

MASTERING ELECTRONICS

THIRD EDITION

JOHN WATSON

M
MACMILLAN

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INTRODUCTION TO ELECTRONICS

Only a few years ago, you would not have found the study of ‘electronics’ on the curriculum of any university or college. The subject was not considered important enough to be given a category of its own, and was studied as a rather specialist branch of electricity. Today, this relatively new branch of technology has made an impact on almost every aspect of our lives. Electronics has made possible a range of inventions, from televisions to spacecraft. Many of these inventions—or the effects of them—have revolutionised the way we live.

The growth of electronics as a branch of technology has been unprecedentedly rapid. Never before has such a completely new technology been developed so quickly or so effectively, and so universally. Electronic techniques are now applied to all branches of science and engineering. A study of electronics is therefore central to any science or engineering course, and more and more people, in all walks of life, are going to be needing a basic knowledge of electronic technology.

It is true that electronics developed from the study of electricity. Early ideas about the way electric current could flow through conductors and through a vacuum led to the development of useful radio systems. It was possible to send messages around the world using what was, by today’s standards, incredibly simple and crude equipment. The Second World War provided an urgent requirement for more sophisticated communication and other electronic systems. The invention of radar (radio direction finding and ranging) required a big step forward in theory and an even bigger step forward in engineering. The study of electronics gradually became an important subject in its own right, and the radio engineer became a specialised technician.

The development of television led to one of the most massive social changes that has taken place. Many households now possessed televisions, radios and record players. In some branches of industry, electronic systems became useful—but electronic devices not directly concerned with the wire-

less transmission of sound or pictures were still something of a curiosity.

Only in the early 1960s did electronics technology 'come of age' thanks to the work of three scientists, Bardeen, Brattain and Shockley, in the Bell laboratories in the USA. In 1957 they assembled the first working transistor.

1.1 THE MICROELECTRONIC REVOLUTION

In order to understand just how much impact the invention of the transistor was to have, it is necessary to realise that every electronic machine required the use of *valves*. Valves will be described in Chapter 5, but for the time being it is enough to know that valves are rather inconvenient devices for handling electrons. Valves are rather large, difficult to produce on a large scale, and extremely wasteful of power. The transistor, on the other hand, can be made quite small and uses relatively little power. It is much cheaper to make than a valve and lends itself to mass-production techniques. More importantly, the transistor can be made *very* small. There is a theoretical limit to the size of a transistor, but this limit is astonishingly tiny. Using transistor technology it became possible to make electronic circuits very complicated and very small. It is quite difficult to get an idea of the difference in scale between electronic devices using valves and electronic devices using microelectronic technology. It does not give a very valid comparison to look at a radio receiver of the 1930s and compare its size with a modern transistor radio. The size of the transistor radio is not limited by technology but rather by the size of the person who is expected to operate it. Transistor radios can be made extremely small, but the lower limit of smallness is reached when it becomes impossible to operate the controls!

A more useful comparison can be made by looking at computers. One of the first working, large-scale computers was made in the late 1940s. It occupied an area about equal to that of an hotel suite, and used as much power as a medium-sized street of houses. It was vastly expensive, and vastly unreliable—on average a valve had to be changed once every ten minutes.

I am fortunate enough to own a computer of substantially more power than that of the giant of the 1940s. It cost me less than one week's pay, and fits neatly into my jacket pocket. It will operate for approximately 300 hours on two tiny batteries and I would be surprised if it ever went wrong.

All this gives an indication of the scale of change that has taken place as a result of the development of electronics, and of the 'microelectronic revolution' sparked off by the invention of the transistor.

1.2 ELECTRONICS TECHNOLOGY TODAY

Most of the development in electronics has taken place since 1960. Inevitably there have been large changes in the way the subject is taught, and indeed in what is taught. Solid-state technology has even led to a change in the way we look at the physics of the atom. Models of the atom which work well for electronics based on the relatively crude 'valve' technology are often not sufficient for a useful description of modern microelectronic components.

This book is divided into three parts. Part I is a revision of **basic electricity**. This part of the book goes rather faster than the other two parts. It will provide you with sufficient knowledge of electricity to enable you to understand the rest of the book. It is not, however, a complete study of the subject but will be a useful memory-jogger for anyone who has studied electricity at school but who needs to be reminded of what was learnt there.

Part II deals with **linear electronics**. Broadly, this is a study of electronic components and systems that deal with continuously varying quantities and represent these quantities by means of an electrical analogue. Electronic systems that involve this technology include television and radio, audio and video reproduction equipment, and a number of electronic instruments.

Part III deals with **digital electronics**. In digital electronics, systems deal only with numbers, usually represented by the presence or absence of an electrical signal. Digital electronic systems include, of course, computers and calculators, and a number of electronic instruments. Digital electronics is probably the most rapidly developing branch of electronics technology. Various functions previously carried out by linear systems are now being dealt with digitally—one major example is studio-quality audio recording and reproduction. A sound signal can now be represented as a stream of numbers, and can be recorded and replayed in this form to give a totally reproducible and high-fidelity audio signal. Most commercial sound-recording studios now use digital techniques for recording.

1.3 ELECTRONIC SYSTEMS

It used to be necessary for students of electronics to understand at a basic physical level the way in which electronic systems worked. This is still true in so far as a student must have a thorough understanding of the physics of electronic devices. However, it is no longer necessary—or indeed possible—for students to understand the detailed workings of individual circuits. A microelectronic counter, for example, may be extremely com-

plex in its actual operation. If a manufacturer has some novel circuit, he may be very reluctant to publish details of the way the device works. In the case of very complex microelectronic systems—such as microprocessors—it would be a major study to examine in detail the operation of just one such device. The technologist today is concerned with *systems*, and with the operating parameters of the individual circuit components. An individual circuit component in this context may be a complete amplifier or counter. The manufacturer will provide very complete data, and provided the user is fully aware of the device's characteristics, it is no longer necessary to understand the precise details of a device's internal functioning. For reasons outlined above, such information may be rather difficult to obtain.

PART I

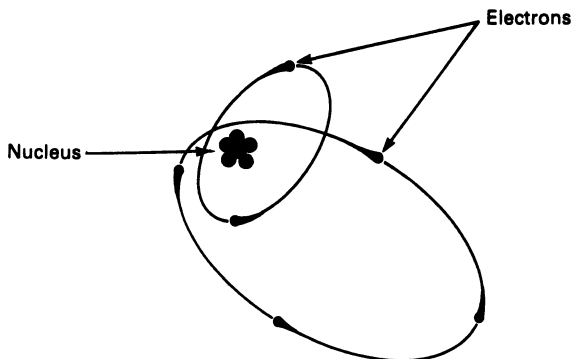
ELECTRICITY

ELECTRICITY

What is electricity? To begin to answer this question, we have to look at the composition of matter. All matter is made up of atoms, but it is far from simple to describe an individual atom. Atoms are of course far too small to be seen under the most powerful microscope, and we have to infer their construction from the way they behave and from the way they affect various forms of radiation beamed at them. Because nobody quite knows just what an atom really looks like, physicists construct *models* of atoms to help them explain and predict atomic behaviour.

One of the simplest and most straightforward models of the atom was proposed by Niels Bohr, a Danish physicist, in 1913. In Bohr's model of the atom it is assumed that tiny electrons move in orbit around a central, much more massive, nucleus. The electrons are confined to orbits at fixed distances from the nucleus, each orbit corresponding to a specific amount of energy carried by the electrons in it. If an electron gains or loses the right amount of energy, it can jump to the next orbit away from the nucleus, or towards it. A typical atom, drawn according to Bohr's theory, is shown in Figure 2.1. Electrons towards the outer edge of an atom are

fig 2.1 *a model atom, according to Bohr's theory*



held in orbit rather loosely compared with those towards the centre. Electrons in the outermost orbits can easily be detached from the atom, either by collision or by an electric field. Once detached, they are known as *free electrons*. All materials contain some free electrons.

Materials that are classed as *insulators* contain only a very few free electrons, while materials that are classed as *conductors* (notably the metals) contain large numbers of free electrons. These free electrons drift around in the material more or less at random. However, under certain circumstances the electrons can be made to flow in a uniform direction. When this happens, they become an *electric current*.

Let us look at one such example, that of a dry cell. A study of the workings of the cell is not part of a book on electronics, but details can be found in textbooks on electricity. The illustration in Figure 2.2 shows a much simplified diagram of a typical dry cell. For our purposes, the important thing is that the internal chemistry of this cell causes the outer casing of the battery to accumulate an excess of free electrons. The centre terminal, on the other hand, has almost no free electrons. If the casing and centre electrode of the battery are connected by a conducting wire—as shown in Figure 2.3—electrons will migrate from the casing to the centre electrode by flowing down the wire. This current flow is explained by the

