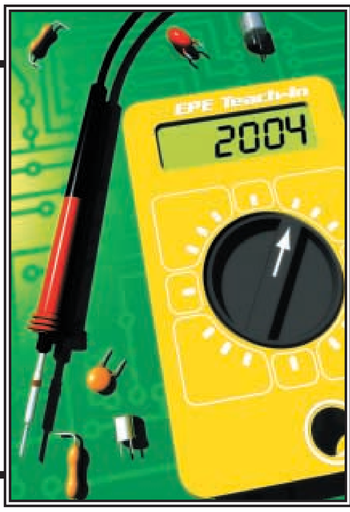

TEACH-IN 2004

Part One – At the Beginning

MAX HORSEY

How to apply electronics meaningfully – the aim of this 10-part series is to show, experimentally, how electronic components function as part of circuits and systems, demonstrating how each part of a circuit can be understood and tested, and offering advice about choosing components

A FIRST glance at an electronic circuit can be very off-putting; there are no moving parts, and it is impossible to know what is happening without a sound knowledge of how the components function and interact.

Throughout this series we ignore what is happening inside a component since all that matters in a circuit is the effect the component has on the current flowing. In other words we use the systems approach and examine what components do, and how they interact with other components.

MEASURING QUANTITIES

When you buy any item, its size or weight determines its suitability and cost. So you may buy 1kg of sugar, and 100m of string. Similarly, resistors are sold according to their resistance in ohms and their power in watts. Capacitors are measured in farads, and their working voltages in volts. We will discuss all these units in detail later, but since each unit has multiples, the chart shown in Table 1.1 may be helpful.

Note that micro (μ) is often written "u" if symbols are not supported by a printing system, and Ω is often written as "R". For example, a 27 ohms resistor may be written 27Ω or 27R. A 33,000 ohms resistor may be written 33kΩ or 33k.

(It used to be common to write 33kΩ as 33K. However, capital K has come to mean a kilobyte as used in computers, and this in turn means 1024 bytes – the nearest binary multiple of two.)

Table 1.1. Useful symbols and values

V = volts
A = amps
Ω = ohms
F = farads

multiply by 1,000,000 10^6 M (mega) e.g. 1MΩ
multiply by 1,000 10^3 k (kilo) e.g. 1kΩ
multiply by 1 e.g. 1V
divide by 1,000 10^{-3} m (milli) e.g. 1mA
divide by 1,000,000 10^{-6} μ (micro) e.g. 1μF
divide by 1,000,000,000 10^{-9} n (nano) e.g. 1nF
divide by 1,000,000,000,000 10^{-12} p (pico) e.g. 1pF

PASSIVE COMPONENTS

When electricity flows through a resistance, electrical energy is converted into heat energy. This is how an electric fire works. The element of an electric fire is a resistor. Electronic circuits employ many resistors to reduce the flow of current and provide the range of voltages needed around the circuit – hopefully they do not become as hot as the electric fire element!

Electricity can produce several effects, including a "field effect". For example, when you rub a balloon on your sleeve the balloon becomes charged with electricity and then attracts objects with a different charge. Hence the balloon will stick to a wall, which is neutral (which counts as a different charge to the balloon). The field effect is exploited in a capacitor, and in some types of semiconductor.

A flow of electricity produces a magnetic effect. When a wire is wound into a coil the magnetism is concentrated. A coil wound around a piece of soft iron is called an electromagnet; it can be turned on and off as required. A hollow coil is called a solenoid and can pull pieces of iron or steel into its centre. This mechanism is employed in electric locks.

In electronic circuits coils of wire are often known as inductors. In practice you will rarely, if ever, need an inductor (other than in radio circuits, or as an output device – like a solenoid), and so we will cover this area briefly.

The preceding components all lose energy – in other words they are *passive*. However, the invention of the thermionic valve – an *active* device – increased the potential of electronic circuits immensely and led to the "radio set" complete with "radio valves" and loudspeaker. For many years, electronics was essentially for radio; one of the most famous component suppliers, RS Components, was originally called Radio Spares.

