{ ohms}$$

The resistivity values of some common materials are listed in Table 2.1. The resistivity figures need to be multiplied by 10^8 to give values in ohm-metres.

Table 2.1 Resistivity of some common materials

Material	*Resistivity* $\times 10^{-8}$
Copper	1.7
Gold	2.3
Aluminium	2.7
Iron	10.5
Manganin	43
Mercury	96
Bakelite	10^5
Glass	10^{12}
Quartz	10^{20}
PTFE	10^{20}

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The material listed as **manganin** is a copper-based alloy containing manganese and nickel, much used in the construction of wire-wound resistors. PTFE is the high-resistivity plastic material whose full name is polytetrafluoroethylene.

Copper has a very low value of resistivity, so that copper is a good conductor and is used in electrical cables. Of all the metals, only silver has lower resistivity, but silver is too expensive to use for cables, although it is often used for small lengths of conductors. Aluminium is used for high-tension cables because an aluminium cable that has the same resistance as a copper cable is thicker but has less weight. Gold has a lower resistivity than aluminium and is used where the features of low resistivity and softness are particularly useful, such as on contacts.

Practical 2.1

Calculate the resistance of 10 m of wire, diameter 0.3 mm^2 if a sample of the same material 50 cm long with diameter 0.2 mm^2 has a resistance of 0.5 ohms.

Practical 2.2

Use a resistance meter and (if available) a Megger, to measure the resistance of a metre of copper wire, a metre of nichrome wire, and a square of paper.

Alternating current mains supply

The mains supply to a house is alternating current (a.c.) at around 240 V, 50 Hz. This has been transformed down from the very high voltages (up to 250 000 V) used for distribution, but factories normally use a higher voltage supply of around 415 V a.c.

The wiring in a house or factory uses mains cable. For a house this consists of stranded copper made into three cores, each insulated and with an outer insulated polyvinyl chloride (PVC) cover for protection. House wiring uses a ring construction, so that each wiring socket is connected in a ring, taking current from all of the cables in the circuit. This scheme has been used for some 60 years, and it makes fusing and cabling simpler, as well as requiring less cable. Wiring in a factory is likely to use either three or four conductors in a cable, and it may require cables that are insulated with fireproof minerals and with a metal outer cover. In a house, electrical equipment will be connected through a flexible mains cable to a three-pin plug.

The conventional house sockets use **live**, **neutral** and **earth** connectors. The live connection provides the full 240 V a.c., and the neutral connection

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is used to complete the circuit. Any equipment that is plugged in will therefore be connected between the live and the neutral. The earth connection is taken to buried metalwork in the house, and is used to ensure that equipment with a metal casing can be used safely, because the casing will be connected through the three-pin plug, to earth. Wiring regulations specify that **protective multiple earthing (PME)** will be used, so that all metal pipes in a house must be connected using large-capacity cable to the same earth.

The neutral wire is earthed at the source, but there may be several volts of a.c. between earth and neutral in a household. **Never** connect the neutral line to earth.

The mains supply, which in the UK and in most of Europe is at 240 V a.c., is the greatest hazard in most electronic servicing work. Three connections are made at the usual UK domestic supply socket, labelled live (L), neutral (N) and earth (E). The live contact at 240 V can pass current to either of the other two. The neutral connection provides the normal return path for current with the earth connection used as an emergency path for returning current in the event of a fault. Earth leakage circuit breakers (ELCBs) work by detecting any small current through the earth line and using this to operate a relay that will open the live connection, cutting off the supply. Connection to domestic supplies is made by a three-pin plug, either the BS type or the International Electrotechnical Commission (IEC) type of connector shown opened in Figure 2.2. The BS plug is designed so that shutters within the socket are raised only when the plug is correctly inserted.

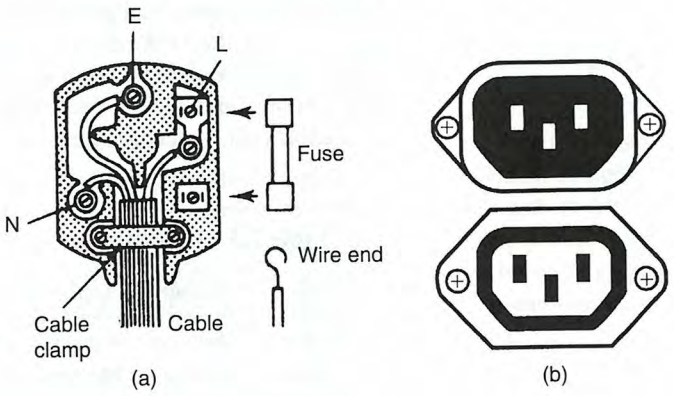


Figure 2.2 (a) BS, and (b) IEC mains connectors

Table 2.2 lists the colour coding of the wire connections to the plug. Although it is many years since the coding colours were changed, older equipment can still be found bearing the older colours (and any such

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equipment should be checked carefully to ensure that it conforms to modern requirements for insulation). Note that these are the colour codes for flexible wiring; internal house wiring still uses the older red, black, green scheme.

Table 2.2 Colour codes for flexible wiring

	Live	*Neutral*	*Earth*
Modern	Brown	Blue	Green/yellow
Old colours	Red	Black	Green

Particular care should be taken in working on cables that have been colour coded to non-UK standards, although all European equipment should now be using the same coding. A plug must be wired so that:

- the cable is firmly held and clamped without damaging the insulation or the conductors
- all connections are tight with no loose strands of wire; the ends of the cable can be coated with solder to prevent loose strands from separating, but the soldered end should not be used for clamping because the wire is more brittle and will loosen off after some time.

The wires should be cut to length so that the live lead will break and pull free before the earth lead if there is excessive force on the cable. The design of some plugs can make this very difficult, and you should select plugs that permit the use of a live lead that will pull out before the earth lead becomes strained.

A **fuse** of the correct rating must be used (Table 2.3). The standard fuse ratings for domestic equipment are 3 A, colour coded red, and 13 A, colour coded brown. Most domestic electronic equipment can use the 3 A rated fuses, and the few items that require a larger fuse should preferably be used with a (non-standard) 7 A fuse rather than the 13 A type, because the appliance cables for such equipment are seldom rated for 13 A.

Table 2.3 Fuse ratings

Value	*Colour*	*Applications*
3 A	Red	All domestic electronic equipment; test gear
13 A	Brown	Heaters and kettles

Note that red and brown are easily confused if you are slightly colour-blind and working at low light levels. Always check wiring using a bright light. Use a torch if room lighting is inadequate.

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The cable should be clamped where it enters the equipment, or alternatively a plug and socket of the standard type can be used so that the mains lead consists of a domestic plug at one end and an IEC socket (Eurosocket), *never a plug* at the other.

Note that non-domestic equipment often makes use of standard domestic plugs, but where higher power electronic equipment is in use the plugs and socket will generally be of types designed for higher voltages and current, often for three-phase 440 V a.c. In some countries, flat two-pin plugs and sockets are in use, with no earth provision except for cookers and washing machines, although eventually uniform standards should have prevailed in Europe, certainly for new buildings.

Practical 2.3

Connect a domestic three-pin plug to a cable and check the resistance of the connections. Check the insulation between live, neutral and earth.

The circuit should also include:

- a fuse whose rating matches the consumption of the equipment. This fuse may have blowing characteristics that differ from those of the fuse in the plug. It may, for example, be a fast-blowing type that will blow when submitted to a brief overload, or it may be of the slow-blow type that will withstand a mild overload for a period of several minutes.
- a double-pole switch that breaks both live and neutral lines; the earth line must never be broken by a switch.
- a mains warning light or indicator which is connected between the live and neutral lines.

All these items should be checked as part of any servicing operation, on a routine basis. As far as possible all testing should be done on equipment that is disconnected and switched off. The absence of a pilot light or the fact that a switch is in the OFF position should never be relied on. Mains-powered equipment in particular should be completely isolated by unplugging from the mains. If the equipment is, like most non-domestic equipment, permanently wired then the fuses in the supply line must be removed before the covers are taken from the equipment. Many pieces of industrial electronics equipment have safety switches built into the covers so that the mains supply is switched off at more than one point when the covers are removed.

The UK has used the three-pin plug with rectangular pins for some time, but in the lifetime of most of us these may be replaced by the pattern used on the continent. The continental pattern is that most plugs are two-pin, with three used only for a few items such as electric files and cookers. There is no fuse in the plug, but an ELCB is incorporated into the socket to

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cut off current if any leakage to earth is detected; similar contact breakers are available in the UK for use with power tools out of doors.

Special regulations apply to electrical tools and other equipment that can be described as **double-insulated**. No earth connection is required for such equipment because the metal parts that are connected to the supply (such as the motor of a power tool) are insulated from the casing, even if the casing is metal. Equipment with plastic casings is normally of the double-insulated type of construction.

The current rating of domestic plugs in the UK is a maximum of 13 A, but for electronic equipment, fusing at 3 A is more common. Despite attempts to standardize only the 13 A and 3 A fuses, you can buy and use intermediate values such as 5 A and 7 A.

Fuses are pieces of thin wire in an insulating container, and the principle is that when excessive current flows the fuse will melt, and so cut off the current. A fuse will not melt immediately, and at the rated current it may take several minutes to blow. A fuse provides protection from a disastrous short-circuit that causes a large current to flow, but it provides no protection to people or to some types of electronic equipment. Contact breakers, which can break the circuit on a precise and very small value of excess current, are to an increasing extent replacing fuses as a method of protection.

Signal connections

Cables that carry signals use different connectors, most of which are rated for low voltages only. Two very common types are the coaxial plug used for television aerial inputs, and the DIN plug for interconnections of audio equipment. Coaxial plugs are often wired without using solder, but soldering makes a more reliable contact. Only the inner lead of a coaxial cable is soldered, with the outer braid wrapped round and clamped. Great care should be taken not to melt the insulation of the plug by keeping the soldering iron in contact too long. It is often useful to insert the end of the plug into a coaxial socket when soldering so as to keep the centre pin in line when the heat of the soldering iron softens the insulator.

DIN plugs are more difficult to work with because of the number of connections (typically three or five) on one small plug. The body of the plug should be held in a vice, and the wire clamped to the pins before soldering. The soldered joint should be made quickly to avoid overheating.

Required tools for working on cables and terminations are screwdriver, tweezers, soldering iron and pliers. You should be familiar with the safe use of all these tools. For testing circuits you will need a good multimeter; a suitable instrument will have a low-resistance range for checking continuity and a high-resistance range for checking insulation.

Practical 2.4

Connect (a) a coaxial cable to a coaxial plug, and (b) a five-pin DIN plug to a five-core cable. Carry out continuity and insulation tests on the cable and connectors.

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Cables that carry signals are often of the type that uses an earthed outer screen to avoid interference (or to prevent the signals on the cable from interfering with other equipment). In some examples, such as coaxial cable, the outer screening is not earthed by a direct connection but only to a.c. Connector terminations for signal cables are almost all soldered, but screw terminations are more common for mains cables.

Multiple-choice revision questions

2.1 The feature that is most typical of a semiconductor is:
- (a) its resistivity value is between that of a conductor and an insulator
- (b) its resistivity can be changed by adding tiny quantities of impurity
- (c) it is composed of crystals
- (d) it melts easily.

2.2 Two strips of the same metal A and B have the same lengths and thicknesses but A is half the width of B. The resistance ratio A to B is:
- (a) 4:1
- (b) 2:1
- (c) 1:4
- (d) 1:2.

2.3 The unit of resistivity is the:
- (a) ohm
- (b) ohm-metre
- (c) ohm per metre
- (d) metre.

2.4 Which of the following has the highest resistivity?
- (a) aluminium
- (b) PTFE
- (c) wood
- (d) mercury.

2.5 A distribution box uses an RCD. This will:
- (a) replace the on/off switch
- (b) blow when any appliance draws excessive current
- (c) light up to indicate a fault
- (d) disconnect when earth leakage occurs.

2.6 The three-pin plug on an audio amplifier lead should have:
- (a) the green/yellow lead on the earth terminal and a 3 A fuse
- (b) the brown lead on the earth terminal and a 13 A fuse
- (c) the blue lead on the earth terminal and a 3 A fuse
- (d) the green/yellow lead on the earth terminal and a 13 A fuse.

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10 Transducers and sensors

Definitions

A **transducer** will convert one form of power into another, and the efficiency of conversion is important. We cannot, for example, convert power in the form of heat into electrical power with efficiency above 45%, but we can convert electrical power into heat with an efficiency of well above 90%. Some transducers, however, have very low efficiency: a high-quality loudspeaker may have an efficiency (converting electrical power into acoustic power) of 1% or less.

A **sensor** also converts power from one form to another, but the efficiency is unimportant. The important factor for a sensor is *linearity*, because sensors are used in detection and measuring actions. Linearity means the extent to which the output is proportional to the input, so that a perfectly linear device would have a graph of output plotted against input that would be a straight line. A few devices (a microphone, for example) may be used as either a sensor or a transducer.

Transducers that are used along with electronics circuits can be either input or output transducers. An **input transducer** will convert power from some other form into electrical signals; an **output transducer** will convert electrical signals into some other form of power. The simplest input transducer is a switch, which converts mechanical movement into an on/off electrical signal.

Switches

Switches have a low resistance between contacts in the **ON** setting, and a very high resistance in the **OFF** setting. The value of resistance when the switch is on (*made*) is called the **contact resistance**. The amount of the contact resistance depends on the area of contact, the contact material, the amount of force that presses the contacts together and the way that this force has been applied. A wiping action provides a lower resistance than a simple pressing action.

Switch contact configurations are primarily described in terms of the number of poles and number of throws or ways. A switch **pole** is a moving contact, and the **throws** or **ways** are the fixed contacts against which the moving pole can rest. The term *throw* is usually reserved for mains switches, mostly single- or double-throw, and *way* for signal-carrying switches. A single-pole, single-throw (SPST) switch will provide on/off action for a single line, and is also described as single-pole on/off. Such switches are seldom used for a.c. mains nowadays and are more likely to be encountered on d.c. supply lines. Figure 10.1 shows the most common switch arrangements in circuit diagram form. For a.c. use, safety requirements call for both live and neutral lines to be broken by a switch, so that double-pole single-throw (DPST) switches will be specified for this type of use.