fig 2.2 a single dry cell

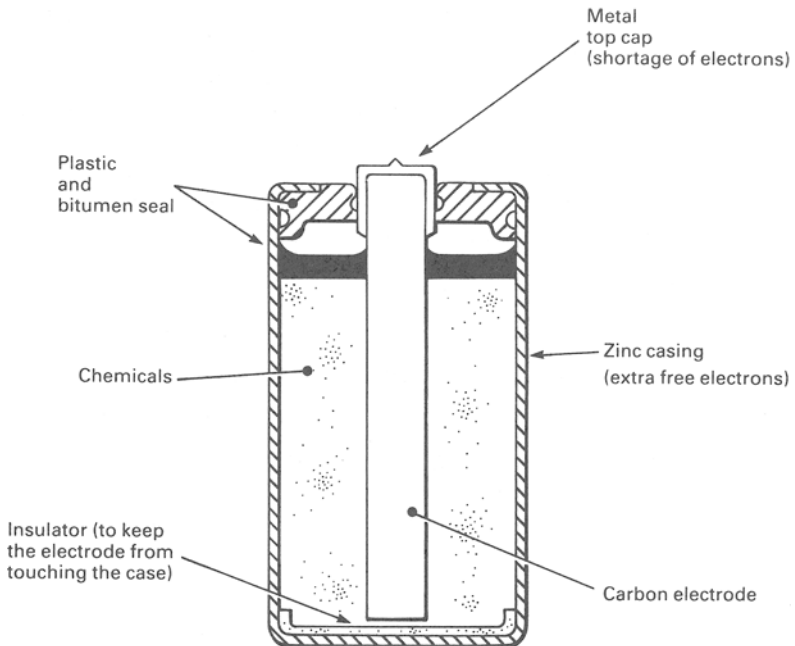
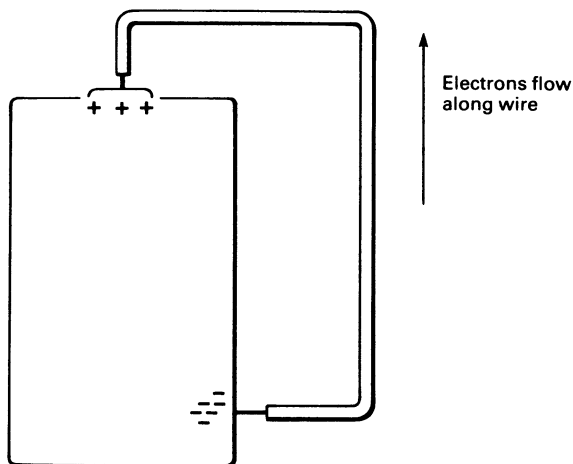
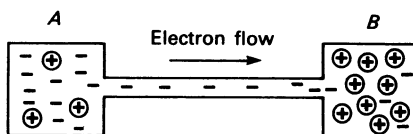


fig 2.3 *electrons flowing in a circuit*

fact that all electrons carry a single unit of negative electric charge. The electric charge is a form of energy, and may in some ways be regarded as analogous to magnetism. In the same way that similar poles of a magnet repel each other (north repels north, south repels south), so do electrons repel each other. In a normal atom the charges on the electrons are exactly balanced by positive charges on the nucleus. An atom in this state is said to be *neutral*. Free electrons are repelled by other free electrons, and, as you might expect, are attracted towards areas with a net positive charge. This is illustrated diagrammatically in Figure 2.4. Area *A* has a large number of free electrons, far more than are necessary to balance the positive charges on the nuclei of the atom. Area *B* has very few free electrons, and indeed a number of the atoms may be missing electrons from their outer orbits and may therefore exhibit a net positive charge. The electrons are repelled by the charge in area *A* and flow along the wire towards area *B*.

The above is something of a simplification, but illustrates the general principle.

fig 2.4 *electrons move from an area having net negative charge to an area with net positive charge*

2.1 UNITS OF ELECTRICITY

It is possible to count (indirectly) the number of electrons flowing along the wire. In order for there to be a useful current, a very large number of electrons must flow. Accordingly, the basic unit of electric current flow is equivalent to around 6.28×10^{18} electrons per second. This unit of electricity is called the *ampere*, after André Marie Ampère, a French physicist who did important pioneering work on electricity and electromagnetism. The ampere, often abbreviated to 'amp', is a practical unit of current for most purposes.

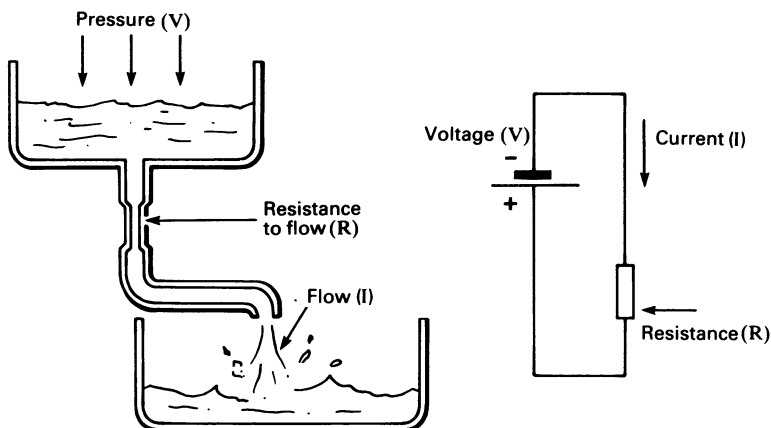
In addition to measuring the current flow, we also need to measure another factor, the *potential difference* between two points. The potential difference between two points is the energy difference between them. Look at Figure 2.4 again, and imagine that there is a much larger number of free electrons on side *A*. This would have the effect of increasing the amount of negative charge on *A* and increasing the amount of energy available to push the electrons along the wire. Similarly, if side *A* had only a very few more free electrons than side *B*, the energy available to push electrons along the wire would be much less. There is a parallel here between the potential difference and water pressure—in fact we can use a 'water analogy' to illustrate the way an electric circuit works. If current flow is the equivalent of a flow of water along a pipe, the potential difference is the amount of pressure available at the end of the pipe. But whereas we might measure pressure in terms of kilograms per square metre, potential difference is measured by a unit called the *volt*. The volt is named after Alessandro Volta, an Italian physicist who, like Ampère, pioneered work in electricity—he produced the first practical battery. As you might imagine from the water analogy, the current flow is affected by the potential difference. All else being equal, the higher the potential difference—or voltage—the greater will be the current flow.

There is one other factor that would affect the flow of water in the plumbing system: that is the size of the pipe. There is a corresponding factor in the electric circuit, and that is the *resistance* of the wire. Resistance is a property of all materials that reduces the flow of electricity through them. The higher the resistance, the more difficult it is for current to flow. The three factors affecting current flow are illustrated—with the water analogy—in Figure 2.5.

The relationship between current, potential difference and resistance was first discovered by Georg Simon Ohm in 1827. It is called *Ohm's Law* after him. Ohm's Law states that the current, *I*, flowing through an element in a circuit is directly proportional to the voltage drop, *V*, across it. Ohm's Law is usually written in the form:

$$V = IR$$

fig 2.5 a plumbing analogy: voltage, current and resistance all have their equivalents in the water system



The unit of resistance is called the *ohm*, for obvious reasons. From the formula above we can see that a potential difference of one volt causes a current of one ampere to flow through a wire having a resistance of one ohm. Given any two of the factors, we can find the other one. The formula can be rearranged as:

$$I = \frac{V}{R}$$

or

$$R = \frac{V}{I}$$

This simple formula is probably used more than any other calculation by electrical and electronics engineers. Given a voltage, it is possible to arrange for a specific current to flow through a wire by including a suitable resistor in the circuit. Similarly, it is possible to determine voltage and resistance, given the other two factors. For some applications in electrical engineering, and for many in electronic engineering, the ampere and volt are rather large units. The ohm, on the other hand, is a rather small unit of resistance. It is normal for these three units to be used in conjunction with the usual SI prefixes to make multiples and submultiples of the basic units. These are given in the chart in Figure 2.6. When using Ohm's Law in calculations, it is vital that you remember to work in the right units. You cannot mix volts, ohms and milliamps!

fig 2.6 *SI prefixes*

Prefix	Symbol	Meaning	Pronunciation
tera	<i>T</i>	$\times 10^{12}$	tare-ah
giga	<i>G</i>	$\times 10^9$	guy-ger
mega	<i>M</i>	$\times 1\,000\,000$	megger
kilo	<i>k</i>	$\times 1\,000$	keel-oh
milli	<i>m</i>	$\div 1\,000$	milly
micro	μ	$\div 1\,000\,000$	—
nano	<i>n</i>	$\div 10^9$	nar-no
pico	<i>p</i>	$\div 10^{12}$	peeko
femto	<i>f</i>	$\div 10^{15}$	femm-toe

2.2 DIRECT AND ALTERNATING CURRENT

So far we have been considering electric current that flows continuously in one direction through a circuit. However, in many applications we will encounter electric current that flows first in one direction and then in the reverse direction. Current that flows first one way and then the other is called *alternating current*, and a voltage source supplying such a current is called an *alternating voltage*. Alternating voltages and currents occur in various circuits, particularly in radio and audio, and in power supplies. Alternating current is used for all mains power supplies because a.c. permits the use of *transformers* to increase and decrease the voltage, so that the power can be transmitted from place to place using efficient high-voltage transmission lines.

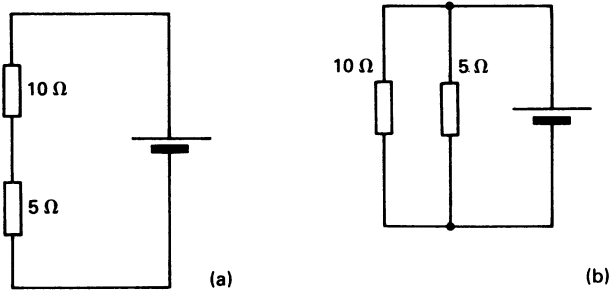
The rate at which the voltage reverses is the *frequency* of the alternation. One complete *cycle*, from one direction to the other, and back to the original direction, is the measure: one cycle per second is given a unit, the *hertz* (symbol Hz) after Heinrich Rudolf Hertz who first produced and detected radio waves. The hertz is equal to one cycle per second, and can be used with the usual SI prefixes; thus 1000 Hz is usually written as 1 kHz, etc.

2.3 RESISTORS IN SERIES AND PARALLEL

An electrical circuit that draws power from a source of electricity is known as a *load*. It is possible to connect two loads in an electrical circuit so that all the current flows through both of them. Equally, it is possible to connect them so that current flow is divided between them. The two possibilities are illustrated in Figure 2.7.

Figure 2.7a illustrates *series* connection. In this illustration the loads have a resistance of 10 Ω and 5 Ω respectively. To work out the combined resistance of the two loads, for use in calculations involving Ohm's Law, the two values can simply be added together. This is true of any number

fig 2.7 resistors in series (a) and parallel (b)



of resistive loads connected in series—just add the values together, making sure that all the resistances are expressed in the same units (once again, you cannot mix ohms and kilohms).