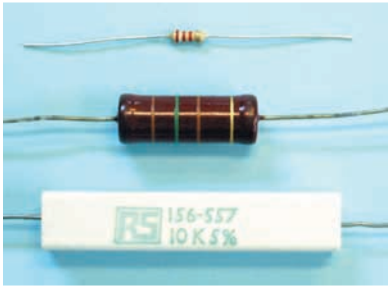

Photo 1.1. Examples of typical resistors. Top to bottom 0·25W, 2W, 11W.

RESISTORS

Resistors are probably the most common component in electronic circuits. Three resistors are shown in Photo 1.1, the most common of which is the smallest. Resistors are designed to waste electrical energy, and in the process they convert it into heat. Hence they are employed to reduce the flow of current, and help create the correct voltage for a particular section of a circuit. A resistor obeys Ohm's Law, whereby:

Resistance (in ohms) = Voltage/Current

For example, we can calculate the current flowing in Fig.1.1 if we know the value of the resistor, and the voltage across the resistor – which in this case is the supply voltage. So, with 9V across the resistor, and a resistance value of 100 ohms, we can change round the formula, namely:

Current = Voltage/Resistance

hence:

Current = 9/100 = 0·09 amps = 90mA

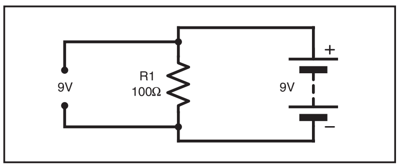

Fig.1.1. Current flow example.

PANEL 1.1. SCHEDULE FOR THIS SERIES

Part 1: At the Beginning
Revisiting passive components, and a few input/output devices.

Part 2: Transistors
Bipolar and MOSFET transistors, with example circuits, including a voltage controller and a simple amplifier.

Part 3: Operational Amplifiers
Useful op.amp circuit configurations, plus example circuits for an audio mixer and microphone amplifier.

Part 4: Logic Gates
Basic logic gates and how to use them in practical applications, including a Quiz Game Controller.

Part 5: Logic Gates as Switches
Logic gates as switches, with special reference to audio applications, and introducing PIC microcontrollers to reduce the chip count.

Part 6: Sound Level Measurement
Sound level measurement, with example detection and display circuits using op.amps, l.e.d.s and bargraphs, and illustrating how data sheets can be turned into real circuits.

Part 7: Moisture Detection and Radio Links
Methods for detecting moisture, and how data can be reliably transmitted via a variety of radio link modules.

Part 8: Movement Detection
Exploring methods for detecting movement, with special regard to avoiding Deep Vein Thrombosis, associated with personal immobility on a coach or aircraft, concluding with a PIC-based "movement reminder".

Part 9: Lock and Alarm Systems
Hard-wired and logic gate control of alarm and lock systems, including use of thyristors and matrixed keypads, and how to use PICs for decoding keypads.

Part 10: Motor Control
Exploring reversible motor control, with the use of switches, light and current sensing to provide automatic "stop" constraint, concluding with an example of a PIC-based curtain winder.

Fig.1.2. A 4-band resistor.

COLOUR CODES

The value of a resistor is indicated by means of a colour code. Consider a 4-band resistor as shown in Fig.1.2, where the last colour is gold.

Assuming that the last band is gold, the value should be read with the gold band on the right-hand side. The first band indicates the first digit, the second band indicates the second digit, and the third band indicates the "multiplier".

Table 1.2 illustrates this. Each colour represents a value, from lowest – black, to highest – white. The last band indicates the tolerance of the resistor, i.e. an indication of its accuracy. Gold means 5% tolerance (good enough for most purposes), red indicates 2% and brown indicates 1%. A 5% resistor whose colours indicate 100 ohms could have a value from 95 ohms to 105 ohms, i.e. 5% either way. For example:

red, red, red, gold = 2 2 00 ohms (2k2 ohms), 5% tolerance

brown, black, green, gold = 1 0 00000 ohms (1M ohms), 5%

brown, black, black, gold = 1 0 ohms (10 ohms), 5%

orange, orange, orange, gold = 3 3 000 ohms (33k ohms), 5%

Note how in the first instance the letter *k* is used in place of the decimal point.

FIVE-BAND RESISTORS

Five-band resistors (see Table 1.3) simply contain an extra digit, but otherwise they are similar to the four-band types. The extra band allows a more accurate value to be indicated, and so five-band resistors will generally have a tolerance of 1%. This means that the fifth band is brown, making it much harder to know which way round the resistor is read.