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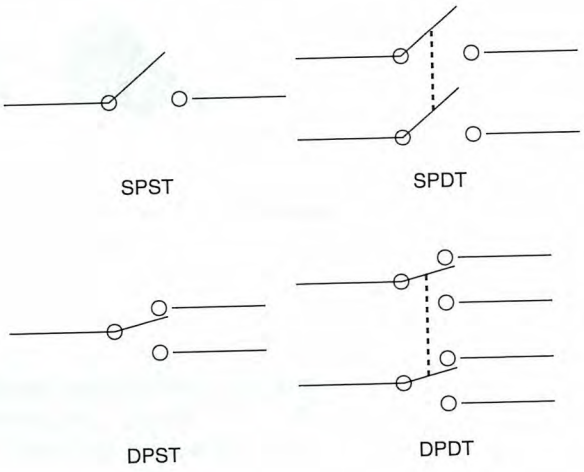


Figure 10.1 Common switch arrangements and symbols

The configuration of a double-throw switch also takes account of the relative timing of contact. The normal requirement is for one contact to break before the other contact is made, and this type of break-before-make action is standard. The alternative is make-before-break (MBB), in which the moving pole is momentarily in contact with both fixed contacts during the changeover period. Such an action is permissible only if the voltages at the fixed contacts are approximately equal, or the resistance levels are such that very little current can flow between the fixed contacts. Once again, this type of switching action is more likely to be applicable in signal-carrying circuits. There may be a choice of fast or slow contact make or break for some switches.

A switch may be **biased**, meaning that one position is stable, and the other, off or on, is attained only for as long as the operator maintains pressure on the switch actuator. These switches are used where a supply is required to be on only momentarily, often in association with the use of a hold-on relay, or can be interrupted momentarily. A biased switch can be of the off–on–off type, in which the stable condition is off, or the on–off–on type, in which the stable condition is on. The off–on–off type is by far the more common. The ordinary type of push-button switch is by its nature off–on–off biased, although this is usually described for such switches as **momentary action** (see, however, *alternate action* below), and biased switches are also available in toggle form.

Switches may be operated in several different ways. The most common types are the toggle switches operated by a toggle lever or by a rocker action. Push-button switches are also commonly used, either alternate action, as a button that is pressed and released for ON and pressed and released again for OFF, or as a button that is pressed for ON and remains depressed until it is pressed again for OFF. The rotary switch is often used in electronic applications to select one out of several choices (Figure 10.2). A switch (or set of switches) can also be operated by a solenoid with a moving core, and this type of device is termed a **relay**.

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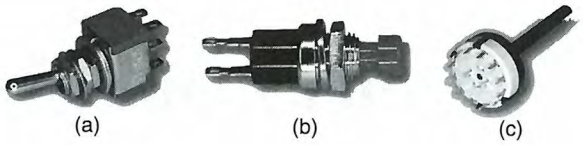


Figure 10.2 Typical switch types, not to scale: (a) toggle, (b) push-button, and (c) rotary [photographs: Alan Winstanley]

Note that switch ratings are always quoted separately for a.c. and for d.c., with the a.c. rating often allowing higher current and voltage limits, particularly for inductive circuits.

Practical 10.1

Use a multimeter to test the continuity of switch and relay contacts. Check the effect of operating the switch/relay.

Microphones

The most familiar transducer for sound energy into electrical energy is the microphone, and microphone types are classified by the type of transducer they use. The overall sensitivity is expressed as millivolts or, more usually, microvolts of electrical output per unit intensity of sound wave. In addition, though, the **impedance** of the microphone is also important.

A microphone with high impedance usually has a fairly high electrical output, but the high impedance makes it very susceptible to hum pickup. A low impedance is usually associated with very low output, but hum pickup is almost negligible.

Another important factor is whether the microphone is **directional** or **omnidirectional**. If the microphone operates by sensing the pressure of the air in the sound wave, then the microphone will be omnidirectional, picking up sound arriving from any direction. If the microphone detects the velocity (speed and direction) of the air in the sound wave, then it is a directional microphone, and the sensitivity has to be measured in terms of direction as well as amplitude of the sound wave. The microphone types are classed as pressure or velocity operated, omnidirectional or in some form of directional response (such as cardioid) (Figure 10.3).

The **frequency response** of a microphone is usually very complicated because the housing of the transducer unit will act as a filter for the sound waves, causing the response to show peaks and troughs unless the housing is very carefully designed.

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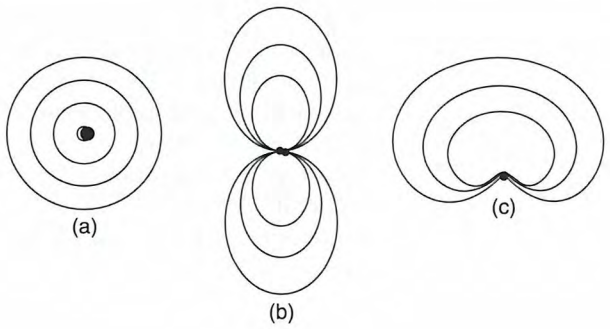


Figure 10.3 Simplified response curves for microphone types: (a) omni-directional, (b) velocity-operated, and (c) cardioid (heart-shaped)

Microphone types

Microphone types in common use include moving iron (dynamic), moving-coil, crystal and electret capacitor types. Of these, we shall pick out the dynamic and the electret types only.

The principle of the moving iron (dynamic, or variable reluctance) microphone is illustrated in the cross-section view of Figure 10.4. A powerful magnet contains a soft-iron armature in its magnetic circuit, and this armature is attached to a diaphragm with a flexible suspension so that sound waves will cause the diaphragm to vibrate. The magnetic flux in the magnetic circuit alters as the armature moves. A coil wound around the magnetic circuit at any point will give a voltage which is proportional to each change of magnetic flux, so that the electrical wave from the microphone is proportional to the acceleration of the diaphragm.

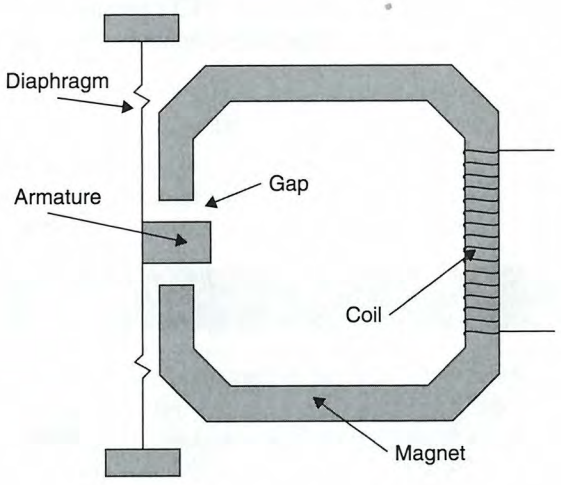


Figure 10.4 Principle of the dynamic microphone

The linearity of the conversion can be reasonable for small amplitudes of movement of the armature, but very poor for large amplitudes. Both the

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linearity, and the amplitude over which linearity remains acceptable can be improved by appropriate shaping of the armature and careful attention to its path of vibration. These features depend on the maintenance of close tolerances in the course of manufacturing the microphones, so that there will inevitably be differences in linearity between samples of microphones of this type from the same production line. The output level from a moving-iron microphone can be high, in the order of 50 mV, and the output impedance is fairly high, typically several hundred ohms. Magnetic shielding is always needed to reduce mains hum pickup in the magnetic circuit.

Moving-coil and ribbon microphones are used professionally, but are not used with domestic electronic equipment. They have been omitted from this book.

The capacitor microphone is now used almost exclusively in electret form (Figure 10.5). An electret is the electrostatic equivalent of a magnet, a piece of insulating material which is permanently charged. A slab of electret is therefore the perfect basis for a capacitor microphone in which the vibration of a metal diaphragm near a fixed charge causes voltage changes between the diaphragm and a metal backplate. This allows very simple construction for a microphone, consisting only of a slab of electret metallized on the back, a metal (or metallized plastic) diaphragm, and a spacer ring, with the connections taken to the conducting surface of the diaphragm and of the electret. This is now the type of microphone that is built into cassette recorders, and even in its simplest and cheapest versions is of considerably better audio quality than the piezoelectric types that it displaced. The use of a field-effect transistor (FET) preamp solves the problem of the high impedance of this type of microphone.

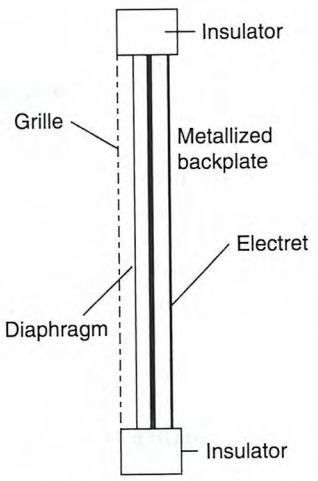


Figure 10.5 Principle of electret capacitor microphone

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Tape playback

Magnetic tape uses the principle of *hard* magnetic material. Early tape recorders in 1898 used steel tape, but it was not until 1941 that the BASF company hit on the idea of coating a thin plastic tape with magnetic powder, using iron oxide. The recording head is made from a soft magnetic material with low hysteresis so that its magnetic flux will follow the fluctuations of a signal current through the winding (Figure 10.6a). The same type of head is also used for replaying tape, using the varying flux from the moving tape to induce currents in the head. The symbol for a tapehead is illustrated in Figure 10.6(b). The replay tapehead is another form of input transducer, converting the varying magnetic signal on the moving tape to an audio electrical signal in the windings of the head.

Domestic cassette recorders normally use just one head for both recording and replaying, with switched connections either to the output of an amplifier or to the input of the amplifier. A separate head is fed with the output from a high-frequency (typically 100 kHz) oscillator to act as an erase head only during recording.

See Chapter 16 for a more complete description of tape-recorder principles.

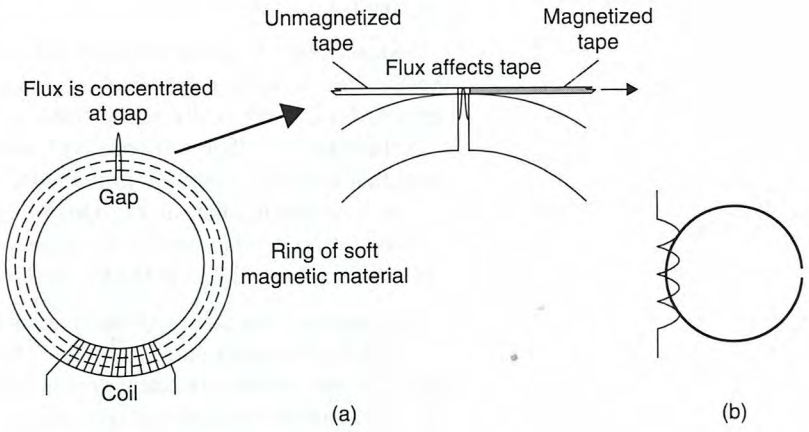


Figure 10.6 (a) Principle of tapehead, and (b) symbol

Practical 10.2

Test the continuity of the recording head of a tape/cassette recorder, using a multimeter. Note that the head will need to be demagnetized after this measurement: use a head demagnetizer if available.

Output transducers

Typical output transducers used in electronics equipment include headphones and loudspeakers. Figure 10.7 shows the symbols that are used. Headphones (or earphones) have been in use for considerably longer than microphones or loudspeakers, since they were originally used for electric

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telegraphs. The power that is required is in the low milliwatt level, and even a few milliwatts can produce considerable pressure amplitude at the eardrum, often more than is safe for your hearing when the earphone is a snug fit into the ear.

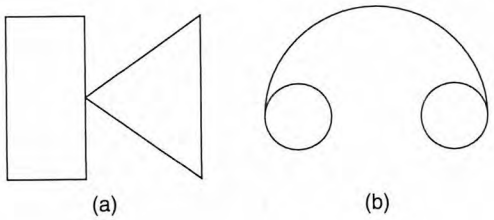


Figure 10.7 Symbols for (a) loudspeaker, and (b) headphones

The methods that are used for loudspeakers and for headphones are essentially the same as are used for microphones, because the action is (unusually) reversible.

Loudspeakers for domestic equipment are often **full-range** units, meaning that one loudspeaker transducer deals with the whole range of audio signals. This is not really satisfactory because it is very difficult to make a loudspeaker unit that will cope with such a range, and the few full-range units that can be classed as hi-fi loudspeakers are usually of exotic (and expensive) design, such as the Quad electrostatic units. Small full-range speakers of acceptable quality are widely used in radios, cassette recorders and compact disc players at the low end of the price range.

For anything that can be (loosely) classed as hi-fi, separate loudspeakers are used for the audio range, with one (woofer) dealing with the lower frequencies and another (tweeter) dealing with the high frequencies. The two units are normally enclosed in one cabinet, but on speaker sets such as those intended for home cinema equipment, the tweeters are arranged around the room and a single subwoofer (for the frequencies in the range 30–150 Hz) is located centrally. The stereo effect depends almost completely on the higher frequencies, so the positioning of a woofer/subwoofer is not critical. A filter, called a **cross-over unit**, separates the signal into lower and upper frequencies so that the higher frequencies are fed to the tweeters and the lower frequencies to the woofers.

Most loudspeakers use the moving-coil principle (Figure 10.8). The coil is wound on a former at the apex of a stiff diaphragm which is held in flexible supports so that the coil is the intense field of a permanent magnet. A signal current through the coil will then vibrate the diaphragm, producing sound waves at the same frequency and with the same waveshape as the signal. To be really effective, a loudspeaker has to be housed in a cabinet (**enclosure**) whose design assists the loudspeaker to move a large volume of air, acting like a transformer for air waves. Even in a fairly good enclosure, the efficiency of a typical hi-fi loudspeaker is very low, around 1%.