The second case, illustrated in Figure 2.7b, is less easy to calculate. The formula for working out combined parallel resistance is:

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots$$

R is the combined resistance, where R_1, R_2 , etc. are the individual parallel resistances. Working this out numerically for the example in Figure 2.7b, we get:

$$\frac{1}{R} = \frac{1}{10} + \frac{1}{5}$$

$$\frac{1}{R} = 0.1 + 0.2$$

$$\frac{1}{R} = 0.3$$

$$R = 3.333 \Omega$$

Thus the combined resistance is around 3.3Ω . It is important at this stage to consider what degree of accuracy is required. My calculator shows that the reciprocal of 0.3 is actually 3.33333333. This seems to be a very high degree of accuracy, but the accuracy is apparent rather than actual. We must consider how accurately the true values of the two resistive loads are known. In order for the calculator's answer to be realistic, we would need to know the resistance of the load to a far greater accuracy than could be measured without the most specialised equipment. We should also consider how accurately we *need* to know the answer. For most

purposes—and bearing in mind the very large number of variables that usually exist within any electric or electronic circuit—it is quite sufficient to say that the combined resistance is equal to approximately $3.3\ \Omega$.

In practice, quite complex combinations of series and parallel resistances may be met with. Figure 2.8 illustrates such an instance. The rule for dealing with part of a circuit like this, and arriving at the combined resistance of all the loads, is to work out any obvious parallel or series combinations first, and progressively simplify the circuit. There is an obvious parallel combination in this figure, so we can work out the combined resistance of the two $100\ \Omega$ and two $50\ \Omega$ resistors first. Using a calculation like the one above, we arrive at a total resistance of about $16.7\ \Omega$ for the parallel combination of the four resistors. Figure 2.8 has now become more simple—the simplified version is illustrated in Figure 2.9a.

fig 2.8 a complex series-parallel network

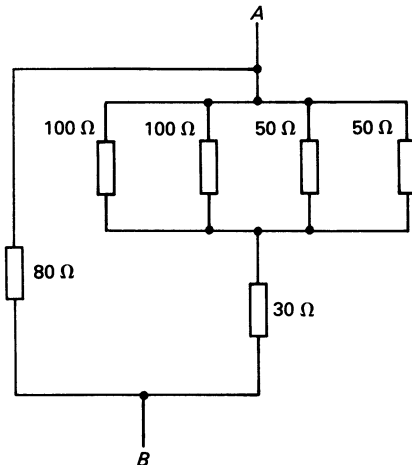
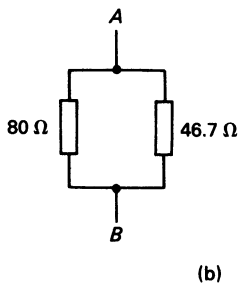
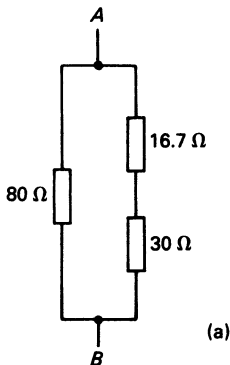


fig 2.9 progressive simplifications of figure 2.8



The series resistors, $16.7\ \Omega$ and $30\ \Omega$, can simply be added together to give a total of $46.7\ \Omega$. This leads us to Figure 2.9b, which is a simple parallel combination which can easily be worked out.

The total resistance between points *A* and *B* in Figure 2.8 is therefore $29.5\ \Omega$ —or, in the real world, about $30\ \Omega$.

Change some of the values in the example given in Figure 2.8 and work through the calculations yourself, to make sure that you are completely happy with these simple calculations. These simple calculations will in fact be a lot simpler if you use a pocket calculator—preferably one that can give you reciprocals. Calculators are inexpensive and any student of electronics should always keep one handy.

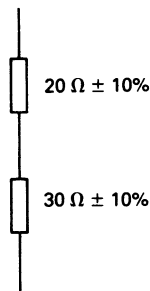
2.4 TOLERANCES AND PREFERRED VALUES

It should be clear that a load having a resistance of, say, $20\ \Omega$ is unlikely to have a value of *exactly* $20\ \Omega$ if you measure it accurately enough. Components having a specified resistance, such as *resistors* used in electronic circuits, may be marked with a specific value of resistance. But inevitably the components will vary slightly and not all resistors stamped ' $20\ \Omega$ ' will necessarily have a resistance of exactly this value. Manufacturing tolerances may be quite wide.

When designing circuits, it is important to bear in mind that components may not be exactly what they seem. As we saw above, this affects the calculations we make, and in any complex circuit we would have to specify circuit values of resistance, voltage and current in terms of a range of values. A resistor marked $20\ \Omega$ might, for example, have a resistance of $18\ \Omega$, or $22\ \Omega$. These two limits represent a departure from the marked value of around ± 10 per cent. This is in fact a typical manufacturing tolerance for resistors.

But let us look at the effect of two such resistors connected in a series circuit. Figure 2.10 shows this. We would expect, using simple addition,

fig 2.10 *the effect of tolerance in values*



that the combined resistance of these two resistors would be 50 Ω . We might base our circuit design on this, and might, for example, predict that this very simple ‘circuit’ would draw 100 mA from a 5 volt supply. However, let us consider two extremes. If *both* resistors happen to be at the limits of their tolerance range, then the combined resistance might be 55 Ω . Our circuit would be drawing only 90 mA. If the resistors happened to be at the low end of the tolerance range, then a combined value of 46 Ω could give us a 108 mA current drain from our 5 volt supply. According to the function of the circuit, this might or might not be important.

In some cases we need to be able to specify a resistor more accurately than ± 10 per cent. Manufacturers of these components therefore produce different ranges, according to the degree of tolerance permitted. The closer the tolerance, the more expensive the resistor, so it is commercially unwise to specify component accuracy greater than the circuit requires. Because of the manufacturing tolerance, and because of the impossibility of producing *all* possible values of resistor, manufacturers restrict themselves to an internationally standardised range of values. Figure 2.11 lists the available values. Intermediate values are not generally available, but can be made by combining preferred values. It is important to be cautious when doing this, and to bear in mind the tolerance range of the resistors you are using. There is little point, for example, in adding a 3.3 Ω resistor

fig 2.11 *preferred values of resistors*

E12 series	E24 series	
10	10	<u>Preferred values of resistance</u> E12 series is available in all types of resistor
	11	
12	12	
	13	E24 series is available in close-tolerance or high-stability only
15	15	
	16	
18	18	All values are obtainable in multiples or submultiples of 10, e.g. 2.2 Ω , 22 Ω , 220 Ω , 2.2 k Ω , 22 k Ω , 220 k Ω , 2.2 M Ω , 22 M Ω
	20	
22	22	
	24	
27	27	Resistance values less than 10 Ω and more than 10 M Ω are uncommon, and may not be available in all types of resistor
	30	
33	33	
	36	
39	39	
	43	
47	47	
	51	
56	56	
	62	
68	68	
	75	
82	82	
	91	

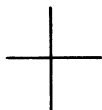
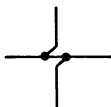
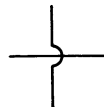
to a $47\ \Omega$ resistor in an attempt to produce something that is exactly $50\ \Omega$ if the tolerance of the combination is likely to be $\pm 5\ \Omega$. Manufacturers in general restrict themselves to three or four ranges of tolerances. Typically, small resistors would have a tolerance of ± 5 per cent, or in some cases ± 10 per cent. Close-tolerance components of $\pm 2\frac{1}{2}$ per cent or even ± 1 per cent are available, but expensive. Components made to this accuracy would normally be used only in accurate measuring equipment or in particularly critical parts of some circuits.

2.5 CIRCUIT DIAGRAMS

I have already used circuit diagrams, and it is usually fairly clear how circuit diagrams are laid out. You will see many in this book, and should get a good idea of the way circuit diagrams should be drawn. It is normal to produce diagrams with vertical and horizontal lines, and as few diagonal or angled lines as possible. It is usually convenient to lay the circuit out so that the potential difference in the circuit (or voltage) varies from the top to the bottom of the page: this means arranging the diagram with one power supply line at the top and the other at the bottom in most cases. Circuit symbols are used to represent different components and different types of components. We have already seen the circuit symbol for a resistor and the circuit symbol for a battery. Other component symbols will be dealt with in context, and explanations will be given where necessary. There are rules about lines in the diagrams crossing, and these must be obeyed rigidly if the diagram is not to be misinterpreted. Figure 2.12 shows some of the conventions. Figure 2.12a illustrates wires crossing, but not connecting. Figures 2.12b and 2.12c show wires that are connected—the little dot is used to indicate a connection.

Sometimes where wires are crossing but not connected the illustrator will use a 'bridge' to emphasise the fact that the wires are not connected. This is illustrated in Figure 2.12d; this particular convention is now disappearing. Figure 2.12e illustrates something which should *never* appear in circuit diagrams. In all cases where wires are crossing and connected the illustration in Figure 2.12c should be used. The reason for this is that, if the circuit diagram is printed, the point where the wires cross may 'fill in' in the printing or photocopying process and make it appear that they should be connected when in fact the circuit designer intended that they should not. As you work through this book you should look at the way the circuit diagrams are laid out, and try to draw neat, *clear* diagrams yourself. Often, this may mean redrawing—but it is worth the trouble.

In the next chapter we will be looking at further 'passive' components. We have already considered resistors, but we shall look at them in more

fig 2.12 *circuit diagrams*(a) *wires crossing but not connected*(b) *wires joined*(c) *wires crossing and connected*(d) *a non-preferred convention for wires crossing but not connected*

No!

(e) *something that should not appear on any circuit diagram*

detail—and in the context of the way they are used in circuits. We shall also look at the other two main classes of passive components, *capacitors* and *inductors*.

QUESTIONS FOR CHAPTERS 1 AND 2

1. Describe the difference between *linear* and *digital* electronic systems.
2. What is the unit of electric current? What is the unit of electrical potential?
3. Calculate the value of the combined value of the following resistors connected in series: $33\text{ k}\Omega$, $18\text{ k}\Omega$, $4.7\text{ k}\Omega$. If a battery supplies a current of $215\text{ }\mu\text{A}$ through the resistors when they are connected to it, what is the battery's voltage?
4. What is the combined resistance of the following resistors connected in parallel: $220\text{ }\Omega$, $100\text{ }\Omega$, $470\text{ }\Omega$?
5. A $10\text{ k}\Omega$ and a $5.6\text{ k}\Omega$ resistor are connected in series. If both resistors have a manufacturing tolerance of ± 10 per cent, what, approximately, are the maximum and minimum values of resistance we would expect to measure across the combination?