Resistor values conform to a system, e.g. the E24 series, and so if the value you have read is not included in the series, you must have the resistor the wrong way round. If all else fails, use a multimeter to measure the resistance!

POWER RATING

Resistors convert electrical energy into heat energy. In most circuits the current flowing through each resistor is so small that the heat produced can be ignored. But low-value resistors can produce significant amounts of heat, as can higher value resistors operating at high voltage. The power formula is:

Power = Voltage × Current

So if you know the current flowing through a resistor, and the voltage across it, the power (in watts) can be calculated.

The power rating of a typical resistor used in circuits is around 0·25W. Looking again at Photo 1.1 a resistor of this rating is shown at the top, together with a 2W resistor, and 11W resistor.

VARIABLE RESISTORS (POTENTIOMETERS)

As the name suggests, a variable resistor is a resistor whose resistance can be varied from zero to the value stamped on its case. It is common practice to build variable resistors with connections at both ends, and a "wiper" in the centre. A symbol of this device is shown in Fig.1.3.

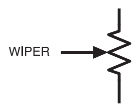

Fig.1.3. Basic symbol for a potentiometer.

If you use the wiper, and one end of the device, it is behaves as a variable resistor. If you use all three connections, the device can be used as a potentiometer (often abbreviated to *pot*). The term potentiometer is that normally used irrespective of the application.

The pots shown in Photo 1.2 illustrate some examples, including the linear slider, popular in mixers and graphic equalisers. Photo 1.3 shows some miniature pots, known as presets. These are operated with a screwdriver, and are useful if their values are changed very infrequently. Note that some are designed for horizontal mounting on a circuit board, and others stand vertically. Dual-gang pots are available as shown in Photo 1.4, and are useful as the volume controls in stereo amplifiers.

Table 1.2. 4-band resistor colour coding

	1st` digit	*2nd digit*	*multiplier*	*tolerance*
GOLD			divide by 10	5%
BLACK	0	0	none	
BROWN	1	1	× 10	1%
RED	2	2	× 100	2%
ORANGE	3	3	× 1000	
YELLOW	4	4	× 10000	
GREEN	5	5	× 100000	
BLUE	6	6	× 1000000	
VIOLET	7	7	× 10000000	
GREY	8	8	× 100000000	
WHITE	9	9	× 1000000000	

Table 1.3. 5-band resistor colour coding

	1st digit	*2nd digit*	*3rd digit*	*multiplier*	*tolerance*
GOLD				divide by 10	5%
BLACK	0	0	0	none	
BROWN	1	1	1	× 10	1%
RED	2	2	2	× 100	2%
ORANGE	3	3	3	× 1000	
YELLOW	4	4	4	× 10000	
GREEN	5	5	5	× 100000	
BLUE	6	6	6	× 1000000	
VIOLET	7	7	7	× 10000000	
GREY	8	8	8	× 100000000	
WHITE	9	9	9	× 1000000000	

Photo 1.2. Example of panel mounting single potentiometers.

Photo 1.3. Example of p.c.b. mounting preset potentiometers.

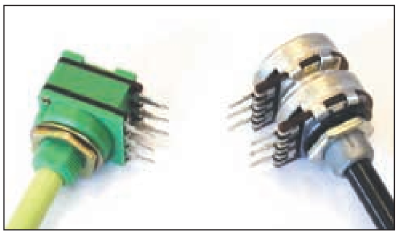

Photo 1.4. Example of panel mounting dual potentiometers.

LINEAR OR LOG

Most potentiometer values are available as linear (lin) or logarithmic (log) types. For most purposes the linear type is best, since the resistance changes evenly as the control is rotated. Log pots are generally used as volume controls in amplifiers, where the sound level needs to rise in ever greater steps – in tune with the way in which humans hear sound.

RHEOSTATS

A rheostat is a type of variable resistor, and will be looked at in more detail in Part 2, next month.