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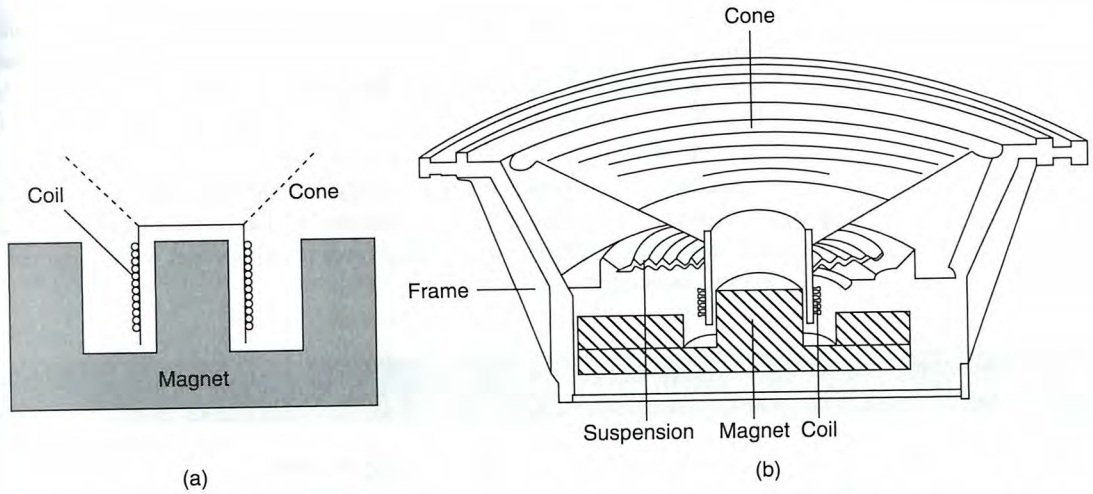


Figure 10.8 Moving-coil loudspeaker: (a) cross-section of coil and magnet, and (b) cutaway view of complete unit

Miniature loudspeakers, typically of diameter 70 mm or less, are used as warning transducers in cars, signal devices on electronic equipment, and in toys. These small units can be used also as microphones, although their efficiency as a microphone is low and the frequency response is uneven. Confusingly, the same term is also used for hi-fi loudspeakers that are noticeably smaller than average.

Headphones

Headphones can be constructed using any of the principles used for loudspeakers, but the most widespread and successful type is the **electrodynamic** (or **orthodynamic**) principle. This uses a diaphragm which has a coil built in, using printed circuit board techniques. The coil can be a simple spiral design, or a more complicated shape (for better linearity), and the advantage of the method is that the driving force is more evenly distributed over the surface of the diaphragm.

The **piezoelectric** principle has also been used for headphones in the form of piezoelectric sheets that can be formed into very flexible diaphragms. A piezoelectric material is one whose dimensions can be changed by applying an electric field, and which will generate an electric field if the material is compressed. Quartz crystals are piezoelectric, and another crystalline material that is extensively used is barium titanate.

Moving-coil headphones have also been manufactured and the quality that can be attained justifies the high prices that are attached to these units.

Subminiature earphones, often referred to as *earbuds*, are designed for use with portable CD or MP3 players, and run at a typical rated power of 3 mW. These use the same dynamic mechanism as larger earphones. The impedance is typically 32 Ω.

Moving-coil loudspeakers and earphones have a nominal value of impedance, typically 4 ohms, but a graph of impedance plotted against frequency

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is very complicated in shape, with peaks and dips caused by the mechanical resonances of the loudspeaker components and the enclosure. Small headphones usually operate with higher impedances, partly to prevent overdriving if they are connected to an amplifier output designed to pass power to a low-impedance loudspeaker.

Miniature loudspeakers can generally handle only the higher frequencies, but hi-fi headphones are miniature loudspeakers in enclosures that are designed to achieve a reasonable level response over a large part of the audio-frequency range.

Multiple-choice revision questions

10.1 A transducer:
- (a) measures power
- (b) converts power to energy
- (c) converts energy from one form to another
- (d) converts high power to low power.

10.2 A switch is described as DPDT. It could be used particularly for:
- (a) switching a single light on or off
- (b) switching two lights on or off
- (c) switching a tape recorder on or off
- (d) switching both leads to a tapehead to either the input or the output of an amplifier.

10.3 A cardioid microphone:
- (a) is equally sensitive in all directions
- (b) has a heart-shaped response characteristic
- (c) has a straight-line response characteristic
- (d) has no response to the side.

10.4 A tape recorder:
- (a) creates a magnetic pattern on tape
- (b) creates an electric pattern on tape
- (c) uses a capacitor for recording
- (d) can record any frequency of sound.

10.5 Most loudspeakers are of the type known as:
- (a) moving iron
- (b) moving field
- (c) moving coil
- (d) moving flux.

10.6 Many makes of headphones use:
- (a) the binary principle
- (b) the photovoltaic effect
- (c) the induction effect
- (d) the electrodynamic principle.

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3 Resistors and resistive circuits

Resistors

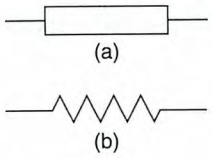


Figure 3.1 Resistor symbols

Resistors are components that have a stated fixed or maximum value of resistance. Methods of construction include wire-wound, carbon moulded, carbon film and metal film resistors. The two commonly used symbols for a resistor in a circuit are shown in Figure 3.1. The older zigzag symbol is still used, particularly in the USA and Japan, and the rectangular symbol is used in Europe, but both are British Standard symbols. Resistors can be fixed, with a fixed value of resistance, or variable, with a value that can be altered from almost zero to a set maximum value.

Values of resistance are given in ohms (Ω) or multiples of ohms. In circuit diagrams, they are coded R for ohms, k for kilohms (thousands of ohms) and M for megohms, or millions of ohms. The letters R, k or M are placed in the position of the decimal point when a resistance value is written against the resistor symbol, as explained in Chapter 1.

Resistors, whether fixed or variable, are manufactured with certain average values aimed at. These values are called **preferred values**. They are chosen so that no resistor, whatever its actual value of resistance, can possibly lie outside the range of all tolerances. Table 3.1 lists the 20%, 10%, 5% and 1% tolerance preferred values. Within Europe, resistor tolerances are described by the letter E and a digit that indicates the number of resistors per decade, and this is related to the value tolerance as follows: 20%–E6, 10%–E12, 5%–E24 and 1%–E96. To accommodate the greater number of values in the series, E96 devices are coded (see later) by using five or six coloured bands.

Table 3.1 Preferred values tolerance series

E6 series 20% tolerance															
1.0	1.5	2.2	3.3	4.7	6.8										
E12 series 10% tolerance															
1.0	1.2	1.5	1.8	2.2	2.7	3.3	3.9	4.7	5.6	6.8	8.2				
E24 series 5% tolerance															
1.0	1.1	1.2	1.3	1.5	1.6	1.8	2.0	2.2	2.4	2.7	3.0	3.3	3.6	3.9	4.3
4.7	5.1	5.6	6.2	6.8	7.6	8.2	9.1								
E96 series 1% tolerance															
1.00	1.02	1.05	1.07	1.10	1.13	1.15	1.18	1.21	1.24	1.27	1.30	1.33	1.37	1.40	1.43
1.47	1.50	1.54	1.58	1.62	1.65	1.69	1.74	1.78	1.82	1.87	1.91	1.96	2.00	2.05	2.10
2.15	2.21	2.26	2.32	2.37	2.43	2.49	2.55	2.61	2.67	2.74	2.80	2.87	2.94	3.01	3.09
3.16	3.24	3.32	3.40	3.48	3.57	3.65	3.74	3.83	3.92	4.02	4.12	4.22	4.32	4.42	4.53
4.64	4.75	4.87	4.99	5.11	5.23	5.36	5.49	5.62	5.76	5.90	6.04	6.19	6.34	6.49	6.65
6.81	6.98	7.15	7.32	7.50	7.68	7.87	8.06	8.25	8.45	8.66	8.87	9.09	9.31	9.53	9.76

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These figures are used for all resistor values of a given tolerance range. Values of 2R2, 3K3, 47K, 100K, lM5 could thus lie in either range; but values of 1R2, 180R, 2K7, 39K, 560K could lie only in the 10% (or closer) tolerance range.

Take, for example, a 2k2 resistor in the 20% series. It could have a value of 2k2±20%, that is to say, a range from 2k64 to 1k76. But if such a resistor has a measured value of 2k7 or 1k6, it would not become a reject. The reason is that the next larger preferred value is 3k3 and 3k3–20% is 2k64. So the 2k7 resistor would quite legitimately be reclassified as a 3k3. Similarly, on the low side, the next value down from 2k2 is 1k5, and 1k5+20% is 1k8. A resistor with a measured value of 1k6 would therefore be acceptable as a 1k8.

In other words, the preferred values are so chosen that no resistor that is manufactured can be rejected simply because of its measured value. The preferred value of a resistor is either printed on the resistor or coded on it by reference to the colour code illustrated and explained below.

The basic relationship between values and colours is shown in Table 3.2 and Figure 3.2. One of the many ancient mnemonics designed to aid memorizing this series goes: 'Bye Bye Rosie Off You Go Birmingham Via Great Western'.

Table 3.2 Colour codes

Figure	*Colour*	*Figure*	*Colour*	*Figure*	*Colour*	*Figure*	*Colour*	*Figure*	*Colour*
0	Black	1	Brown	2	Red	3	Orange	4	Yellow
5	Green	6	Blue	7	Violet	8	Grey	9	White
Multiplier colours can also be:									
0.1	Gold	0.01	Silver						
No tolerance band is used if the resistor has 20% tolerance									
Tolerance:									
10%	Silver	5%	Gold	2%	Red	1%	Brown		

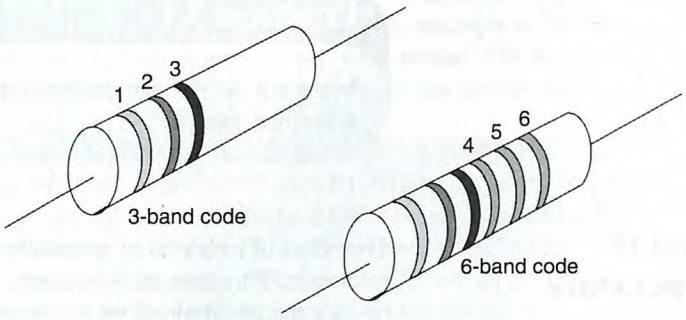


Figure 3.2 Resistor colour coding using three or six bands

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In the three-band code resistor pictured in Figure 3.2, all the colour bands are printed towards one of its ends. The first band (the one nearest the end) represents the first figure of the coded value, the second band represents the second figure, and the third band the number of zeros following this second figure. The three bands painted in the sequence, beginning from the end of the resistor – blue, grey, red – would mean (see Table 3.2) a resistor with a preferred value of 6–8–two zeros, or 6800 ohms. Such a resistor would in practice always be described as a 6k8. This colour coding system can be extended by adding a fourth band to indicate the component tolerance. No fourth band means ±20%, but a gold band indicates ±5% and a silver band indicates ±10%.

Up to six bands may be used for close-tolerance resistors as shown in the six-band example of Figure 3.2. Here, the first three bands are used to represent significant figures, while the fourth band indicates the multiplier or number of following zeros. Bands five and six then indicate component tolerance and temperature coefficient, respectively.

Moulded carbon resistors are usually colour coded. Wire-wound and film type resistors generally have the resistance value printed on them, using the R, k, M notation. These resistors are cheap to manufacture but cannot be made to precise values of resistance. Their large tolerances mean that the values of individual resistors have to be measured and suitable ones selected if a precise value of resistance is needed. Moulded resistors are no longer in use in the UK, although they can be found on some imported equipment.

Wire-wound resistors are constructed from lengths of insulated wire, often a nickel–chromium alloy, and they are used when comparatively low values of resistance are required. They are particularly useful when the resistor may become very hot in use, or when precise resistance values are needed.

Carbon film and **metal film** resistors are made, as the name suggests, from thin films of conducting material. They can be manufactured in quantity batches, but to fairly precise values. They are now the standard type of resistor used in domestic electronic equipment, and are often found in the miniature surface mount (SM) form.

Practical 3.1

Inspect a set of six colour-coded resistors and write down their resistance values.

Effect of temperature

The effect of a change of temperature on a resistor is to change its value of resistance. This change is caused by alteration of the resistivity value of the resistor material rather than by the very small change in dimensions (length and cross-sectional area) that also takes place.

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This effect of temperature on resistance is measured by the **temperature coefficient of resistance**, which is defined as the fractional change in resistance per degree of temperature change. As a formula this is:

$$\frac{\text{Change in resistance}}{\text{Original resistance} \times \text{Change in temperature}}$$

or it can be written as $\Delta R/R\ \Delta T$, with the Δ (Greek delta) symbol meaning 'change in'.

Temperature coefficient values may be either positive or negative. A **positive** temperature coefficient means that the resistance value of a resistor at high temperature is greater than its resistance value at low temperatures. A **negative** temperature coefficient means that the resistance value at high temperatures is lower than its resistance value at low temperatures. Coefficients are often quoted as parts per million per degree Celsius.

For example, if a resistor is quoted as having a temperature coefficient of +250 ppm/°C, this means a change of 250 units for each million units of resistance for each degree Celsius of temperature rise.

For a 100 k resistor raised in temperature from 20°C to 140°C (a change of 120°C), this means: (250/1 000 000) × 1 000 000 × 120 = 3000 ohms, or 3k0, making the value a total of 103 k at the higher temperature.

Taking another example, if an insulator has a resistance of 100 M at 20°C and has a temperature coefficient of −500 ppm/°C, then at 200°C (a *rise* of 180°C) its resistance will **drop** by: (500/1 000 000) × 1 000 000 × 180 = 9 000 000 or 9 M, so that the resistance at 200°C is 91 M.

Materials that are widely used for manufacturing resistors normally have positive coefficients of small value. Insulating materials generally have negative temperature coefficients, and insulation becomes less effective at high temperature. There are also materials that have very large coefficients of temperature change, and some that have very low values.