PASSIVE COMPONENTS AND POWER SUPPLIES

The components used in electronic circuits are divided into two main classes. These are referred to as 'active' and 'passive' components. Active components use the movement of electrons either through a vacuum or through a semiconductor to perform some function in the circuit. Passive devices, on the other hand, do not control the movements of the electrons, but rather allow the electrons to flow through them. It could be argued that the simplest of all passive devices is a length of wire!

3.1 RESISTORS

Resistors are components intended to insert a known amount of resistance into an electrical circuit. As we saw in the last chapter, they are available in a range of different values and tolerances. It will also be evident to anyone who has looked at an electronic circuit that they are also available in a range of *sizes*. The sizes relate to the amount of power that the resistor can dissipate. An electric current passing through a resistor will always cause a certain amount of energy to be dissipated as heat. The amount of energy dissipated can be calculated by the simple formula:

$$P = VI \text{ watts}$$

where P represents power.

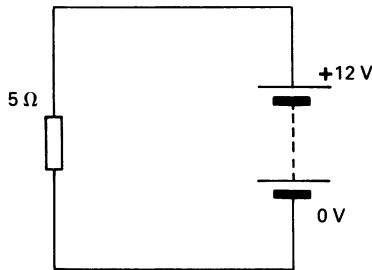
Let us consider the case of a $5\ \Omega$ resistor connected across a 12 volt battery. This is illustrated in Figure 3.1. We can use Ohm's Law to calculate the amount of current flowing through the resistor. This is given as:

$$I = \frac{V}{R}$$

$$I = \frac{12}{5}$$

$$I = 2.4\ \text{A}$$

fig 3.1 *power: a simple circuit like this will dissipate heat*



It is clear that the voltage, when measured across the resistor, must be equal to the battery voltage, provided we neglect any resistance in the wires. We can now use the formula to calculate the amount of power that the resistor is dissipating as heat:

$$\begin{aligned} P &= VI \\ P &= 12 \times 2.4 \\ P &= 28.8 \text{ watts} \end{aligned}$$

28.8 watts is a respectable amount of heat—the above calculation might be made for a car’s rear-window heating element. It is quite obvious that a tiny component such as a resistor one might find in an electronic circuit could not possibly dissipate this much heat without damaging itself. In fact, a resistor designed to dissipate around 30 watts would be quite large—perhaps 5 cm long. It would also be made in such a way that the body of the resistor could become quite hot. In practice, the designers of most electronic circuits try to avoid such large heat outputs which can cause problems in cooling the equipment.

Resistors used in electronic circuits are designed with power dissipations of 0.25, 0.5 or 1 watt. Larger sizes are available, but are less commonly used.

The same formula as the one above is used to calculate the power dissipation of series and parallel combinations. Figure 3.2 shows such circuits. Figure 3.2a illustrates two resistors connected in series. It is quite clear that the same current flows through both resistors. However, when measured across each resistor, the voltage will be different. The total potential difference is given as 5 volts. We can find the voltage across each individual resistor by using Ohm’s Law. We know that the total resistance of the circuit is 3.2 k Ω and can use Ohm’s Law to calculate that the current flowing through the circuit is about 1.562 mA. Using the form of Ohm’s

Law $V = IR$, we can calculate the voltage drop across each resistor. For the first resistor:

$$V = 1000 \times 1.562 \text{ mV}$$

$$V = 1.562$$

And for the other resistor:

$$V = 2200 \times 1.562$$

$$V = 3.44$$

Now that we know the voltage dropped across each resistor we can calculate the amount of power that each resistor is dissipating. For the $1 \text{ k}\Omega$ resistor this is:

$$P = 1.562 \times 1.562$$

$$P = 2.43 \text{ mW}$$

And for the $2.2 \text{ k}\Omega$ resistor the power dissipated is given as:

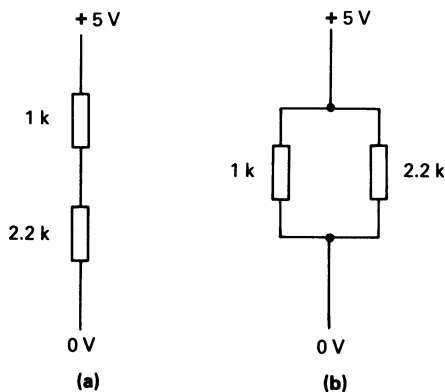
$$P = 1.562 \times 3.44$$

$$P = 5.37 \text{ mW}$$

Look carefully at the units used in these calculations! The amounts of power dissipated are very small, typical, in fact, of the sort of thing we will become used to in electronic circuits. The smallest commonly available size of resistor (0.125 watts) is substantially larger than is necessary to dissipate this amount of power.

Exactly the same kind of calculation is used to work out the power dissipations in resistors in parallel. In this case—illustrated in Figure 3.2b—the voltage across both resistors is the same (5 V), but the current is different. We can use Ohm's law to ascertain the current flowing through

fig 3.2 *resistors in series and in parallel*



each resistor, and arrive at 5 mA and 2.27 mA for the 1 k Ω and 2.2 k Ω resistors respectively. We can now use our power calculation to determine that the 1 k Ω resistor is dissipating $5 \times 5 = 25$ mW. The 2.2 k Ω resistor is dissipating $2.27 \times 5 = 11.35$ mW. If you are in any doubt about this calculation, work it out on a piece of paper. Another, equally valid way of working out power dissipations in series or parallel combinations of two resistors is to calculate the total dissipation of the pair (very simply done) and then use a ratio calculation to determine how much power is dissipated by which resistor. Note that in *series* combinations it is always the resistor with the *higher* value that dissipates the most power. In *parallel* combinations, it is the resistor with the lower resistance that dissipates more power.

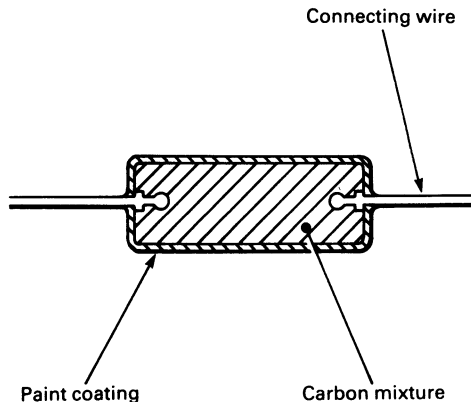
Before leaving resistors, we should look at the physical structure of the three main types of resistor. These are all electrically comparable—there is only one kind of resistance—but they are mechanically different, being suitable for slightly different applications.

Types of resistor

The most usual type of resistor is the solid carbon resistor (see Figure 3.3). Its structure is very simple, consisting of a small cylinder of carbon which is mixed with a non-conductor. A connecting wire is fixed into each end, and the resistor is given a coat of paint to protect it from moisture which might alter the resistance.

Resistors are always marked with a *colour code* to indicate the value. The colour code consists of three or four coloured bands painted round the resistor body. This system is used because it makes the resistor's value

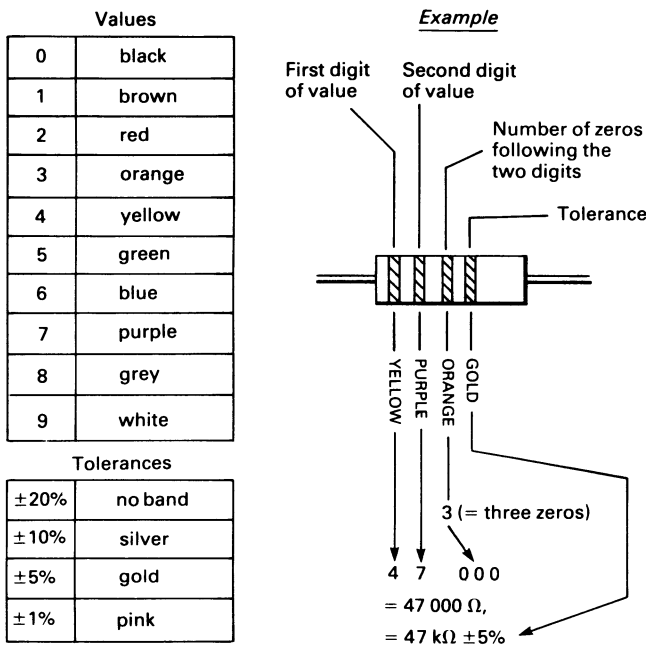
fig 3.3 *a solid carbon resistor (this component might be anything from a few millimetres to a few tens of millimetres long)*



visible from any direction—a printed label could be hard to read with the component in place on a crowded board. Also, a painted or printed value could easily get rubbed off, whereas painted-bands are relatively permanent.

The first three bands of the colour code represent the value of the resistor in ohms. Bands 1 and 2 are the two digits of the value, and band 3 represents the number of zeros following the first two digits. Figure 3.4 gives the resistor colour code; the standard is international. The fourth band is used to indicate the tolerance of the resistor's stated value.

fig 3.4 the international standard resistor colour code

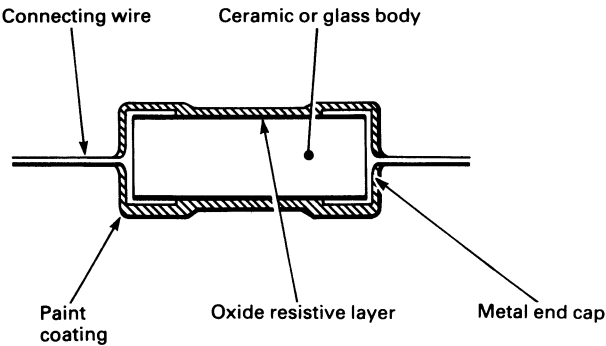


Where values of resistance less than two digits are required, the two bands are followed by a gold band. Thus $4.7\,\Omega$ would be represented as yellow, purple, gold, plus a tolerance band.