CAPACITORS

A capacitor *temporarily* stores electricity. This should not be confused with the function of a battery, which chemically

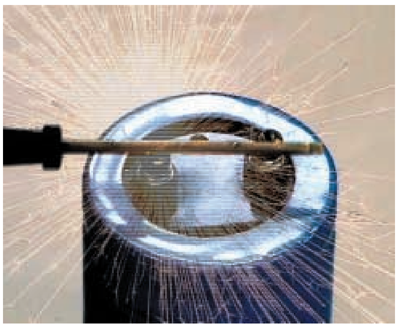

Photo 1.5. A dramatic (but dangerous) illustration that a capacitor stores electrical charge (see text).

PANEL 1.2. TOOLS AND EQUIPMENT

One of the advantages of experimental electronics is that it need cost very little. In fact, now that digital multimeters have fallen in price, the most expensive single item may well be a prototype board – a system which enables components to be plugged into it and connected together temporarily for testing and trialling. So a basic shopping list would be as follows:

- Prototype board (plug-in breadboard)
- Wire strippers/cutters
- Screwdrivers
- Small pliers
- Digital multimeter

A proposed list of the electronic components required for this series is shown below. The quantities given assume that components are re-used between the different parts of the series. Be aware that there may be minor changes or additions to the list as the series progresses.

Throughout this series a 9V PP3 battery can power most of the circuits, even where 12V is suggested.

If serious experimental or faultfinding work is planned for the future, an oscilloscope will be useful, though this will cost far more than everything else put together! It is not necessary to the successful following of this series.

Anyone wishing to construct circuits permanently will need a few small stripboards, a small soldering iron and multicore solder.

COMPONENTS

Approx. Cost Guidance Only **£27** *excl. misc.*

(Assumes that some components are re-used between different parts)

See SHOP TALK page

Resistors
8Ω2 3W
12Ω
100Ω
330Ω (7 off)
470Ω (2 off)
680Ω
1k (5 off)
2k2
4k7 (4 off)
10k (3 off)
22k (6 off)
47k (3 off)
51k
82k
100k (4 off)
680k (2 off)
1M (3 off)
All 0·25W 5% unless marked.

Potentiometers
1k
10k (3 off)
22k
47k
100k
470k
1M
All preset or panel mounting rotary linear.

Capacitors
100n disc or polylayer etc. (6 off)
470n disc or polylayer etc.
1µ polylayer (2 off)
1µ radial elect. 16V
2·2µ radial elect. 16V
4·7µ radial elect. 16V (2 off)
10µ radial elect. 16V (3 off)
100µ radial elect. 16V
220µ radial elect. 16V (2 off)
470µ radial elect. 16V
1000µ radial elect. 16V
All working voltages quoted are the minimum. Higher voltage ratings may be used.

Semiconductors
1N4001 rectifier diode (4 off)
1N4148 signal diode (3 off)
3V9 Zener diode, e.g. BZYC3V9
BC549 *npn* transistor (or any high-gain *npn* type, e.g. 2N3704) (3 off)
BC214 *pnp* transistor (or any high gain *pnp* type, e.g. 2N3702)
TIP122 (or TIP121) *npn* Darlington transistor (3 off)
TIP127 *pnp* Darlington transistor
TIP41A *npn* power transistor (2 off)
TIP42A *pnp* power transistor (2 off)
BUZ11A *n*-channel MOSFET
741 op.amp
4001B quad 2-input NOR gate
4011B quad 2-input NAND gate
4069UB hex inverter
4081B quad 2-input AND gate
4071B quad 2-input OR gate
4050B hex buffer
4052B dual 4-input analogue multiplexer
PICAXE-18 or PIC16F627 microcontroller (see text Part 8)
LB1412 VU i.c.
HT12E encoder
HT12F decoder
78L05 +5V 100mA voltage regulator
ICL7660 voltage converter

Miscellaneous
AM-RT4-433 radio transmitter module
AM-HRR3-433 radio receiver module
d.p.d.t. toggle switch
s.p. push-to-make switch (4 off)
Microswitch (optional)
Torch bulb (e.g. 3V) (2 off)
Electret microphone insert
Red l.e.d. (12 off)
Green l.e.d. (2 off)
Bi-colour l.e.d.
Relay, 12V coil (optional)
Shrouded 3-pin header (only required for PICAXE)
Stripboard for moisture sensor (4cm x 3cm) (see text Part 4)
Buzzer (solid state)
Siren (loud buzzer), any 6V to 12V type
Vibration switch, any type
Matrix keypad, 12-key
Solenoid lock (optional), any 12V type
Thermal fuse 1A
Motor and gearbox, e.g. Rapid 37-1238 or RS 336-337
Miniature 12 l.d.r.
Thermistor, n.t.c., 5kΩ at 25°C

generates electricity. A capacitor can be likened to the water storage tank in your loft; a battery is like the central heating pump pumping the water around the radiators.