Power dissipation

When selecting a resistor, you have to consider its **power dissipation** as well as its resistance. A resistor that is rated at 1/4 W runs noticeably hot when it is asked to dissipate power of 1/4 W, and it will be damaged if it is expected to dissipate more power than that. In electronic circuits, most resistors have to dissipate considerably less than 1/4 W, so that 1/4 W or even 1/8 W types can be used. Component lists therefore specify only those few resistors that need higher ratings. The description 2k2 W/W 5W, for example, means 2200 ohm resistance, wire-wound, 5 W dissipation. For calculations of how power is dissipated in watts see later in this chapter.

Some resistors appear on circuit diagrams with **safety-critical** warnings, meaning that if this resistor fails it must be replaced by another that is of exactly the same type. This is important, and a service engineer could be held responsible for any damage caused if an ordinary resistor was used to replace a special component.

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When resistors fail, they commonly become open-circuit (o/c), rarely short-circuit (s/c), or they may change their value. This change in value may be either upwards or downwards, and a faulty resistor that has changed value is said to have gone high or gone low. Excessive dissipation is one main cause of resistor failure, and when a resistor has to be replaced, the replacement must be of a suitable power rating, and one must also ensure that the resistor is not surrounded by other components that would make cooling difficult.

Thermistors

Thermistors have a large temperature coefficient of resistance in the order of 15–50 $\times$ 10^{-3}. These devices may be in rod, bead, washer or disc form. They are made from carefully controlled mixtures of certain metallic oxides. These are sintered at very high temperatures to produce a ceramic finish. Negative temperature coefficient (NTC) thermistors have resistances that fall with a rise in temperature and are commonly made from mixtures of metal oxides. Positive temperature coefficient (PTC) components whose resistance increases with a rise in temperature can be made from barium titanate with carefully controlled amounts of metals added.

Thermistors are used extensively for temperature measurement and control up to about 400°C. An obvious use is in temperature sensors, but they are also extensively used along with conventional resistors in compensating for the effects of changing temperature in semiconductor amplifiers. Another application is to provide temperature compensation for the change in the winding resistance of alternators and other generators which affects their performance when the operating temperature rises.

Resistive circuits

Resistors can be connected either in series or in parallel, or in any combination of series and parallel. When resistors are connected in series (Figure 3.3a), the same current must flow through each resistor in turn. The total resistance encountered by the current is the sum of all their separate values.

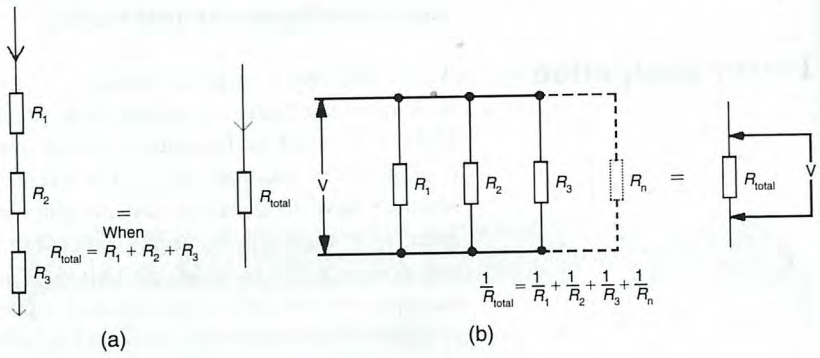


Figure 3.3 Connecting resistors (a) in series, and (b) in parallel

When resistors are connected in parallel (Figure 3.3b), the current flow is divided among the resistors according to their values, with the most current flowing through the lowest value resistor(s). The same voltage, however, is maintained across all the resistors, and the total current is equal to the sum of the currents in each resistor.

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Any combination of resistors connected in series and in parallel is capable of being replaced, as far as the flow of current is concerned, by a single resistance of equivalent value. These single resistances are then combined by using the formulae given in Figure 3.3, until a single resistance equivalent in value to the resistance of the combination as a whole is achieved. This is called the **equivalent resistance**.

The equivalent value of a set of resistors in series is simply the sum of the resistance values in the series. For example, the equivalent value of 6k8 + 3k3 + 2k2 connected in series is 6.8 + 3.3 + 2.2 = 12.3k, or 12k3. The equivalent resistance of the series is thus greater than the value of any of the single resistors.

The equivalent value for resistors connected in parallel is rather more difficult to calculate. The rule is to calculate the inverse ($1/R$) of the value of every resistor connected in parallel, to add all the inverses together, and then to invert the result. As a formula this is

$$1/R_{\text{total}} = 1/R_1 + 1/R_2 + 1/R_3 + \ldots$$

for however many resistors there may be in the parallel combination. For two resistors this can be simplified to product/sum, so that for two resistors R_1 and R_2 in parallel, the equivalent is $R_1R_2/(R_1 + R_2)$.

Example: Find the equivalent resistance of 2k2, 3k3, 6k8 connected in parallel.

Solution: Working in kilohms:

$$\frac{1}{R} = \frac{1}{2.2} + \frac{1}{3.3} + \frac{1}{6.8} = 0.4545 + 0.3030 + 0.4170 = 0.9046$$

so that if $1/R$ is 0.9046, then $R = 1/0.9046$, which is 1.1054k, or 1105.4ohms. A calculator will invert a number when you press the Inv or x–1 key.

When a circuit contains resistors that are connected both in series and in parallel, the calculations must be carried out in sequence. The example of Figure 3.4 shows two circuits whose total equivalent resistance needs to be found. The procedure is set out in the following.

In the example (a), the value of the parallel resistors is calculated first. The 10k and the 15k combine as follows

$$\frac{1}{R} = \frac{1}{10} + \frac{1}{15} = 0.166$$

so that $R = 6$k (units of k have been used throughout). This 6k is now added to the 6k8 series connected resistor to give a total equivalent resistance of 12k, which is the total resistance of the circuit. Note that we need

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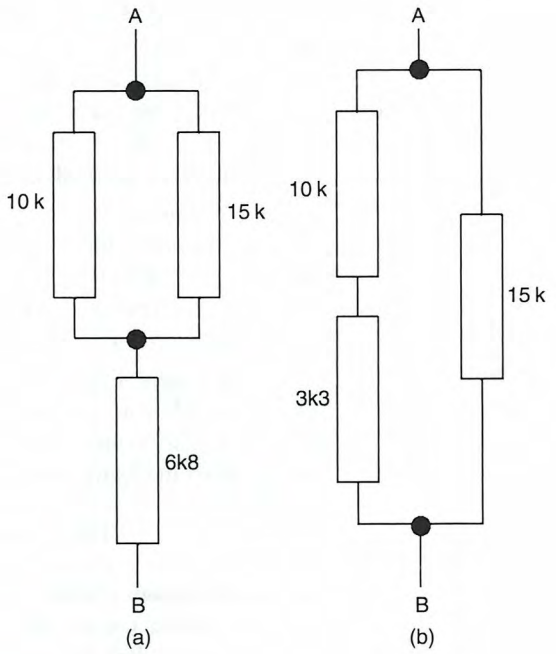


Figure 3.4 Solving series/parallel circuits

to find the equivalent of the parallel resistors before we can add in the value of the series resistance.

In example (b), the series resistance values are combined first. The 10k plus the 3k3 gives 13k3, and this value is now combined in parallel with 15k.

$$\frac{1}{R} = \frac{1}{13.3} + \frac{1}{15} = 0.1418$$

so that $R = 7.05\,\text{k}$ or 7k05.

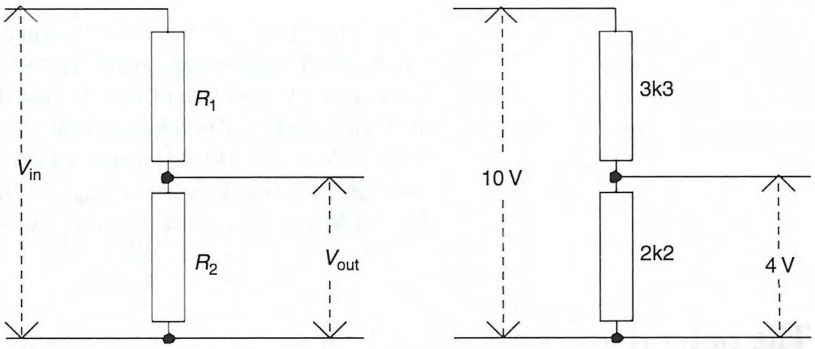
Both series and parallel combinations of resistors can produce values of total resistance that are unobtainable within the normal series of preferred values. This can often be useful as a way of obtaining unusual values.

Potential divider

A highly important circuit using two resistors connected in series is the potential divider circuit illustrated in Figure 3.5. The total resistance is $R_1 + R_2$, which in the example shown is 5k5. By Ohm's law, the current flow must be $= 1.8182\,\text{mA}$.

Such a current flowing through R_2 requires voltage V which, by Ohm's law again, must be $I \times R_2$. Substitute the known values of current and resistance, and the voltage across R_2 works out at 1.8182 mA (2k2), or about 4 V in the example shown.

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$$V_{out} = V_{in} \times \frac{R_2}{R_1 + R_2}$$

Figure 3.5 The potential divider circuit

A potential divider (or attenuator) circuit is used to obtain a lower voltage from a source of high voltage. Where E is the higher voltage and V the lower voltage, the lower voltage can be calculated by using the formula:

$$V = \frac{ER_2}{R_1 + R_2}$$

For example, if 10 V is applied across a series circuit of 2 k and 3 k resistors, the voltage across the 3 k resistor is:

$$V = \frac{10 \times 3}{3 + 2} = 6 \text{ V}$$

Example: Given the circuit shown in Figure 3.6(a), calculate V_{out}, I_1, I_2 and I_3.

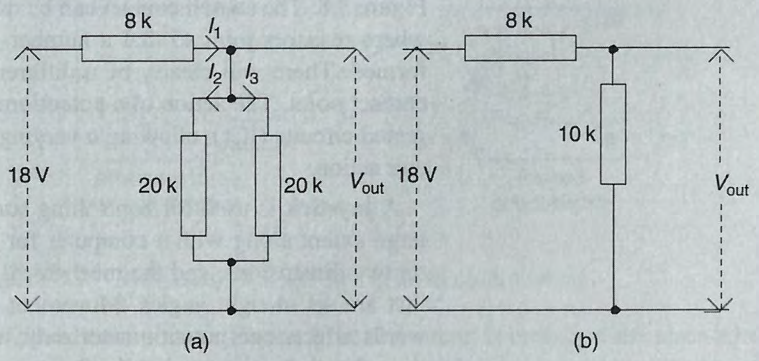


Figure 3.6 (a) A further series parallel problem, and (b) its solution

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Solution: Start with the parallel, equal 20k resistors. Use either the product/sum rule or recognize that two equal parallel resistors have a value equal to half that of one, so that the circuit becomes that shown in Figure 3.6(b). The total resistance is therefore 10k + 8k = 18k. Now 18V across 18k will cause a total current $I = 1$mA. This current through 10k will produce a V_{out}, = 10V. This is the voltage across both 20k resistors, so that I_1 and I_2 are both equal to 10/20k = 0.5mA.

The potentiometer

Figure 3.7 shows the working principle, symbol and a typical photograph for the component called the **potentiometer**, which is in effect a variable potential divider. A sector of a circle, or of a straight strip, of resistive material is connected at each end to fixed terminals, and a sliding contact is held against the resistive material by a spring leaf. As the position of the sliding contact is altered, so will different values of resistance be created between the sliding contact and each of the two fixed terminals. The symbol is a reminder of the principle.

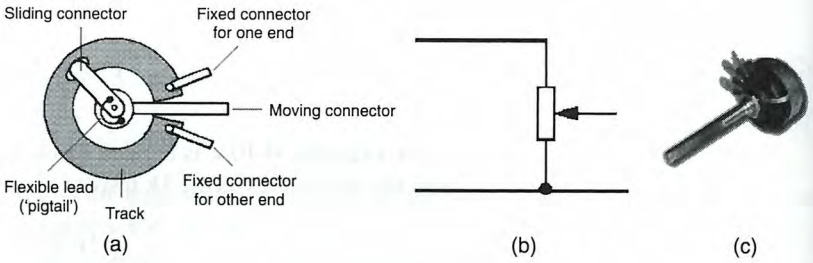


Figure 3.7 (a) Circular potentiometer construction, (b) symbol, and (c) typical component [photograph: Alan Winstanley]

A variety of potentiometer circuit is the switched potentiometer, using a switch with separate fixed resistors, the principle of which is shown in Figure 3.8. The switch contact can be moved to connect to any of the points where resistors join, so that a number of potential divider circuits can be formed. There will clearly be a different value of voltage division at each contact point. The action of a potentiometer can also be carried out by integrated circuits (ICs), allowing a varying voltage to implement a potentiometer action.

A **joystick** is used for controlling some types of action, and is used to a large extent along with a computer for games. The joystick can be moved on two dimensions, and the mechanical action operates two potentiometers that are set at right angles. Movement of the joystick forwards and backwards affects one potentiometer only, and movement left and right affects the other potentiometer. All other movements of the joystick will affect both potentiometers, so that the two potentiometer output provide signals that accurately represent the position of the joystick.

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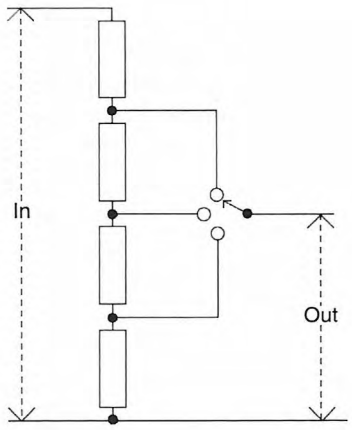


Figure 3.8 A simple switched potentiometer

All resistors, whether fixed or variable, are specified by reference to their resistance value, their method of construction and their power rating. The abbreviation ww or WW is normally used to indicate wire-wound resistors.

Measurements

Electrical quantities are measured by instruments such as **multimeters** and **oscilloscopes**. A multimeter (or multirange meter) is an instrument that is capable of indicating the values of several ranges of currents, voltages and resistances.

To measure a voltage, the multimeter is first switched to the correct range of voltage and the leads of the multimeter are clipped to the points across which the voltage is to be measured. One of these points will often be the chassis, earth or negative supply line. The circuit is now switched on. The voltage is then read from the correct scale (Figure 3.9). The meter is shown as a dial type, but modern digital meters produce a readout of digits.