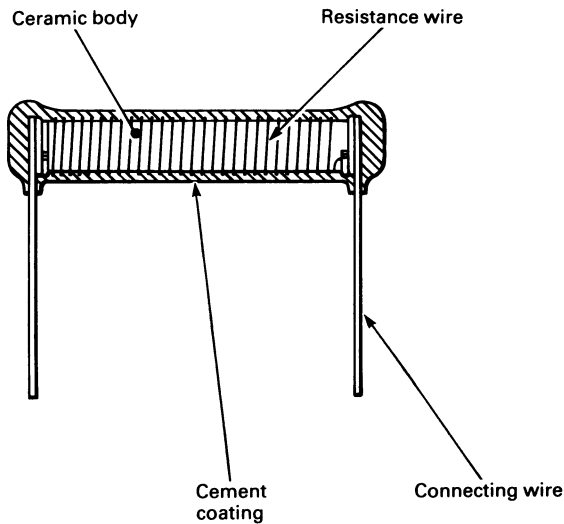
The next kind of resistor is the *metal oxide* or *metal glaze* resistor. This looks rather like the carbon resistor from the outside, but the internal structure is different. Figure 3.5a shows a cross-section.

Metal oxide resistors can be made to closer tolerances than carbon resistors, and change their resistance less with changes in temperature. For this reason they are sometimes called *high-stability* resistors. The resistance of a metal oxide resistor changes by approximately 250 parts per million

fig 3.5



(a) a metal oxide resistor



(b) for high power applications, a wire-wound resistor is used

per °C. This compares with about 1200 parts per million per °C for carbon resistors.

Both carbon and metal oxide resistors are made in a range of stock sizes, from about 0.125 W dissipation to about 3 W. Sometimes it is necessary to have resistors that can cope with higher powers; for this, *wire-wound* resistors are used. The wire-wound resistor is shown in Figure 3.5b.

It is easy to make wire-wound resistors in low resistance values, down to fractions of an ohm. High resistance values use wire of low conductivity,

requiring many turns of fine gauge wire as well. The maximum practical value for a wire-wound resistor is a few tens of kilohms, at least for components that are a reasonable size. Power ratings range from 1–50 W in the stock sizes; there is no limit to the size in practice, and larger special-purpose wire-wound resistors are common.

It is possible to make *precision wire-wound resistors* in which the resistance is specified to a very close tolerance, within ± 0.1 per cent. Such resistors are expensive and would be used only in measuring equipment.

Variable resistors

For applications such as volume controls and other ‘user controls’ in electronic equipment, it is often necessary to have a resistor that can be altered in resistance by means of a control knob. Such resistors are called *variable resistors*, or *potentiometers*. They consist of a resistive *track*, made with a connection at either end. A movable *brush*, generally made of a non-corroding metal, can be moved along the track; an electrical connection to the brush allows a variable resistance to be obtained between either end of the track and the brush.

Three forms of variable resistor are shown in Figure 3.6b. Note that the shaft (or slot) that moves the brush is generally connected to the brush; it is important to know this for safety reasons.

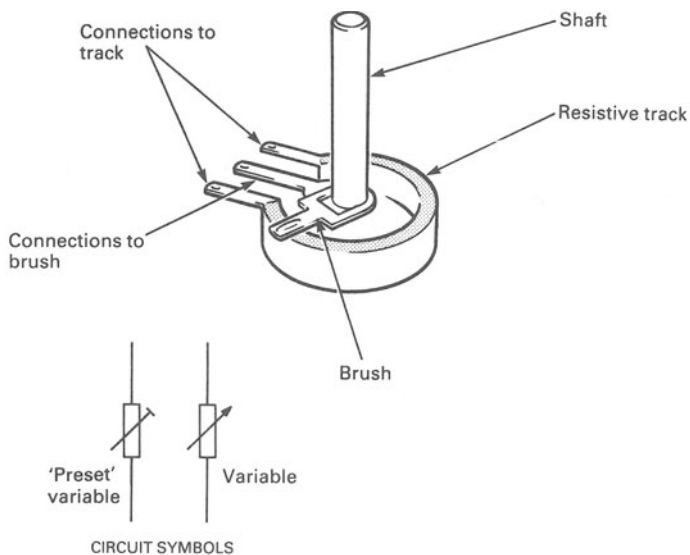
Variable resistors are available in various shapes and sizes, with power dissipations from around 0.25 W upwards. Tracks are either carbon, conductive ceramic (‘cermet’) or wire-wound. Resistance ranges are available between fractions of an ohm and a few megohms.

The track can be made in such a way that the resistance increases smoothly along the track—the usual, *linear*, type of potentiometer. For some audio uses (such as volume controls) *logarithmic* potentiometers are made in which the resistance increases according to a logarithmic law rather than a linear law. For most purposes you need only remember that the way logarithmic potentiometers control volume approximates the way the human ear responds to sounds of different loudness. If you use a linear potentiometer for a volume control, the effect of the control seems to be ‘all at one end’ of the scale.

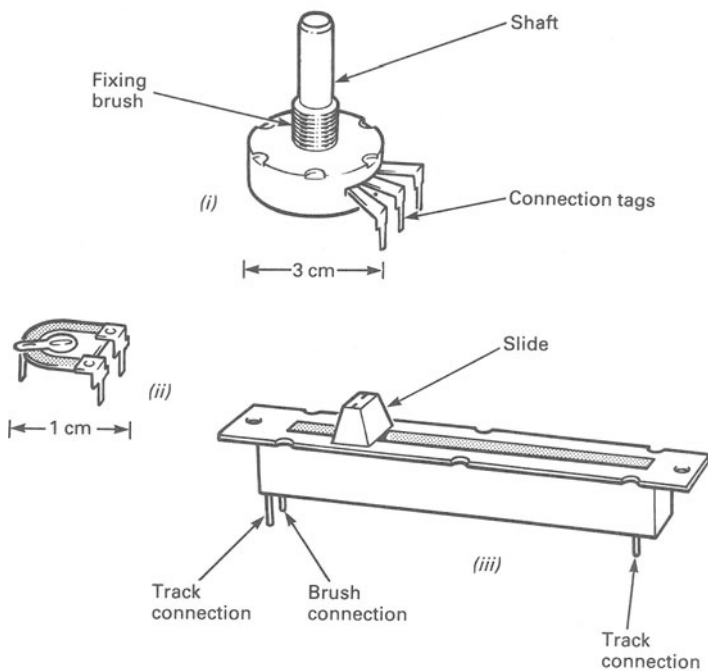
3.2 CAPACITORS

Next to resistors, the most commonly encountered component is the *capacitor*. A capacitor is a component that can store electric charge. In essence, it consists of two flat parallel plates, very close to each other, but separated by an insulator (see Figure 3.7).

When the capacitor is connected to a voltage supply, a current will flow through the circuit (see Figure 3.8). Electrons are stored in one of the



(a) *principle of the potentiometer or variable resistor*



(b) *three different types of potentiometer*

fig 3.7 *schematic view of a capacitor*

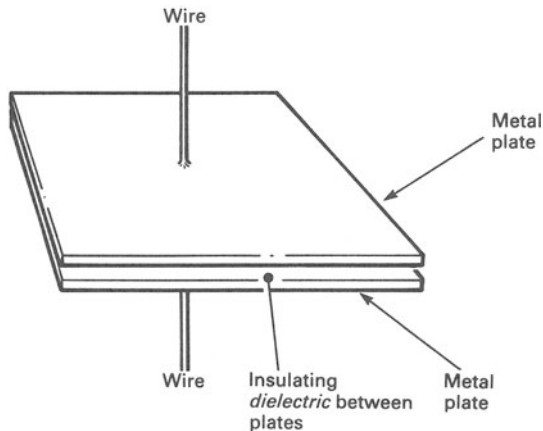
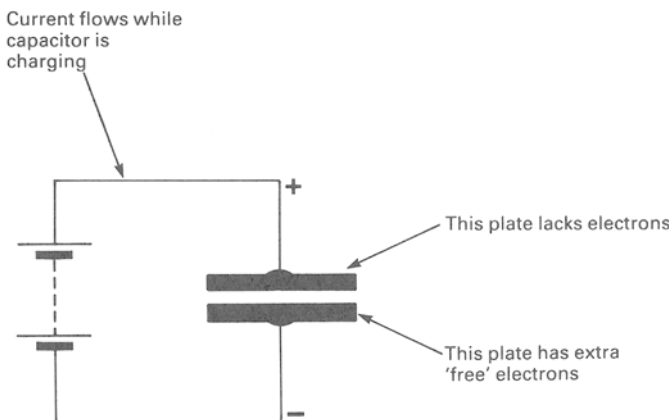


fig 3.8 *a capacitor connected to a power supply; current will flow until the capacitor is charged*



plates of the capacitor; in the other there is a shortage of electrons. In this state the capacitor is said to be *charged*, and if it is disconnected from the supply, the imbalance in potential between the two plates will remain.

If the charged capacitor is connected in a circuit, it will, for a short time, act as a voltage source, just like a battery. This can be demonstrated quite nicely with nothing more than a large capacitor, a 9 V battery such as PP9, and a capacitor rated at 10 V, 1000 μF (see below regarding *units of capacitance*). Note that the capacitor will be an *electrolytic* type (again, see below) and must be connected to the battery with its + terminal

towards the positive (+) terminal of the battery. The demonstration is shown in Figure 3.9.

Try the experiment again, this time allowing two minutes between charging the capacitor and discharging it into the bulb. Try waiting progressively longer, and you will see that the charge gradually leaks away on its own. This is due to the imperfection of the insulator separating the plates, allowing a tiny *leakage current* to flow.

A graph of the current flowing through a charging and then discharging capacitor is compared with the voltage measured across it in Figure 3.10.