You can conduct a very crude experiment to show that a capacitor stores electricity, as shown in Photo 1.5. Here we have taken a large electrolytic capacitor, and charged it from a power unit by connecting its terminals directly to the 12V supply from a power supply unit.

WARNINGS:

- **This experiment may damage the capacitor, so use an old one!**
- **Always check that the capacitor is connected the correct way round i.e. positive of the capacitor to positive of the power supply, and check that the working voltage of the capacitor is higher than the voltage of the supply.**

Now disconnect the capacitor from the supply, and place a screwdriver across its terminals. The large spark illustrates that it was charged. (NOTE: shorting a capacitor in this way may cause it damage).

Photo 1.6 shows a more elegant, if less dramatic illustration. A buzzer is connected to the capacitor and it will sound for some time, though the changing note from the buzzer indicates that the voltage is falling quite rapidly.

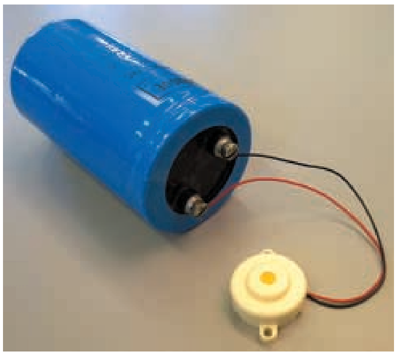

Photo 1.6. Audibly demonstrating that a capacitor stores electrical charge.

A battery of the same physical size as the capacitor would work the buzzer for very much longer. Hence capacitors are not very effective when used as rechargeable batteries. They can only be employed in this way for use in very low consumption circuits – such as keeping the clock going for an hour in your video recorder during a power cut!

The storage ability of a capacitor is measured in farads (in honour of Michael Faraday, one of Britain's greatest scientists). In practice we require smaller units such as microfarads (μF), nanofarads (nF) and picofarads (pF):

$1F = 1,000,000\mu F$
$1F = 1,000,000,000nF$
$1F = 1,000,000,000,000pF$

or put another way:

$1\mu F = 10^{-6}$ F
$1nF = 10^{-9}$ F
$1pF = 10^{-12}$ F

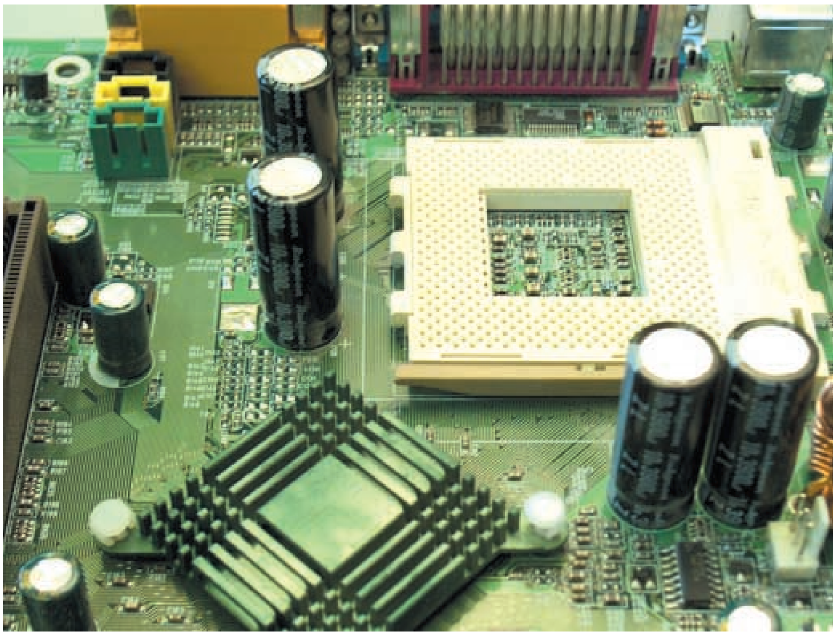

Photo 1.7. Electrolytic capacitors can dominate even the most sophisticated of circuit boards.