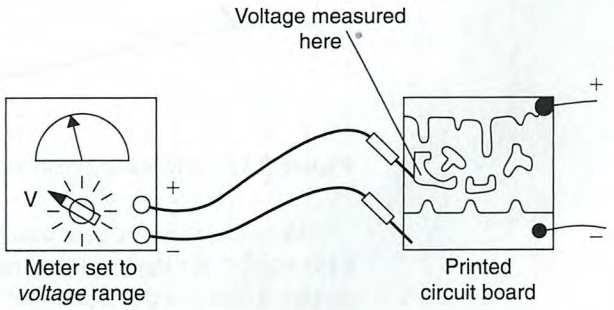


Figure 3.9 Measuring voltage on a printed circuit board

To read current flow (Figure 3.10), the circuit is broken at the place where the current is to be measured; in this example, the current supplied to the whole circuit. The multimeter leads are then clipped on, one to each side of the circuit break. The meter is set to a suitable range of current flows,

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and the circuit is switched on. Current value is then read from the correct scale. It is seldom practicable to read current in this way, however, and circuits often contain small resistors so that current in a part of the circuit can be calculated by measuring the voltage across one of these resistors.

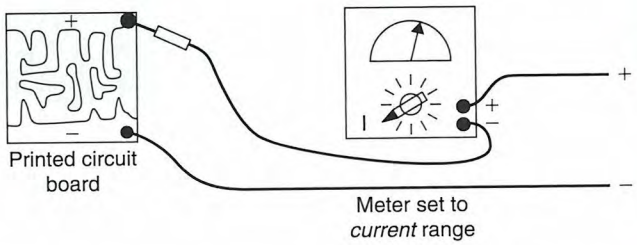


Figure 3.10 Measuring current flow to a printed circuit board

Note that, for measurements of either voltage or current, the meter must be connected in the correct polarity, with the + (usually red) lead of the meter connected to a more positive voltage.

To read resistance values (Figure 3.11), the multimeter leads are first short-circuited. The meter is switched to the 'ohms' range, and the set zero adjuster is used to locate the needle pointer over the zero ohms mark. The leads are then reconnected across the resistor to be measured, and its resistance is read off the scale.

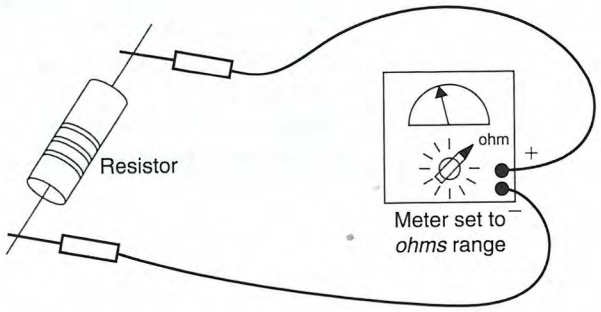


Figure 3.11 Measuring resistance

If there is any doubt as to which sort of values of voltage or current will be encountered, the highest likely range of each must first be tried on the multimeter. If the circuit is powered from a battery, it can usually be assumed that no voltage will exceed the battery voltage, but this is not always true, because some circuits contain inverters that multiply the input voltage to a higher level. It is safer always to start with the meter set on its highest voltage range. The range switch is then used to select a lower range of values, until a range is found which gives a reading that is not too near either end of the scale. Note that the resistance ranges make use of a battery inside the meter, and if this battery is dead resistance readings cannot be made.

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Multimeters always draw current from the circuit under test, so the values of voltage or current that are measured when the meter is connected are not necessarily the same as those that exist when the meter is not connected. Using modern digital meters overcomes this problem to a considerable extent. These instruments have very high resistance and so draw very little current from a circuit. They should always be used when measurements have to be taken on high-resistance circuits. Note, however, that they rely entirely on their battery to operate on all readings, unlike the older analogue type of meter. If you do not check the battery at regular intervals your readings will not be reliable.

When you have finished using a multimeter **always** leave it switched to its highest voltage range.

Practical 3.2

Construct the circuit shown in Figure 3.12. With an analogue multimeter switched to the 10 V scale, connect the negative lead to the negative line. Measure the supply voltage, and adjust it to exactly 9 V. Measure the voltages at points X and Y, and record the two values.

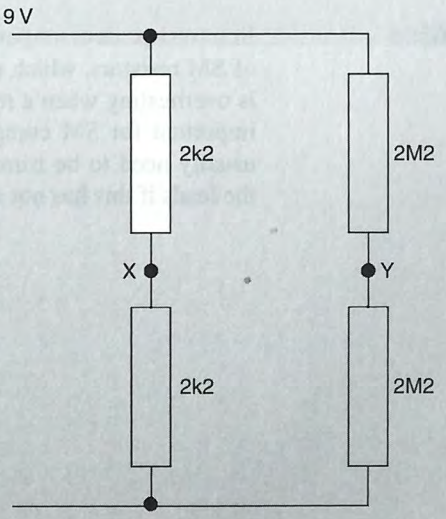


Figure 3.12 Circuit for Practical 3.2

Now use the potential divider formula to calculate what voltages would be present at X and at Y if no meter were connected. Use a digital voltmeter to read the voltage at point Y. Which type of meter is preferable for measuring the voltage at Y, and why?

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Examples: These examples should be solved by mental arithmetic, but you can use a calculator to check your answers if necessary. In each question, two quantities are given and you should calculate the third.

$V = 9\,V$	$V = 6.6\,V$	$V = ?$	$V = 27\,V$	$V = 12\,V$	$V = ?$
$R = 18\,k$	$R = ?$	$R = 10\,k$	$R = 1k8$	$R = ?$	$R = 2k2$
$I = ?$	$I = 2\,mA$	$I = 3\,mA$	$I = ?$	$I = 4\,mA$	$I = 3\,mA$

Insulation testers are used to measure the very high resistances of insulators. Testers such as the well-known Megger™ operate by generating a known high voltage and applying it through a current meter to the insulator under test. Any current flowing through the insulator causes the meter needle to deflect, and the scale indicates the resistance value of the insulator in megohms. Typical proof test voltages are 250 V or 500 V d.c. and 500 V a.c. Megger is a registered tradename, but it is widely used to mean any meter for high resistance measurements.

For measurements of very low resistance, such as connectors, printed circuit board tracks or soldered joints, the lowest range of a digital multimeter (typically 0.001 Ω minimum reading) can be used, or a digital milliohmmeter, many models of which can read down to 1 μ Ω.

Resistor notes

Resistors present no particular handling problems apart from the small size of SM resistors, which need to be handled with tweezers. The main hazard is overheating when a resistor is soldered into place, and this is particularly important for SM components. For a conventional resistor the leads will usually need to be trimmed to the required size, and you may have to tin the leads if this has not already been done.

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Multiple-choice revision questions

3.1 In the three-band resistor colour code, the third band represents the:
(a) first significant figure
(b) second significant figure
(c) tolerance
(d) number of zeros.

3.2 Two resistors connected in parallel will have a resistance that is:
(a) higher than either single resistor
(b) lower than either resistor
(c) equal to the sum of the resistance values
(d) higher than the sum of the resistance values.

3.3 The resistance of a metal increases when it is heated. Its temperature coefficient is:
(a) positive
(b) negative
(c) zero
(d) infinite.

3.4 A resistor is rated at 1/4 W. With 6 V across it would be just about overloaded if the current flowing were:
(a) 5 mA
(b) 10 mA
(c) 20 mA
(d) 40 mA.

3.5 A reading on a potentiometer circuit is 5 V, but a calculation suggests that it should be 8 V. This is because:
(a) the potentiometer circuit is faulty
(b) the resistors in the circuit are of low wattage
(c) the meter used has a high resistance
(d) the meter used has a low resistance.

3.6 Generally, a circuit has to be broken to measure:
(a) insulation
(b) voltage
(c) current
(d) power.

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4 Magnetism

Flux patterns

When iron filings are sprinkled on to a sheet of paper that has been placed over a bar magnet, the filings will arrange themselves into a definite pattern, which is called a **field** or **flux pattern**. This flux pattern (Figure 4.1) is a map of the direction and strength of the forces which are exerted on the iron filings because they are close to the magnet. The lines that the filings set into indicate the direction of the force. The clumping together of filings is some indication of the strength of the force. The greatest amounts of clumping exist at the ends of the magnet, and these ends are called the **poles** of the magnets, the places where the magnetic effect is strongest.

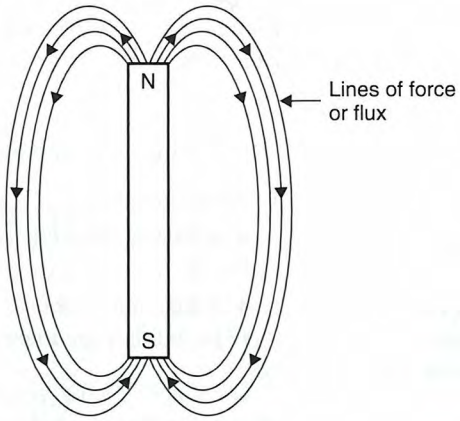


Figure 4.1 A typical flux pattern around a bar magnet. The arrows indicate the direction that a compass needle would point to at that position in the field

These forces exist and can be detected without any physical contact between the magnet and the iron filings. The general name for a force of such a type is a **field force**. The flux pattern, therefore, is a map of the **magnetic field** of the magnet, and it indicates the direction and strength of this field.

The pattern of the field that exists around a magnet can be changed in several ways. Figure 4.2 shows how the flux pattern appears when two magnets are placed close to one another. When both magnets are aligned in the same north–south direction, the pattern is as shown in the upper diagram. When one of the magnets is reversed, the pattern alters to that shown in the lower diagram.

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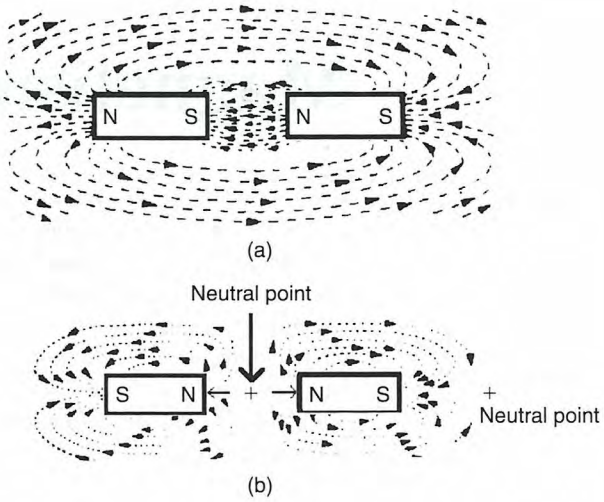


Figure 4.2 The flux pattern around two adjoining magnets: (a) N to S, and (b) N to N

The shape of a flux pattern is governed by two rules:

- A line behaves as if it were carrying a magnetic 'current' (a **flux**) in the direction of the line. This direction can also be indicated by a compass needle.
- The flux lines become closely spaced together where there is a strong field, but they are more widely spaced where the field is weaker.

The shape of a flux pattern is not noticeably altered by being close to non-magnetic materials such as plastics, copper or aluminium. Placing magnetic materials in a magnetic field, however, causes the flux pattern to change as shown in Figure 4.3(a). The magnetic material behaves as an easy path for the lines of flux, just as a metal offers an easy path for current. This allows us to manipulate and control lines of flux in a **magnetic circuit**, a topic that is important for all magnetic devices such as motors, relays and solenoids.

Some metal materials, called soft magnetic materials, can concentrate flux lines, although they are not themselves permanent magnets. These metals (such as soft iron, permalloy and mumetal) can be used as magnetic screens because flux will flow along the material rather than through it. Figure 4.3(b) shows that a cylinder of soft magnetic material will have no flux pattern inside the cylinder even when there is a strong field outside it. Such screening materials are used to shield cathode ray tubes and other components from stray magnetic fields.

A **soft magnetic material** is one that is easily magnetized by another magnet, but it loses that magnetism equally easily. A **hard magnetic material** (such as steel and several steel alloys with cobalt and nickel) is difficult to magnetize, but it will retain its magnetism for long periods unless it is heated, struck with a hammer or demagnetized by alternating fields. Hard

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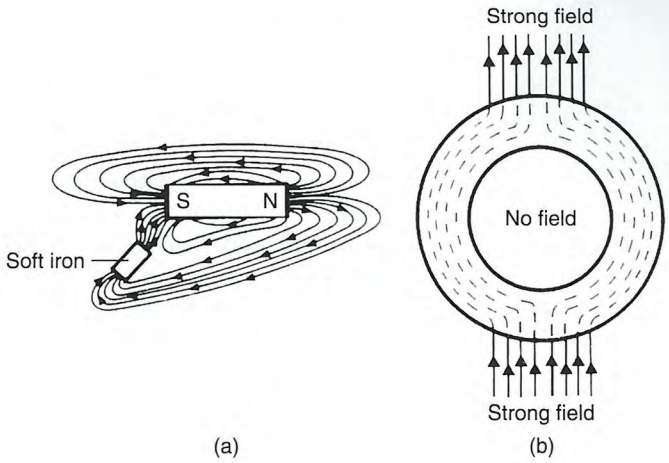


Figure 4.3 (a) Flux lines concentrated by presence of a piece of soft iron, and (b) magnetic screening

magnetic materials are used for making permanent magnets; soft magnetic materials are used for electromagnets and magnetic shields.

Electromagnets

Permanent magnets are not the only source of magnetic flux. When an electric current is passed through any conductor, a magnetic flux pattern is created around the conductor. The shape of this flux pattern around a straight conductor (Figure 4.4a) is circular, unless it is distorted by the presence of other magnetic material, and the pattern has no start or finish points. This leads us to the conclusion that all flux lines are, in fact, closed lines without either a start or a finish.