The unit of capacitance is the *farad*, named after Faraday. One farad is a very large unit of capacitance, in the context of electronic circuits, and the smaller derived units of capacitance are used. The largest practical unit is the *microfarad*, symbol μF . Although values of capacitance in the range

fig 3.9 a simple experiment for demonstrating the way in which capacitors can store power; a large capacitor is first charged up from a 9 volt supply, and then discharged into a small lamp

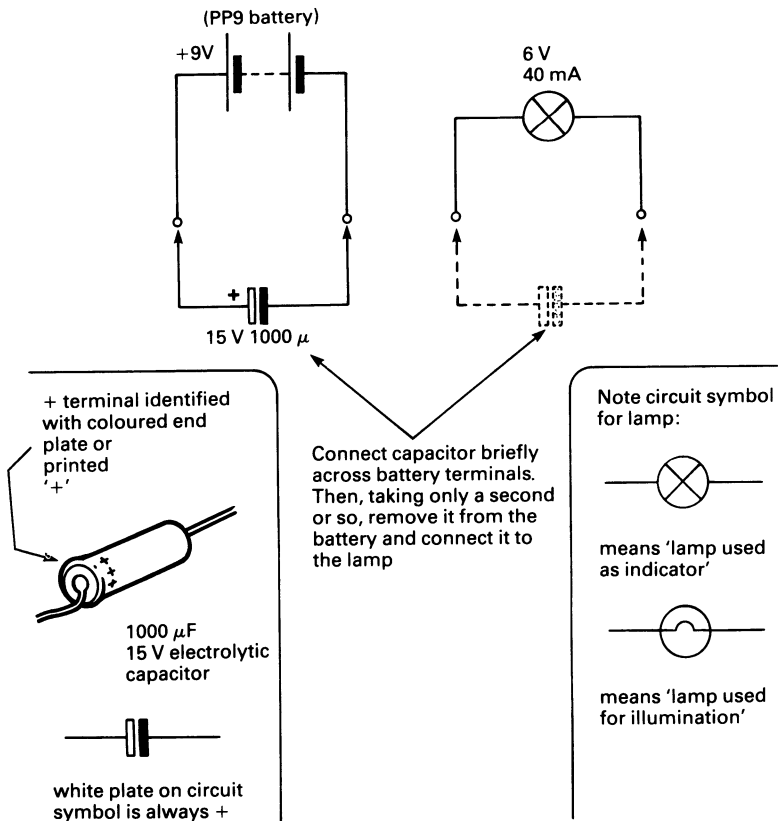
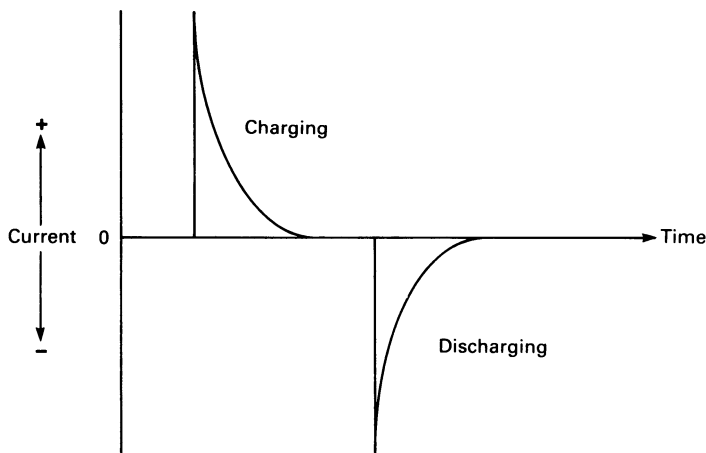


fig 3.10 a graph showing a capacitor charging and discharging



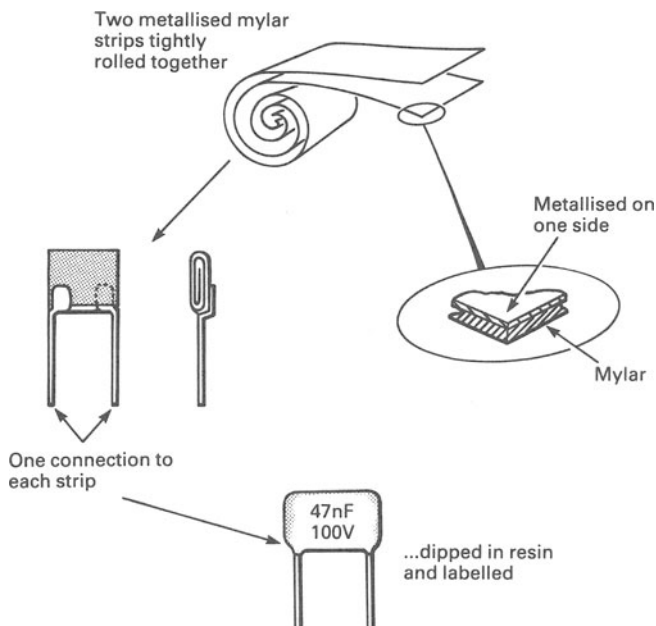
of thousands of microfarad are sometimes used, the millifarad is never encountered—a capacitor would be marked $10\,000\,\mu\text{F}$, for example, not 10mF . If you do see a capacitor marked ‘mF’, it is almost certainly meant to be μF , with that manufacturer (Far Eastern?) using a non-standard abbreviation. In addition to the μF , the nF and the pF are commonly used units.

There are many different types of capacitors, according to the use to which the component is to be put, and also to the operating conditions. The capacitance of the component is determined by three factors: the area of the plates, the separation of the plates, and the insulating material that separates them, known as the *dielectric*. For the same dielectric material, the closer and larger the plates, the greater the capacitance. Another factor determines the thickness of the dielectric, and that is the maximum voltage to which it is going to be subjected. If the dielectric is very thin, it will *break down* with a relatively low voltage applied to the plates of the capacitor. Once the dielectric has been damaged, the capacitor is useless. High voltage capacitors need thicker dielectrics, to withstand the higher voltage. To produce the same capacitance, the plates have to be larger in area—so the component is bigger.

The simplest type of capacitor uses a roll of very thin aluminium foil, interleaved with a very thin plastic dielectric such as *mylar*. A physically smaller capacitor can be made by actually plating the aluminium on to one side of the mylar (see Figure 3.11). For higher voltages, *polyester*, *polystyrene* or *polycarbonate* plastic material is used as the dielectric.

Ceramic capacitors are used where small values of capacitance and large values of leakage current are acceptable—the ceramic capacitor is inexpen-

fig 3.11 *a typical capacitor, used in electronics work—the 'metallised film' type*



sive. A thin ceramic dielectric is metallised on each side, and coated with a thick protective layer, usually applied by dipping the component.

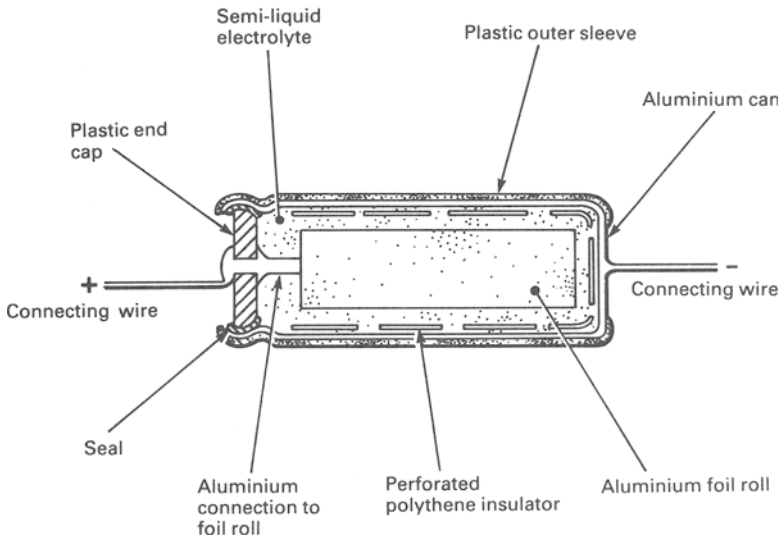
Both plastic film and ceramic capacitors are available in the range 10pF – $1\text{ }\mu\text{F}$, though plastic film types may be obtained in larger values.

Where really high values of capacitance are needed, *electrolytic capacitors* are used. Electrolytic capacitors give very large values of capacitance in a small component, at the expense of a wide tolerance in the marked value (-25 to $+50$ per cent) and the necessity for connecting the capacitor so that one terminal is always positive.

The most commonly used type of electrolytic capacitor is the *aluminium electrolytic capacitor*. The construction is given in Figure 3.12. After manufacture, the capacitor is connected to a controlled current source which electrochemically deposits a layer of aluminium oxide on the surface of the 'positive' plate. The aluminium oxide makes an excellent dielectric, with very good dielectric strength (resistance to voltage applied across the plates). Since the layer is chemically deposited it is very thin.

The electrolytic capacitor must not be subjected to voltages applied in the wrong direction, or the aluminium oxide layer will be moved off the positive plate, and back into the electrolyte again.

fig 3.12 *construction of an aluminium electrolytic capacitor*



Variable capacitors

Capacitors are made that can be varied in value. Either air or thin mica sheets are used as the dielectric, so the capacitance of variable capacitors is usually low. *Rotary* or *compression* types are made. In the former, the capacitance is altered by changing the amount of overlap of the two sets of plates; see Figure 3.13a. In compression trimmers, the spacing between plates is altered, as in Figure 3.13b.

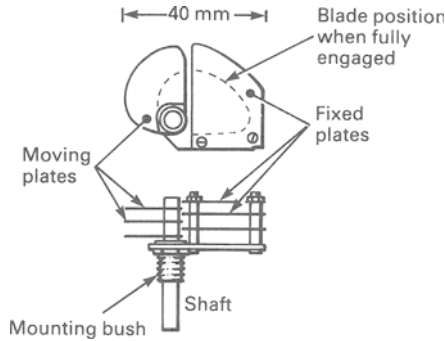
Variable capacitors can be obtained with maximum values from 2 pF to 500 pF.