USING CAPACITORS

Capacitors, like resistors, are so widely used that whole books are written about them. So we will just summarise some applications, and see them in action throughout this series. Capacitors are used for:

- storing small amounts of electrical energy
- smoothing (decoupling) power supplies
- removing voltage spikes from power supplies
- timing circuits
- oscillator circuits
- radio tuning
- tone control circuits
- blocking d.c. whilst coupling a.c.

TYPES OF CAPACITORS

Capacitors tend to be rather bulky when compared with other components. The circuit board in Photo 1.7 shows part of a computer motherboard, where the black dots are tiny surface mount resistors, transistors and diodes. As the name suggests, these components are soldered on the upper surface of the p.c.b. and are ideal for mass production.

But standing like sky-scrapers are the capacitors (electrolytic in this instance), almost as if from another age. Some very small capacitors are capable of being surface mounted like resistors, but large value capacitors take up a large amount of space. Open up a hi-fi amplifier and you will find that nearly half the case is filled with the power transformer and capacitors.

The reason for an electrolytic capacitor's size is that it is comprised of two metal foil conductors, separated by an insulator. The whole thing can be rolled up like a Swiss roll, and although the conductors and insulator can be made very thin, there comes a point where the insulator is so thin that it breaks down when voltage is applied. So capacitors have a voltage rating known as a *working voltage*, above which you **should not** go!

Non-electrolytic (i.e. "normal") capacitors tend to have a reasonably high working voltage, typically 100V. The insulator may be made of polyester, polystyrene, mica, etc., and the size, shape, price and effectiveness tend to depend on the type of insulation employed.

Rolled-up capacitors can have an inductive effect. This may be of no consequence in many circuits, but is best avoided where possible. So particular capacitors, such as "polylayer" types, are available which are not rolled-up and are useful in many circuits, including audio amplifiers and tone networks.

Using a non-electrolytic capacitor of a type different to that specified in a given component list is unlikely to prevent most circuits from working, providing the working voltage of the capacitor is sufficiently high, and it physically fits into the space provided on the circuit board. The price of "expensive" types of capacitor has fallen over recent years, and so there is often little point in the home-constructor using "cheaper" types.

ELECTROLYTIC CAPACITORS

Electrolytic capacitors are polarised – in other words – they must be connected the correct way round with respect to positive and negative voltages. If you connect an electrolytic capacitor the wrong way round it is likely to explode. Photo 1.8 shows an

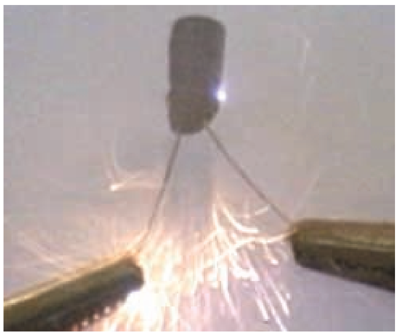

Photo 1.8. The dangerous effects of connecting an electrolytic capacitor to the wrong power supply polarity (photo created in a protected environment – see text).

experiment where a small electrolytic capacitor was connected with the wrong polarity to a 12V supply.

WARNING: The experiment was conducted inside a sealed container, in a laboratory – do NOT try this at home!

Electrolytic capacitors provide a large storage capacity in a reasonably compact case and at a reasonable cost, when compared with non-electrolytic capacitors. Their voltage ratings can be as low as 3V, so watch this when selecting your capacitor. In general, buy a capacitor with a voltage rating (i.e. working voltage) higher than the power supply voltage employed in your circuit.

There are two package types commonly employed – axial capacitors, and radial capacitors, as shown in Photo 1.9. An axial type (on the right-hand side) is designed to lie down like a resistor; a radial type has both its leads extending from the same end, and so stands upright and takes up less space on the circuit board. For this reason, radial capacitors are more commonly used.