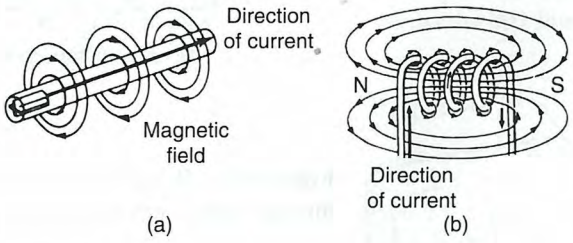


Figure 4.4 The flux pattern around (a) a wire carrying current, and (b) a solenoid carrying current

A conductor that is wound into the shape of a coil is called a **solenoid**. When current flows through the wire of a solenoid, the flux patterns of each part of the wire in the solenoid add to one another, so producing the pattern shown in Figure 4.4(b). This pattern is similar to that of a bar magnet, except that the shape of the flux pattern inside the coil can be seen.

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The addition of a soft magnetic material as a **core** inside a solenoid coil greatly concentrates the flux pattern inside the core and therefore also at its ends. The concentration of the flux pattern means that a coil becomes a much stronger magnet when it has a soft magnetic core, although only for as long as current is flowing through the wire of the coil.

A suitable core material can in practice increase the strength of a magnetic field several thousand-fold. This allows us to make electromagnets which are very much stronger than any permanent magnet could possibly be. Such solenoids are used to move soft iron pieces (armatures) so that passing current through the solenoid will cause mechanical movement of the armature.

All magnetic flux is caused by the movement of electrons. This can be the movement of electrons through a conductor, called **electric current**, or it can be the spinning movement of electrons within the atoms which occurs in permanent magnetic materials. These spinning movements balance each out in most materials (so that most materials are only very faintly magnetic), but the materials that are classed as strongly magnetic (called **ferromagnetic** materials) are made up of atoms that have more electrons spinning in one direction than in the opposite direction.

Motor effect

Another important type of alteration in the flux pattern of a magnet occurs when a wire is placed in a magnetic field and has a current flowing through it. In Figure 4.5, the points marked N and S are the north and south poles, respectively, of two bar magnets. The little circle with a cross inside it which lies between them represents a conductor wire seen end on, that is to say, with one of its ends running into the paper away from you, and the other end running out of the paper towards your eye.

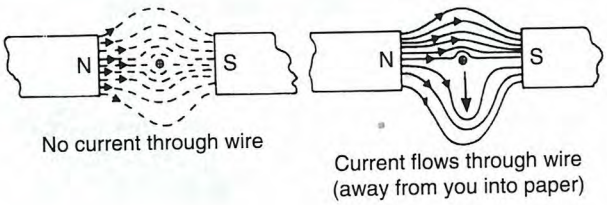


Figure 4.5 What happens to the flux lines of magnets when current flows through a wire in a magnetic field

When an electric current is passed through the wires the flux pattern between the magnets becomes distorted and this pattern can be revealed using iron filings or small compass needles.

When current flows and causes this distortion of the field, a magnetic force is exerted on the wire itself, acting at right angles to the wire and also at right angles to the flux lines. The direction in which this force is exerted can be remembered by using the **left-hand rule**, as pictured in Figure 4.6. The thumb and first two fingers of the left hand are extended at right

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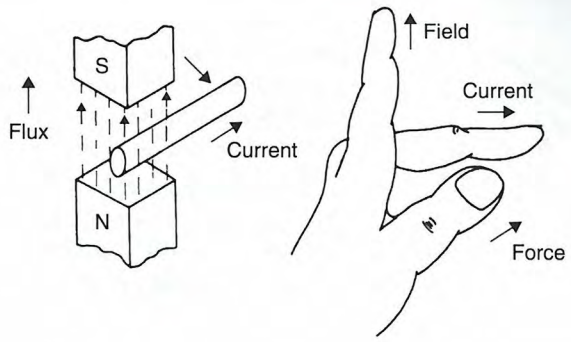


Figure 4.6 The left-hand rule for finding the direction of force on a conductor

angles to one another. The **F**irst finger then points in the direction of the **F**lux (N to S direction); the se**C**ond finger shows the direction of **C**urrent flow (positive to negative); while the thu**M**b points along the direction of the **M**agnetic force exerted on the wire. Unless the wire is held firmly, it will move in the direction of this force. A familiar illustration of this effect is the way that the cables to an electric welder jump apart when the arc is struck: each cable generates a magnetic field and so exerts a force on the other cable.

The force that exists between a magnetic flux pattern and a wire carrying current is the principle of the electric motor. When current flows through the coil of wire, shown in cross-section in Figure 4.7(a), the ends of the coil will experience forces that are equal in size but opposite in direction. The coil will therefore rotate about its central axis. This rotation will only continue, however, until the plane of the coil lies in line with the flux (in what is called its neutral position). In this position no force is acting to cause rotation because the coil is now aligned with its flux pattern. Another way of saying this is that the coil axis no longer cuts across the flux lines.

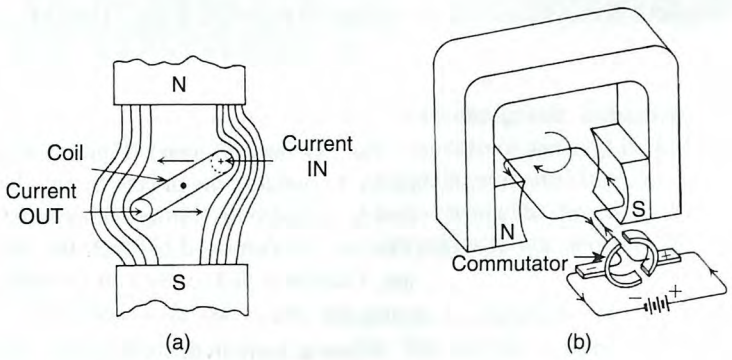


Figure 4.7 (a) Forces acting on a coil that carries current in a magnetic field, and (b) electric motor principle

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Continuous rotation is possible if the direction of current flow through the coil of wire is reversed just as the neutral position is reached. The momentum of the rotating coil will carry it a little way past the neutral position, and the reversed current will exert a force on both ends of the coil which keeps the coil rotating.

The direction of current flow through the wire can be reversed at the correct point in its rotation by using a rotary switch called a **commutator** (Figure 4.7b). The segments of the commutator are made of copper, and the contact (or **brush**) is of soft carbon, which conducts current but allows the movement of the commutator segments with fairly low friction.

An electric motor with a single coil and a two-segment commutator does not run at a perfectly uniform speed. The coil moves most rapidly when it is at 90 degrees to the plane of the flux and most slowly as it passes the neutral position. In practice, d.c. motors use several coils and corresponding pairs of commutator segments. This provides smoother running and avoids the problem of 'sticking' when the motor will not start if the coil happens to be at rest near its neutral position. Small motors usually have a twin coil arrangement with four commutator segments.

The set of revolving coils is known as the **armature** of the motor, and each end of a coil is called a **pole**, so that a small motor can be described as having, for example, a four-pole armature. The magnet (which may be either a permanent magnet or an electromagnet) is known as the **field** or **field winding**. Direct current motors are easy to control and their direction of rotation can be reversed by reversing the direction of current in either the armature or the field, but not both together.

Practical 4.1

Connect up a small electric motor so that you can measure the current through the armature winding. Measure this current (a) when the armature is revolving freely, (b) when there is a load (clamp the shaft lightly between your fingers), and (c) when the shaft cannot move (this reading must be taken quickly to avoid damage to the armature and brushes).

The moving coil meter (Figure 4.8) uses the same principle as the electric motor to measure the direct current flowing through the coil. In this case, the coil is wound on a former with a pointer attached and mounted in bearings. The coil is positioned between the shaped poles of a powerful electromagnet. Current is fed to the coil through a pair of spiral springs which act to cause the coil to take up a zero position when no current is flowing.

When a current flows through the coil, the magnetic field of the coil works with the flux of the permanent magnet to turn the coil. The amount of turning is proportional to the amount of current flowing in the coil because the pointer stops at a position where the magnetic force is exactly

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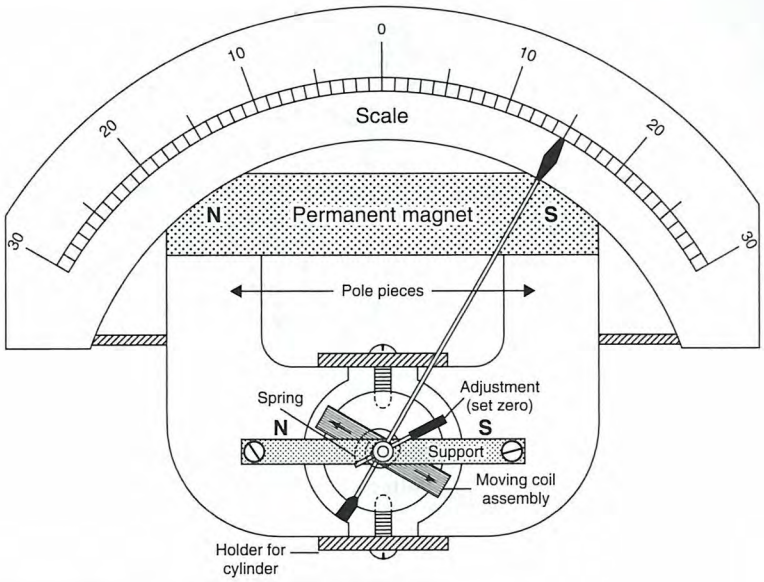


Figure 4.8 Moving coil meter principle

balanced by the mechanical force of the springs. Moving coil meters have now been replaced for most measuring purposes by digital meters, which use an entirely different principle.

Practical 4.2

Connect up a voltage source with a low-value wire-wound variable resistance and an ammeter in series with a solenoid (which can be the winding of a relay). Find the minimum value of current that will just pull in the armature of the solenoid.

Electromagnetic induction

The reverse of motor action is called **electromagnetic induction**. When the flux pattern around a conductor (with no current passing) is changed by moving the wire through the flux, a voltage is generated between the ends of the wire. This induced voltage is greatest when the direction of the flux and the movement of the wire are at right angles to one another. This is the basic electrical generator principle.

The polarity of the induced voltage can be remembered by using the **right-hand rule** illustrated in Figure 4.9. The first two fingers and the thumb of the right hand are extended at right angles to one another. The first finger is pointed in the direction of the field of the magnet (N to S), and the thumb in the direction of the motion of the wire. The second finger then indicates

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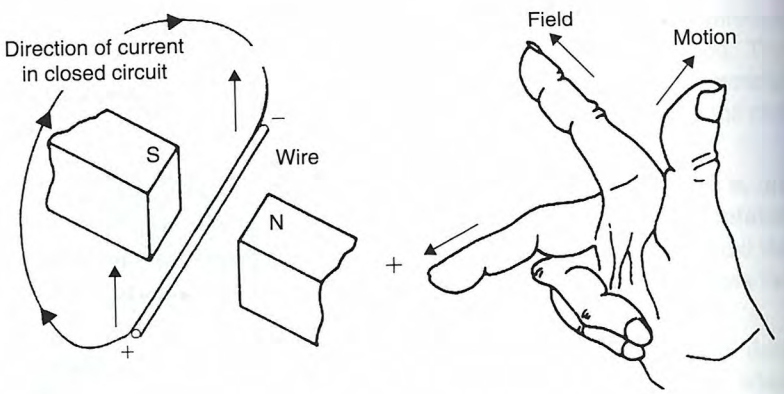


Figure 4.9 The right-hand rule for finding the polarity of an induced voltage

the end of the wire which is positive. If the ends of a wire are connected to a load, current will flow. Remember that the **F**irst finger points in the **F**ield direction, the **M**otion is in the thu**M**b direction, then the **I**ndex finger points to the direction of current (**I**).

This principle of motional induction is used to generate a.c. in an alternator. Figure 4.10 shows a simple alternator using the same construction as an electric motor but with the commutator replaced by **slip-rings**. These slip-rings do not reverse the connections to the coil. The voltage produced when the alternator is set spinning is not a steady (d.c.) one but takes the shape of a wave, a sine wave (more details later), whose voltage reaches maximum when the wire of the coil is momentarily moving at right angles to the flux, and zero at the instant when the wire of the coil is moving in line with

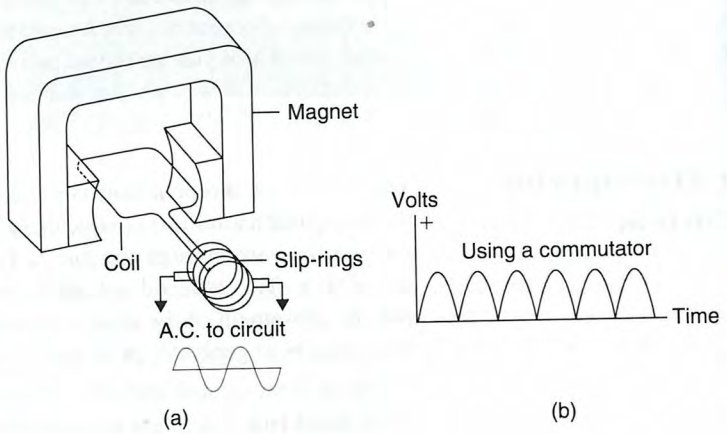


Figure 4.10 (a) The principle of the a.c. generator, using slip-rings, and (b) output wave when a commutator is used in place of slip-rings

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(parallel to) the flux direction. The reversal of polarity is caused by the fact that the wire during its rotation must cut across the flux lines in one direction for half of its rotation and in the opposite direction for the other half.

The voltage and the frequency of a.c. produced by an alternator both increase as the speed of rotation increases. Large voltage outputs can be obtained by using large magnetic fields and many turns of wire in the rotating coil. The frequency of the a.c. output is determined entirely by the rotating speed of the spinning coil and the number of poles of the magnet.

If the slip-rings are replaced by a commutator, the waveform generated will be of the unidirectional form (Figure 4.10b). This is close enough to d.c. to be useful for some purposes, such as battery charging. Alternators for cars use a three-pole arrangement with a set of six diodes rectifying the output to a reasonably smooth d.c.

A d.c. generator that uses several coils and commutator segments, however, produces a reasonably smooth d.c. output, although the switching at the commutator segments produces sparks, causing spikes of voltage to appear. This causes interference, called *hash*, on car radios, and the use of alternators and diodes on car electrical systems was a major step forward in improving car radio reception.