Capacitors as frequency-sensitive resistors

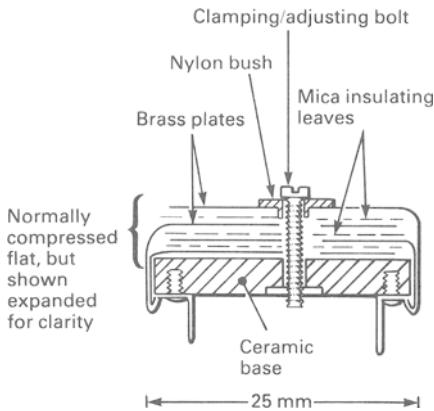
Once a capacitor has charged up, it will not pass current when connected to a direct voltage supply. However, if we *reverse* the polarity of the supply, the capacitor will permit a current to flow until it has charged up again, with the opposite plates positive and negative. The capacitor will then, once again, block the flow of current. If the frequency of an alternating voltage applied to a capacitor is high enough, the capacitor will actually behave as if it were a low value resistor, as it will never become charged in either direction. At lower frequencies, the capacitor will appear to have a higher resistance, and at zero frequency (d.c.) it will, as we have seen, have an infinitely high resistance if you disregard the leakage current.

The precise value of resistance shown by the capacitor will depend upon the capacitance, the applied voltage and the frequency. The property

fig 3.13



(a) *a variable capacitor of the 'air space' type (this component would be used for tuning a radio receiver, for example)*



(b) *a 'compression trimmer', a form of variable capacitor used to preset circuit values (adjustment is by means of a screw)*

is known as *reactance*. It enables the circuit designer to use the capacitor to block or accept different frequencies in a variety of different circuit configurations, many of which you will meet later in this book.

Capacitors in series and parallel

Capacitors can be used in series and in parallel. When used in series, the working voltage is the sum of the two working voltages, so two capacitors intended for a 10 V maximum supply voltage could be used, in series, with a 20 V supply.

The calculation of capacitor values in series and parallel is similar to the

calculation used for resistors in series and parallel, but in the opposite case. Thus for capacitors in *parallel* the formula:

$$C = C_1 + C_2 + C_3 + \dots$$

is used, simply adding the values together. For capacitors in *series*:

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \dots$$

gives the total value of capacitance.

Unfortunately, there is no internationally agreed colour code for capacitors, so manufacturers usually stamp the value on a capacitor, using figures in the normal way. A few capacitors are marked with coloured bands, but it is wise to look at the maker's catalogue to check what the code means.

3.3 INDUCTORS

The third major passive component is the inductor. This is a coil of insulated wire that may, or may not, be wound over a ferrous metal former. When a coil is connected in a circuit, as in Figure 3.14, the flow of current through the coil causes an electromagnetic field to be created around the coil. Building the field absorbs energy, and the electromagnetism produces its own current in the coil, opposing the direction of the applied current. The effect is that, when current is first applied to the inductor, it seems to have a high resistance, reducing the current flow through it. Once the electromagnetic field is established, the resistance drops. A graph of the current flowing through an inductor, and the voltage measured across it, is given in Figure 3.15.

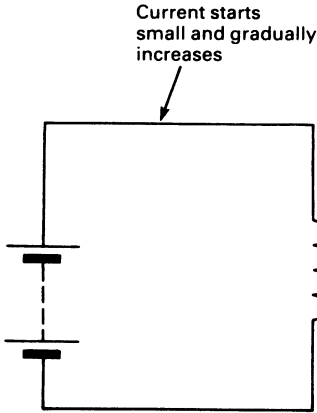
Compare this graph with the one in Figure 3.10, and you will see that the inductor is the 'opposite' of a capacitor! Once the current flowing through the inductor is constant, the only opposition to current flow comes from the resistance of the coil wire—usually small compared with the apparent resistance (called inductive *reactance*) when the current is building up.

The opposing force that prevents current flowing right away is *induced current*, trying to flow the opposite way. We can make great use of this phenomenon in constructing a *transformer*.

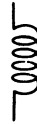
The unit of inductance is the *henry*, symbol H. In electronics, mH and μH are commonly found, but the henry, like the farad, is rather a large unit.

Inductors are available as a range of components, in small inductance values from a few μH to a few mH. However, there are so many variable

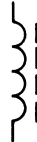
fig 3.14 *an inductor connected in a simple circuit; the current rises to a fixed level, determined by the resistance of the inductor's windings*



Note: the circuit symbol



is sometimes used, but it is non-standard. A dotted line may be added to denote a ferrite core:



or a double solid line to denote a laminated core:



But conventions vary!

factors that a 'stock range' of all required types would be too large for a supplier to produce. Where inductors are needed (and they are relatively rare in modern circuits) they may well be specified in terms of wire thickness, number of turns, core type, etc.

The unit used to measure inductance is the *henry*, symbol H. The henry is a descriptive unit, and is the potential difference generated across an inductor when the current flowing through it is changing at the rate of one ampere per second.

3.4 TRANSFORMERS

Transformers make use of *mutual inductance*, in which a current flowing in a coil produces an electromagnetic field, which in turn induces a current to flow in a second coil wound over the first one.

The construction of a transformer is shown in Figure 3.16. The iron

fig 3.15 *graphs showing voltage and current in the circuit of Figure 3.14*

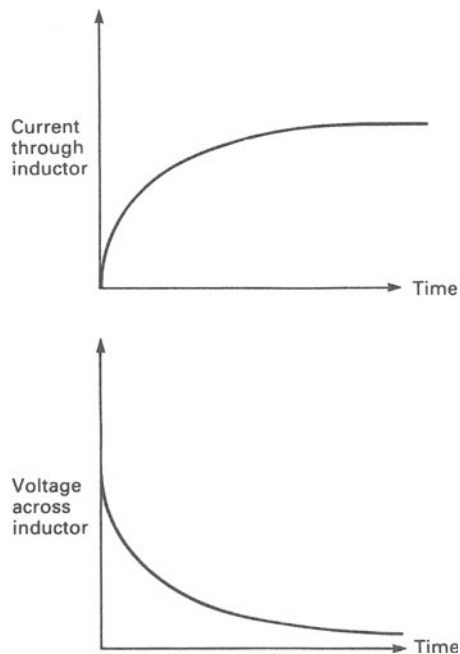
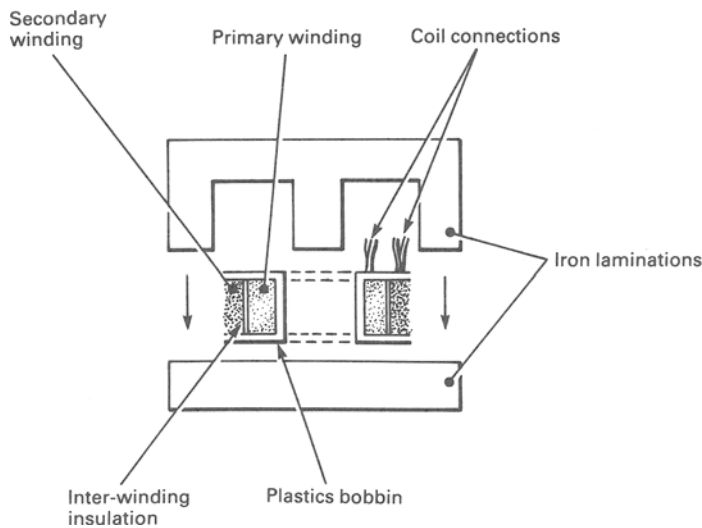


fig 3.16 *a typical small transformer, showing the iron laminations*



laminated core is used to concentrate the electromagnetism and thus improve the efficiency. It is important that the iron laminations are insulated from each other; if they are not, the core itself will behave as if it were a one-turn coil, and a current will be induced in it. The current would be very large, and cause the transformer to overheat.

The ratio of the *input voltage* to the primary winding to the *output voltage* from the secondary winding depends on the turns ratio of the coils, and is approximately equal to that ratio. Thus a transformer with 2000 turns on the primary and 1000 turns on the secondary will have an output voltage that is half the input voltage.

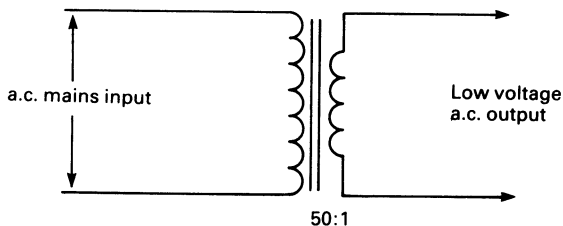
Since currents are induced only by *changing* magnetic fields, the transformer will operate only if the input voltage is constantly changing. The transformer could be used with alternating current (such as the mains supply), and one of the main uses for a transformer in electronics is to reduce the voltage of the a.c. mains to a lower level, suitable for electronic circuits. This is illustrated in Figure 3.17.

Transformers are rated according to the turns ratio, the power handling capability (in watts), and the type of application. *Power transformers*, intended for power supplies, usually have mains voltage primaries, and a high standard of insulation between the primary and secondary coils, for safety.

The secondary winding may have a range of connections, or *taps*, so the transformer can be used in different applications. It is important to realise that the transformer simply transforms voltages; there is no net power gain, always a small loss. If a transformer has a 200 V primary and a 1000 V secondary, the voltage will be increased by a factor of five times, but it will require more than five times the current in the primary than will be available from the secondary. You can trade current for voltage and vice versa, but the *power* will always be slightly less at the output, due to various losses in the transformer (dissipated, as usual, in the form of heat).

Any component having a coil carrying current will have an inductive characteristic, though it may be swamped by other factors (resistance or capacitance). This may sometimes be important. For example, a *relay* is

fig 3.17 circuit symbol for a transformer with a laminated core



an electromagnetic switch, the coil being used to operate a mechanical switch. However, the coil has inductance. A relay operating from a 6 V supply can, when suddenly disconnected, produce an output pulse of 100 V or more as the current flowing through it drops very rapidly to zero. This voltage may be high enough to harm semiconductor components, and precautions should be taken to ensure that this 'spike' of high voltage is made harmless.

3.5 POWER SUPPLIES

I am going to introduce, prematurely, a semiconductor component that is described fully in Chapter 7. This is the *diode*, a sort of electronic one-way street that will let current pass through it in one direction but not in the other direction.