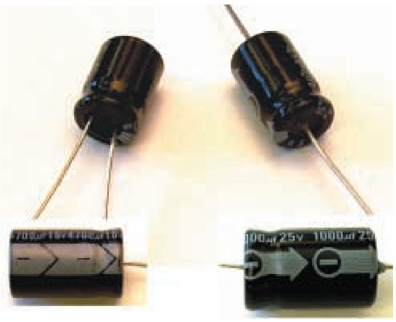

Photo 1.9. Examples of radial (left) and axial (right) electrolytic capacitors.

Notice that a band on the side of the body indicates the negative side of both types of capacitor. Additionally, in the case of a radial capacitor, positive is indicated by the longer lead

TOLERANCE

No component can be manufactured perfectly, and all are made to a certain accuracy or tolerance. Electrolytic capacitors are notoriously imperfect and the actual value may be between half the stated value, or up to double the stated value. Fortunately, the *actual* value of an electrolytic capacitor is often not important, and circuit designers are used to making allowances for electrolytic capacitors!

LEAKAGE

The plates of an electrolytic capacitor are not as well insulated as non-electrolytic types, and current can "leak" between the plates. This can adversely affect some circuits. For example, a popular timing circuit based on a chip known as a 555 timer measures the rising voltage on a capacitor, which is being charged via a resistor.

If times of several minutes are required, the resistor needs to restrict the flow of current so that the capacitor charges very slowly. You can use a larger capacitor to increase the timed period still further, but the size required to permit times of up to one hour, for instance, increases the risk of "leakage" which in turn affects the accuracy.

This can be very frustrating, when your calculations no longer work in practice!

TANTALUM BEAD CAPACITORS

Tantalum bead capacitors are a form of electrolytic capacitor but have a better tolerance rating, and are generally smaller. They also have better leakage ratings (i.e. leak less), but – as you would expect – are more expensive.

INDUCTORS

An inductor is a coil of wire either hollow, or wound around some ferrous (magnetic) material. When current flows through the coil a magnetic field is produced. When the current stops flowing the magnetic field collapses. If the coil is connected to a d.c. supply, a steady current will flow, and the opposition to the flow will be mainly due to the resistance of the wire used to make the coil.

However, at the moment when the current is switched on or switched off the rising or falling magnetic field also opposes the flow of current. This means that if an alternating supply is connected to the coil the opposition to the flow is greater than that due to the resistance alone.

The amount of opposition to a.c. depends upon the wire used, the number of turns, type of material inside the coil etc., and the effect is known as the inductance of the coil. Inductance is measured in henrys, and a small inductor may have a value of, say, 10mH.

There is also some capacitance associated with the coil, and this too affects the way it behaves with a.c. So the whole effect due to the resistance of the wire, the inductive effect and capacitive effect is summed up by referring to the impedance of the coil. Impedance is the total opposition to a.c. and will depend upon the a.c. frequency.

You will probably know that one of the important loudspeaker measurements is its impedance. If your amplifier has an output impedance of 8Ω, then you need a speaker of 8Ω impedance if you wish to extract the maximum power.

Inductors are often used to reduce voltage spikes in a circuit – in fact you often see ferrous material wrapped around mains leads or other leads associated with computers, video recorders etc. Inductors are also used in radio tuning, and combined with capacitors can form a "tuned circuit" i.e. one which resonates with a particular frequency – to tune in your favourite radio station for instance.

TRANSFORMERS

A transformer normally consists of two or more coils of wire wound around a common core. Transformers which are designed to operate on 50Hz or 60Hz (the European/US mains frequencies) have cores made from laminated soft iron. The laminations (insulated sections) prevent the core acting like a coil of wire and conducting electricity.

When a.c. is applied to one coil known as the primary, a voltage of the same frequency is induced in the other coil known as the secondary. The voltage produced is in exact proportion to the ratio of turns. In other words:

$$\frac{\text{Output voltage}}{\text{Input voltage}} = \frac{\text{Secondary turns}}{\text{Primary turns}}$$

If the secondary coil has more turns than the primary, the transformer is known as a "step-up" type. However, the power output can never be greater than the power input (that's a law of nature – you can't get something for nothing!), and so the current available from the secondary coil is reduced by the same ratio.

The majority of electronics projects that require a transformer employ a "mains type". These generally step down the voltage. For example, a mains transformer with a ratio of 20:1 will change an input of 230V a.c. down to 11·5V a.c.