Inductors

It is also possible to generate a voltage by induction without any mechanical movement. If the strength of the flux that cuts across a conductor is varied, a voltage will be induced in the conductor, just as if the variation of flux had been caused by movement. This effect, called **transformer induction**, is responsible for the very important electrical effects known as **mutual inductance** and **self-inductance**.

When a current starts to flow through a coil of wire, or is switched off, the flux lines around the coil will respectively expand or collapse. This variation in the flux lines induces a voltage in the coil itself and this induced voltage is always in a direction that will **oppose** the change of current flow. When, for example, a coil is suddenly connected to a battery, the induced voltage acts to oppose the battery voltage so that current changes more slowly. When the coil is disconnected from the battery, the induced voltage will aid the battery voltage, trying to keep the current flowing and generating a brief pulse of voltage.

Both of these effects, which are illustrated in Figure 4.11, are momentary; they last only for the brief period in which current flow through the coil is changing. If the current through the coil is an alternating current (which is continually changing) an induced a.c. voltage will always be present. This induced voltage is also alternating, and it acts to oppose the flow of current, making the coil behave as if it possessed greater resistance to a.c. than for d.c.

Because it is the coil itself that induces the opposing voltage, this opposing voltage is called an electromotive force (emf) of **self-induction** or **back emf**. The size of the induced voltage depends on the rate at which the flow of current changes, and on the shape and size of the coil. These geometrical factors of shape and size are measured by the quantity called **self-inductance**, which is measured in units of henries (H). A coil has an

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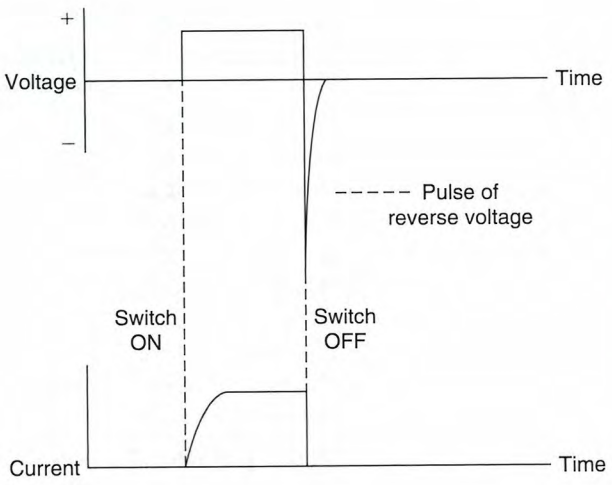


Figure 4.11 The effect of inductance when current through an inductor is switched ON and OFF

inductance of 1 H when a rate of change of current of 1 A per second causes an induced voltage of 1 V.

In practical work, the smaller units of millihenries (mH) and microhenries (μH) are more useful. A few centimetres of straight wire will have an inductance of less than 1 μH. A coil used to tune a medium-wave radio will only have an inductance of some 650 μH. An iron-cored choke which is intended to act as a high impedance to audio signals might typically have an inductance of 50 mH. Only a very large coil wound on a massive laminated iron core would have an inductance that needed to be measured in units of henries.

Practical 4.3

Connect up a solenoid or other large inductance winding to a suitable voltage source, and connect a neon lamp (which lights at 80 V applied) across the solenoid. Does the neon flash when you abruptly cut off the current? This indicates the back emf.

Transformers

The changing flux around a coil that carries a changing current will also induce a voltage in another coil. This is the principle of the **transformer**, a device that is used extensively in electricity and electronics. A simple transformer, pictured in Figure 4.12(a), consists of two coils that are wound on a common magnetic core. When the current through one coil (the **primary** winding) changes, a voltage is induced in the other winding (the **secondary** winding). The symbol (b) indicates the construction.

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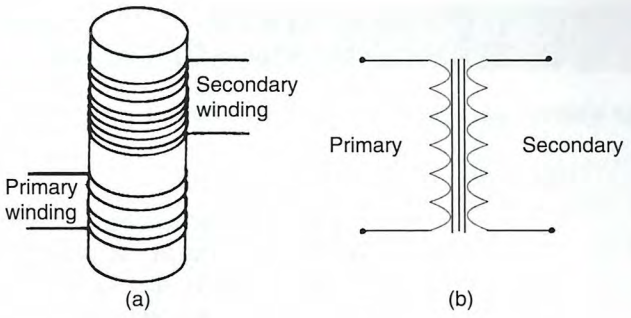


Figure 4.12 (a) Transformer principle, and (b) circuit symbol

Remember that a single inductor has self-inductance. When inductors are wound on the same core, or close together, each winding still has **self-inductance**, and there will also be **mutual inductance** between windings. The mutual inductance that exists between the windings of a transformer means that a changing *current* passed through the secondary winding will cause a *voltage* to be induced in the primary winding. The construction of a transformer will be more easily understood if you look at the cross-section of a strip of transformer core and its windings illustrated in Figure 4.13(a). The primary and secondary windings of a transformer are always arranged to be as close to each other as possible. Figure 4.13(b) shows a typical small transformer.

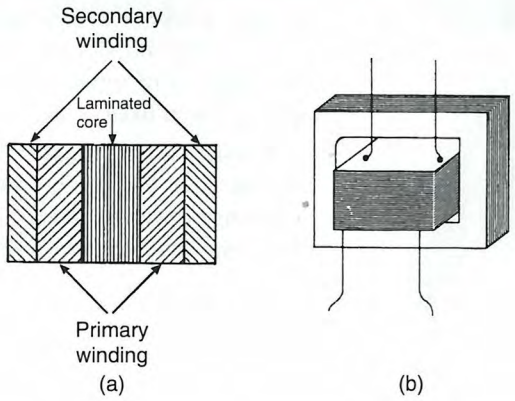


Figure 4.13 (a) Cross-section of windings on a transformer core, and (b) a typical small transformer

One of the principal actions of a transformer is to pass signals from one circuit to another without any connection other than the magnetic flux existing between the two circuits. The transformer therefore passes a.c. signals but blocks d.c. A transformer can also achieve a **step-up** or **step-down** of alternating voltage or current depending on the ratio of the number of turns

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of wire in each of its two windings. For a given a.c. voltage across the primary winding (V_p), the voltage across the secondary winding will be

$$V_s = V_p \frac{N_s}{N_p}$$

where N_s is the number of turns in the secondary winding and N_p is the number of turns in the primary winding of the transformer. If the transformer is perfect, meaning that there is no power loss between primary and secondary, the current ratio I_p/I_s will be equal to N_s/N_p, the turns ratio.

The construction of a transformer core depends on the frequency range of the signals that the transformer is designed to handle. For the lowest audio frequencies, a large core of soft magnetic material in the form of thin laminations is enough. At higher frequencies, ferrite dust cores must be used to reduce as far as possible the magnetic losses (**eddy-current** losses) that arise in metal cores when high-frequency signals pass through them. At the highest frequencies for which coils are used, no metal core material is acceptable. Coils either have to be wound on plastic formers, or they are made self-supporting. For the ultra-high frequencies (UHF) used for television transmission, short, parallel metal strips carry out transformer action.

The **autotransformer** uses a single winding to act as both primary and secondary of the device; it amounts to a tapped inductor. The autotransformer behaves exactly as does the transformer just described, except that it provides no d.c. isolation between its primary and secondary windings. The ratios of voltage, current and resistance (impedance) in the autotransformer are identical to those in the ordinary transformer, and the ratio of turns is worked out in exactly the same way. Many autotransformers are used for stepping down voltage, so that the primary number of turns is the total number of turns on the core, and the secondary number is the small amount taken from one end of the winding to the tap point.

A commonly used type of autotransformer, called a Variac™, has a sliding tapping point that can be continuously varied to provide an output (secondary) range of zero to some 130% of the nominal primary voltage. It is useful in circuits in which the voltage needs to be set precisely to a known value.

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Multiple-choice revision questions

4.1 The cores of electromagnets are usually made from:
(a) steel
(b) nickel
(c) soft iron
(d) hard iron.

4.2 When two permanent magnets with like poles are placed close to each other, the effect is to:
(a) attract each other
(b) repel each other
(c) induce a current into each other
(d) generate heat.

4.3 When a current flows in a wire that is placed in a magnetic field there is a mechanical force exerted on the wire. The direction of this force is:
(a) the same as that of the magnetic field
(b) the same as the current
(c) at right angles to both field and current
(d) opposite to the direction of the current.

4.4 A sine wave voltage is generated when a coil :
(a) revolves in a magnetic field
(b) moves in line with the magnetic field
(c) moves in a straight line across the magnetic flux
(d) is held stationary.

4.5 When a current that has been flowing through an inductor is suddenly cut off, there is a:
(a) large pulse of voltage
(b) small pulse of current
(c) large pulse of current
(d) continuous voltage.

4.6 A transformer has 1000 turns in its primary winding and 2000 turns in its secondary. It will give:
(a) 20 V d.c. output for 10 V d.c. input
(b) 10 V d.c. output for 20 V d.c. input
(c) 20 V a.c. output for 10 V a.c. input
(d) 10 V a.c. output for 20 V a.c. input.

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11 Transducers (2)

Permanent-magnet motor

The d.c. permanent-magnet motor, whose symbol and typical connections are illustrated in Figure 11.1(b), is used extensively in equipment that needs mechanical actions, such as video recorders and compact disc (CD) players. As the name implies, the motor uses a rotating armature with a winding connected through a commutator, with a field supplied by a permanent magnet. Figure 11.1(a) shows a simple example with a one-turn rotor. We can think of the motor as a transducer whose input is electrical and whose output is mechanical. Miniature general-purpose d.c. motors, using permanent magnet fields, can be controlled by the output from a comparatively low-output semiconductor amplifier. Typically they have voltage requirements of 6–12 V and currents of 200–400 mA. Small electric motors of this type can be used in models, rotating signs, display systems and to some extent in robotics.

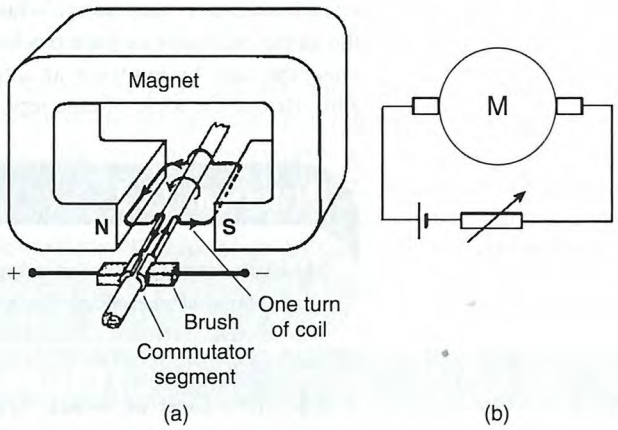


Figure 11.1 (a) Permanent magnet motor principle, and (b) symbol and motor circuit with current controller

The permanent-magnet type of motor is favoured because its speed can be controlled by controlling the current through the armature winding, and the direction of rotation can be reversed by reversing the direction of current through the armature winding. The armature current can be supplied from a circuit incorporating a power transistor, so that the current can be closely regulated to provide precise speed control.

For closer control and higher power, the permanent magnet can be replaced by an electromagnet, energized by a **field** winding. Using separate control of current through the field, the speed of the motor can be controlled over a wide range, so that this type of motor is used where precise speed control is important. When the armature and the field windings are

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connected in parallel, the motor is said to be **shunt wound**, but if the field and armature windings are connected in series the motor is **series wound**. Series-wound motors have very high starting torque and can spin at very high speeds on a light load, although their rotational speed drops considerably under load. They can deliver high torque at low speeds under load. Shunt-wound motors have a very low starting torque (and may have to be assisted), but when running their speed is relatively constant as the load changes. For reversing a motor with a wound field, the direction of current through either the armature or the field (but not both) can be changed.

Tape-recording and erase heads

These are transducers with an electronic signal input and a magnetic field output. The tape-record head is a transducer with electrical input and magnetic output, and one head can be used for both purposes, although this is not an ideal arrangement. The head gap is usually of around the same size as the thickness of the magnetic coating on the tape, and for a good-quality cassette recorder can be as small as 1 μm (10^{-6} m). Ideally, the head gap for a recording head should be larger than for the reading head, and figures of around 6–10 μm are common. The gap for the replay head should be as small as head technology can provide (allowing for the price of the recorder). The erase head has a comparatively large gap. It is fed from an oscillator, usually the same oscillator as provides bias (see Chapter 10), and its purpose is to erase the tape by applying an alternating field that is gradually reduced to zero. Revise the topic of tape replay head (Chapter 10).

Practical 11.1

Measure the resistance of a tape-recording head. Use a demagnetizer on the head after making the measurement.

Relays

A relay is a form of switch, with the mechanical action of moving the switch contacts being carried out by a solenoid and armature. The classical form of relay (Post Office type 8000) is illustrated in Figure 11.2. The solenoid is wound on a former around a core, and a moving armature forms part of the magnetic circuit. When the coil is energized, the armature moves

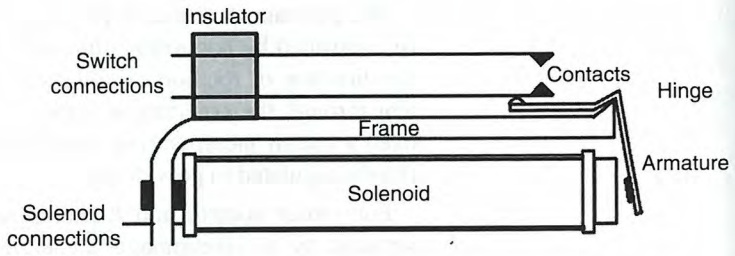


Figure 11.2 The classic type 8000 relay construction. Modern relays are smaller, but the working principles are unchanged

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against the opposition of a spring (or the elasticity of a set of leaves carrying the electrical contacts) so as to complete the magnetic circuit. This movement is transmitted to the switch contacts through a non-conducting bar or rod, so that the contacts close, open or change over depending on the design of the relay.

The contacts are subject to the same limits as those of mechanical switches, but the magnetic operation imposes its own problems of make and break time, contact force and power dissipation. Like so many other electronics components, relays for electronics use have been manufactured in decreasing sizes, and it is even possible to buy relays that are packaged inside a standard TO-5 transistor can.