Diodes are used in power supply circuits, in association with transformers. A transformer is used to reduce the voltage of the a.c. mains to something more usable in electronic circuits, say 10 V in this case. However, the output is still a.c., and most electronic circuits require a direct current supply. The transformer's output can be converted, or *rectified*, by one or more diodes. Figure 3.18 shows a transformer operating a circuit with a bulb. The waveform of the voltage across the bulb is shown also.

Now compare the waveform with the one in Figure 3.19. The diode has blocked current flowing in one direction, so the top connection of the bulb is always positive. Only half the power reaches the bulb, so this is not a very efficient design. If four diodes are used, in a configuration called a *bridge rectifier*, the whole of the current available from the transformer can be passed through the bulb. Follow the current path through Figure 3.20, first for one direction of output from the secondary, and then from the other.

fig 3.18 waveforms at the input and output of a transformer driving a lamp

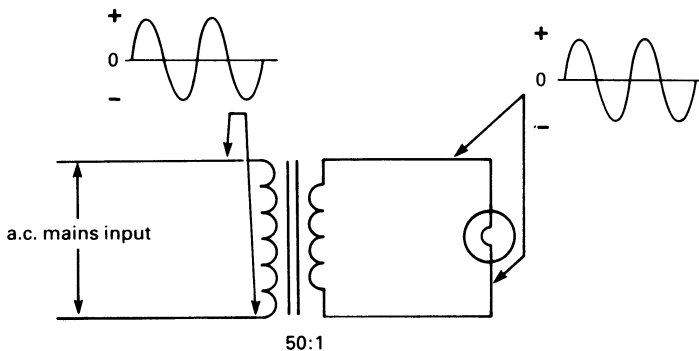


fig 3.19 *waveforms for half-wave rectified direct current, supplied by the secondary of the transformer, through a diode*

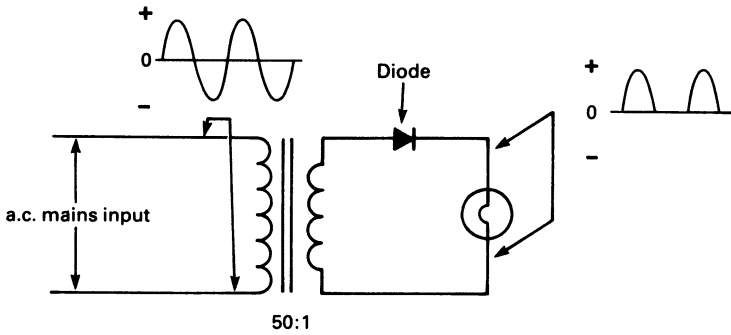
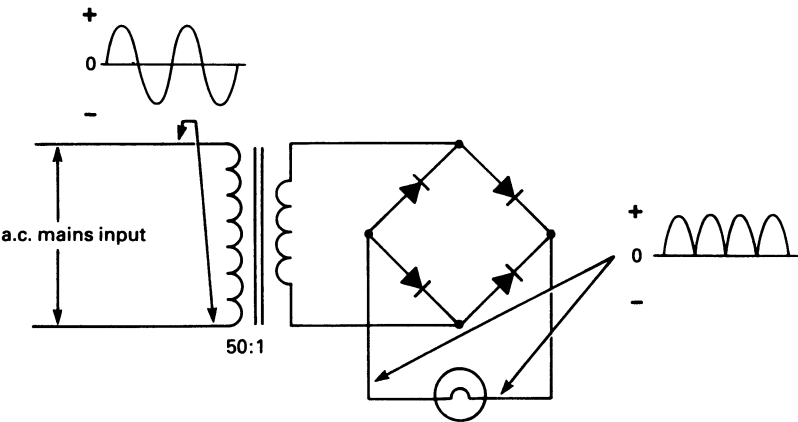
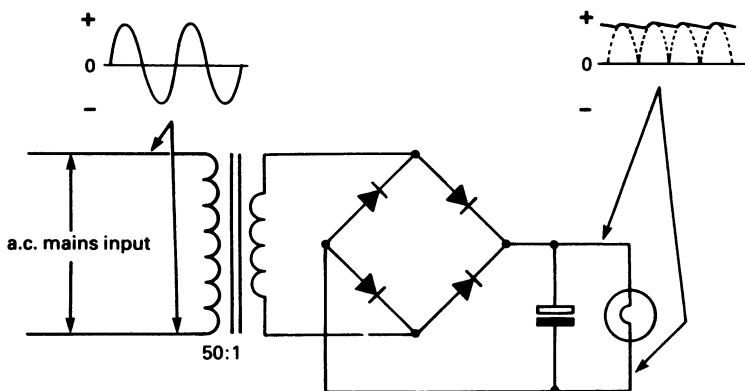


fig 3.20 *the diode 'bridge rectifier' configuration, used to provide full-wave rectification of an a.c. supply (although both halves of the a.c. input waveform pass through the lamp, the current flow through the lamp is not smooth—and this would upset the operation of many circuits)*



The supply to the bulb is now d.c., but constantly changing in voltage. The voltage supplied to the bulb (or any other circuit) can be *smoothed* by means of a large-value capacitor connected in parallel with the load (the bulb in this case). The effect of the capacitor is to supply the required current when the voltage drops during each half-cycle of the mains supply. When the voltage rises, the capacitor is recharged, so that it has energy available to fill in the 'gaps' in the supply. Figure 3.21 illustrates this.

fig 3.21 *the bridge rectifier with smoothing capacitor; a large capacitor is used to provide power during the 'gaps' in the rectified waveform*



This circuit is the basis of almost all power supply systems used in electronic circuits. Although much more sophisticated 'regulated' power supplies are often used—as you will discover when you get to Chapter 20—the transformer, bridge rectifier and smoothing capacitor feature in all the designs.

Before leaving the subject of diodes and circuits, I will use this opportunity to mention an important fact that electronics engineers, secretly, are a little ashamed of.

The current flowing through the power supply circuits above is flowing in the direction of the arrowhead of the diode symbol. The arrowhead to indicate current flow occurs over and over again in circuit diagrams. Current, we say, always flows from positive to negative.

Actually, it doesn't.

Electrons move the other way, from negative to positive, opposite to what has been called 'conventional current'. This is an odd fact, but one that only rarely complicates circuit design and analysis. The reason for it, frankly, is a Mistake. When the study of electricity was in its infancy, there was a need to standardise (in books and notes) on the direction of current flow. In the absence of our knowledge of electrons and atoms, someone sat down to perform an experiment that would settle the problem of current flow once and for all. It might even have been Volta, or Faraday, I can't remember. The experiment consisted of setting up equipment that would make a very long electric spark, and then repeatedly watching the spark. Eventually the experimenter made up his mind that the spark always jumped from *here* to *here*. It was at this point that the Mistake was made.

When, years later, it was discovered that (i) electrons go from negative to positive, and (ii) electric sparks jump too fast to see which way they are going anyway, 'conventional current' was established in all the textbooks, and it would have been disastrous to have tried to change it.

So we *still* say that 'conventional current' flows from positive to negative, except when we are discussing semiconductor physics, where electron flow is what matters.

3.6 PRINTED CIRCUITS

Before leaving passive components, mention must be made of that most ubiquitous of passive components, the *printed circuit board*. It used to be necessary to build a *chassis* for every piece of electronic circuitry, with insulating strips carrying rows of tags for component connections. The printed circuit board (PCB), however, has made possible small, light-weight circuits, easy to construct and repair.

The PCB consists of a strong plastic laminate or fibreglass laminate board, with a thin sheet of copper bonded to one (or sometimes both) side(s). The sheet is drilled with holes that enable the circuit components to be pushed into place with their connecting leads through the holes. The underneath (copper) side of the PCB is made in a pattern which corresponds to the required wiring pattern. The components are soldered in place, and the PCB provides both support for the parts and the necessary electrical interconnections. A completed PCB can be seen in Figure 15.23. Appendix 1 shows some examples of PCB patterns.

In production, the PCB is produced using automatic processes. The required pattern is produced as a photographic negative, and this is printed on to the PCB, which has been coated on the copper side with a photographic emulsion. The PCB is then developed like a photograph, leaving emulsion only on the parts that were exposed to light.

Next, the PCB goes into a bath of a powerful chemical that will dissolve copper—ferric chloride is often used. The ferric chloride etches away all the copper, *except* where it is protected by the emulsion. The emulsion is cleaned off, leaving the copper pattern. Holes are drilled or punched as required, and the board is ready for assembly (although the copper is often coated with a thin layer of solder by a process known as *roller tinning* to improve ease of soldering).

Anyone can make PCBs. For single PCBs, the circuit is simply drawn on to the copper with an etch-resistant ink (special pens are available) or with rub-on transfers. The rest of the process is the same as that used commercially.

Be careful with the strong ferric chloride solution—it is corrosive, poisonous, and will gallop through most metals. Use safety goggles, rubber gloves, plastic dishes, plastic tongs, and *don't* work on a stainless steel drainer!

* * * * *

Electricity and Passive Components

Chapters 2 and 3 have been intended as revision only. If you want to know more about electricity, there are many good textbooks available. If, however, you have found the first three chapters of this book fairly easy going, you will be able to understand the rest without too much trouble.

QUESTIONS

1. State the value and tolerance of the following resistor colour codes, as read from the resistors in a circuit board in a radio receiver: *brown, black, red, silver; brown, grey, yellow, silver; red, black, black, silver; gold, red, blue, green.*
2. What is the largest commonly used unit of capacitance?
3. Three capacitors are connected in parallel. Their values are $4.7\ \mu\text{F}$, $10\ \mu\text{F}$ and $3.3\ \mu\text{F}$. What is the combined capacitance? If the tolerance of each is +20 per cent and –10 per cent, what are the maximum and minimum values of capacitance to be expected for the combination?
4. The following two capacitors are connected in series: $3.3\ \text{nF}$, $2.2\ \text{nF}$. What is the combined capacitance?
5. A transformer is taking a current of 500 mA from a 220 V a.c. supply. If the output of the transformer is at 440 V, what is the maximum current the transformer could deliver from its secondary winding?