The relay has to be specified by the operating voltage and current, and also by the switching arrangements. These are commonly classed as normally open (NO), meaning that applying power to the relay will close the contact(s), or change-over (CO), meaning that applying power will change over the switch connections. Normally closed connections are less usual, and applying power to such a relay will open the contacts. Contacts are usually single or double pole, so that typical arrangements are SPNO, SPCO, DPNO or SPCO (also known as DPDT). At one time, separate symbols were used for these contact arrangements, but this has changed.

Circuit diagrams now use the **detached contact method**. The coil of the relay is shown in one part of the diagram (in the collector circuit of a transistor, perhaps), and the switching contacts are in another part of the diagram. This avoids the need to show long and confusing connecting lines on a diagram. It also allows the use of two standard contact symbols, one for normally open and the other for normally closed. These symbols are illustrated in Figure 11.3.

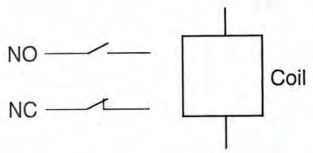


Figure 11.3 Contact symbols for diagrams including relays

Practical 11.2

Measure the resistance of a relay operating coil, using a multimeter. Measure also the resistance of closed contacts.

Monochrome cathode-ray tube

The cathode-ray tube (CRT) is a transducer component which nowadays is just about the only device you are likely to come across that uses the same principles as the old-style radio valves. The CRT is used to convert variations of voltage into visible patterns, and is applied in instruments (oscilloscopes), for television, and for radar. Colour tubes are used for television and monitor purposes, but monochrome (black and white) tubes are still used in considerable numbers for instruments and for low-cost closed-circuit television (CCTV). For computer and (gradually) television receivers they are being replaced by LCD and plasma devices. They, in turn, are likely to be replaced by other types of displays in the near future, such as SED (or FED), OLED and PDP.

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The three basic principles of the CRT are:

- Electrons can be released into a vacuum from a red-hot cathode (a metal coated with metal oxides).
- These electrons can be accelerated and their direction of movement controlled by using either a voltage between metal plates or a magnetic field from a coil that is carrying an electric current.
- A beam of electrons striking some materials such as zinc sulphide will cause the material (called a phosphor) to glow, giving a spot of light as wide as the beam.

In the monochrome tube electrons from the **cathode** are attracted to the positive **anode** by an accelerating voltage of several kilovolts. On their way, they have to pass through a pinhole in a metal plate, the **control grid**. The movement of the electrons through this hole can be controlled by altering the voltage of the grid, and a typical voltage would be some 50 V negative compared to the cathode. At some value of negative grid voltage, the repelling effect of a negative voltage on electrons will be greater than the attraction of the large positive voltage at the far end of the tube, and no electrons will pass the grid: this is the condition called **cut-off**.

Electrons that pass through the hole of the grid can be formed into a beam by using metal cylinders at a suitable voltage. By adjusting the voltage on one of these cylinders, the **focus electrode**, the beam can be made to come to a small point at the far end of the tube. This end is the **screen**, and it is coated with a material (a **phosphor**) that will glow when it is struck by electrons. The phosphor (which does **not** contain phosphorus) is usually coated with a thin film of aluminium so that it can be connected to the final accelerating (anode) voltage. The whole tube is pumped to as good a vacuum as is possible; less than a millionth of the normal atmospheric pressure.

This arrangement will produce a point of light on the centre of the screen, and any useful CRT must use some method of moving the beam of electrons. For small instrument CRTs a set of four metal plates can be manufactured as part of the tube and these deflection plates will cause the beam to move if voltages are applied to them. The usual system is to arrange the plates at right angles, and use the plates in pairs with one plate at a higher voltage and the other at a lower voltage compared to the voltage at the face of the tube. This system is called **electrostatic deflection**.

A typical electrostatically deflected CRT is intended for oscilloscope use, and will use a screen size of, typically, 5–7 inches diameter. Rather than earthing the cathode and connecting the anode to several kilovolts voltage, the tube is used with the anode earthed, and the cathode at a high negative voltage. This makes it possible to connect the deflection plates directly to a modest voltage that can be supplied from transistor circuits. The other voltages for focus and accelerating electrodes can be supplied from a resistor network connected between the earth and the most negative voltage (applied to the grid). Figure 11.4 shows the symbols for the electrodes and the typical voltage in a small instrument CRT. Note that high voltage levels exist particularly around the cathode.

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In oscilloscope use, steady voltages are applied to the anodes, although the supply to the second anode can be varied to allow for focusing the electron beam on the screen. Alternating current is applied to the heater coil, and a modulating pulse is applied to the cathode (as well as a d.c. bias) to switch the electron beam on and off. The vertical deflection plates are supplied from an amplifier which provides a d.c. bias, and is used to place an alternating signal voltage. This is an amplified version of the signal input to the oscilloscope.

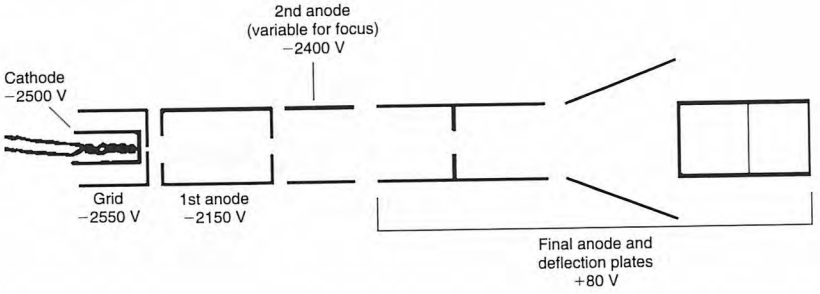


Figure 11.4 Electrode symbols and typical voltages used for a small instrument CRT

The form of deflection that is most common for CRTs is a linear sweep. This means that the beam is taken across the screen at a steady rate from one edge, and is returned very rapidly (an action called **flyback**) when it reaches the other edge. A sawtooth waveform is needed to generate such a linear sweep. An electrostatic tube can use a sawtooth voltage waveform applied to its horizontal deflection plates.

There is an alternative method for deflecting the electron beam which is used for larger tubes, particularly for computer monitors, radar and television. A beam of electrons is a current flowing through a vacuum, and magnets will act on this current, deflecting the beam. A tube of this type (Figure 11.5) can have a much shorter neck and a much wider angle of deflection than an instrument tube with electrostatic deflection. The easiest way to carry out beam deflection is to place coils around the neck of the tube and pass current through these coils to control the beam position on the face of the tube. This **magnetic deflection** method is better suited for large CRTs such as are used for simple radar, CCTV or computer monitor applications. The coil windings are usually shaped so that they can be placed over the curved portion of the neck of the tube, as illustrated in Figure 11.6.

Figure 11.7 shows typical connections to a small monochrome monitor or television tube. These are fewer than for the electrostatic type because there are fewer electrostatic components (only focus is achieved by voltage on a focus cylinder) and the magnetic components are external. A magnetic-deflection system must use a sawtooth current applied to its deflection coils. The difference is important, because the electrostatic deflection requires only a sawtooth voltage with negligible current flowing, but the magnetically

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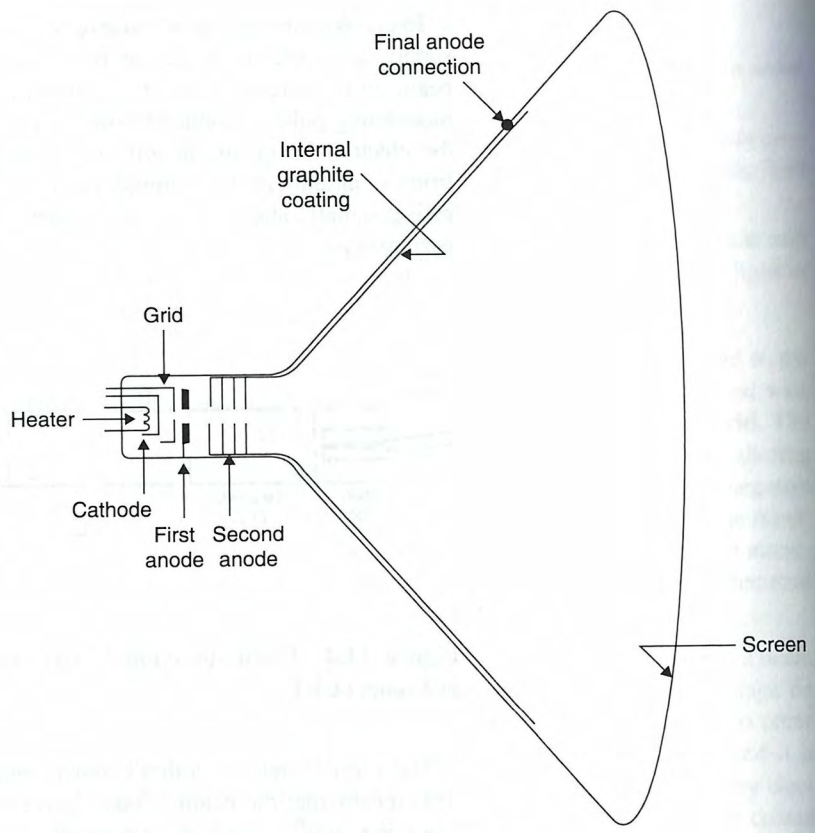


Figure 11.5 Cross-section of a magnetically deflected tube

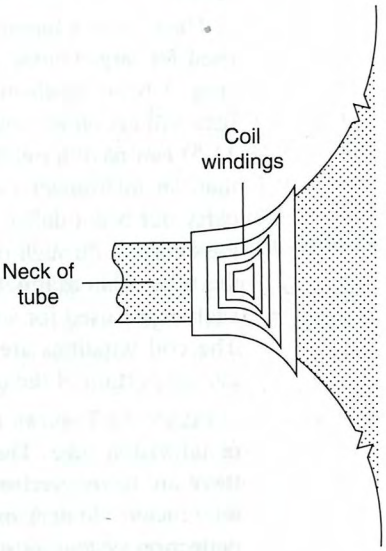


Figure 11.6 Position of the deflection coils

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deflected tube requires a sawtooth current, and the voltage across the deflection coils will not be a sawtooth, because the coils act as a differentiating circuit converting a sudden change of voltage into a steadily rising or falling current. In fact, the voltage waveform is a pulse, and this is used in television receivers to generate a very high voltage for the CRT. Chapter 18 deals with colour CRTs and their use in television receivers, and Chapter 22 deals with computer monitors.

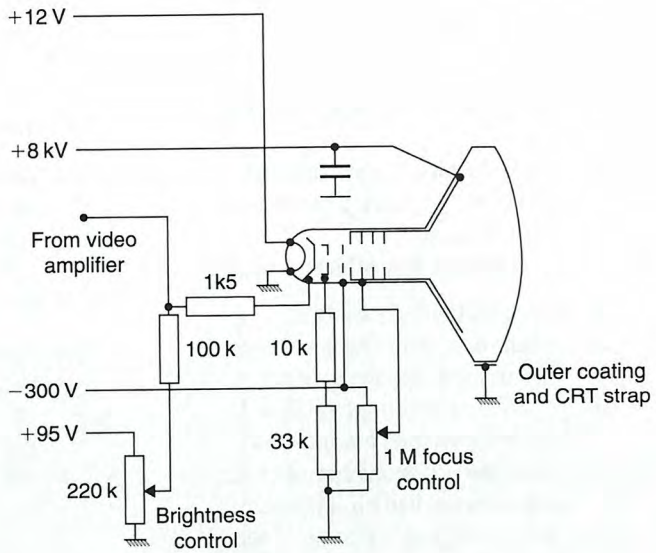


Figure 11.7 Typical connections to a monochrome monitor tube

CRT faults

Experience with CRTs has proved them to be remarkably reliable components, and it is not unusual for a television colour CRT to have a life of 25 years or more. When a tube becomes faulty, the usual fault is loss of emission from the cathode, so that screen brightness drops and the brightness (grid voltage) control has to be taken to its limit to provide a visible trace. At one time it was a normal servicing procedure to revive failing emission by running the tube heater at a higher current than normal, and applying a small positive bias to the grid. This often provided a few years of extra life, but with the improvement in materials used in cathodes, loss of emission is now quite rare.

Other faults, also quite rare nowadays, are grid-cathode shorts and open circuits. A grid-cathode short will make the tube show a permanent bright trace, and for a monitor tube no picture information. Open circuits will result in no form of trace or picture on the screen. In either case, the tube will have to be replaced, and because of the hazard of implosion (the vacuum inside causing the glass to fly inwards when it shatters) you should take care to ensure that the tubes (old and replacement) are protected and your eyes shielded when you replace a tube. Large television tubes are a

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much greater hazard because of their weight and glass content, but at the time of writing they are being replaced by plasma and LCD screens.

Multiple-choice revision questions

11.1 A permanent-magnet motor:
- (a) uses a wound armature and field
- (b) uses a wound field only
- (c) uses a wound armature
- (d) uses no armature.

11.2 The gap in the record head of a tape recorder:
- (a) is for the tape to pass through
- (b) allows for expansion of the metal
- (c) must be large
- (d) is where the flux affects the tape.

11.3 A relay is particularly useful:
- (a) when more than one actuating circuit must operate a switch
- (b) when the actuating circuit is d.c. and the switched circuit is a.c.
- (c) when the actuating circuit is a.c. and the switched circuit is d.c.
- (d) when complete isolation is needed between the actuating circuit and the switched circuit.

11.4 The cathode of a cathode-ray tube:
- (a) provides a source of electrons at all times
- (b) provides a source of electrons when heated
- (c) gathers electrons from the anode
- (d) deflects electrons from the grid.

11.5 In an instrument CRT:
- (a) the beam is magnetically deflected
- (b) the heater must be fed with d.c.
- (c) deflection is electrostatic
- (d) the phosphor must be white.

11.6 A monitor or small television tube:
- (a) is usually magnetically deflected
- (b) has a signal applied to its anode
- (c) needs electrostatic deflection plates
- (d) is longer than an instrument tube of the same screen size.

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