Remember that transformers only work with a.c., and the current available from the secondary will be determined by the thickness of the wire used. If you require a large current, you need to obtain a larger, more expensive transformer.

A 20:1 ratio transformer which offers a current of, say, 1A from its secondary will consume 1/20A from the mains supply. These figures assume that the transformer is 100% efficient. In practice they are around 98% or worse.

Small mains transformers – the type often needed in projects – have quite poor "regulation". This means that the output voltage claimed will only be correct when the current used from the secondary is near the maximum allowed. If less current is used, the output voltage will rise – by up to 25% or more. So a 12V transformer may supply a voltage of 15V or more when "off load".

DIODES

A diode allows current to flow in only one direction. Sounds easy – but whole books have been written on the development of the diode, including such classics as the thermionic radio valve and the "crystal and cats whisker". Our present solid state diodes owe their existence to the latter device, although their development took a surprisingly long time.

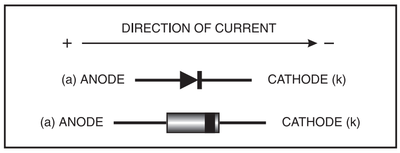

Fig.1.4. Diode symbol and polarity markings.

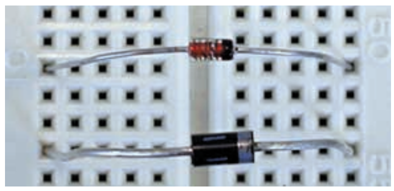

Photo 1.10. A 1N4148 (top) signal diode and a 1N4001 rectifier diode.

The symbol for a diode is shown in Fig.1.4. Note the direction of the current through the diode. Fig.1.4 also shows how the band around the real life diode corresponds with the cathode end of the symbol. Two common diodes are shown in Photo 1.10. The upper is a type 1N4148, and the lower is type 1N4001.

In all the following experiments, a type 1N4001 diode has been employed.

USING DIODES

- Protecting against reverse polarity
- Steering applications
- Radio detection
- Rectification
- Protection from back e.m.f.

Protecting against reverse polarity

Most electronic circuits will be damaged if you connect the power supply or battery the wrong way round. You can protect against this event by connecting a diode in series with the power supply as shown in Fig.1.5.

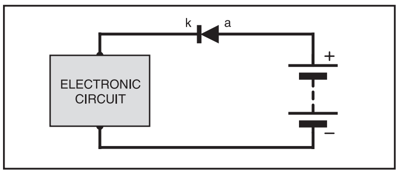

Fig.1.5. Common method of using a diode to protect a circuit against reverse power supply connection.

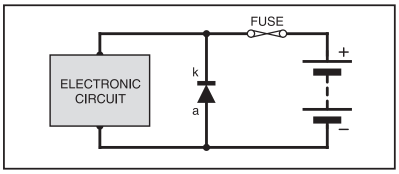

Fig.1.6. Another method of protecting a circuit, using a diode and a fuse.

If the battery is reversed, the diode will prevent any current flowing. The only problem with this arrangement is that the diode loses about 0·7V. So if you are using a 3V battery, the voltage applied to your circuit will be only 2·3V.

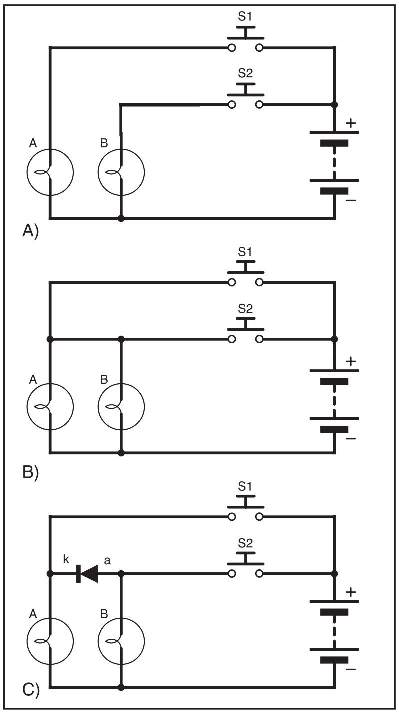

Fig.1.7. Using switches to control lamps, (a) individual switching, (b) dual-control of both lamps, (c) controlling lamp A by S1, but both lamps by S2, by using a steering diode.

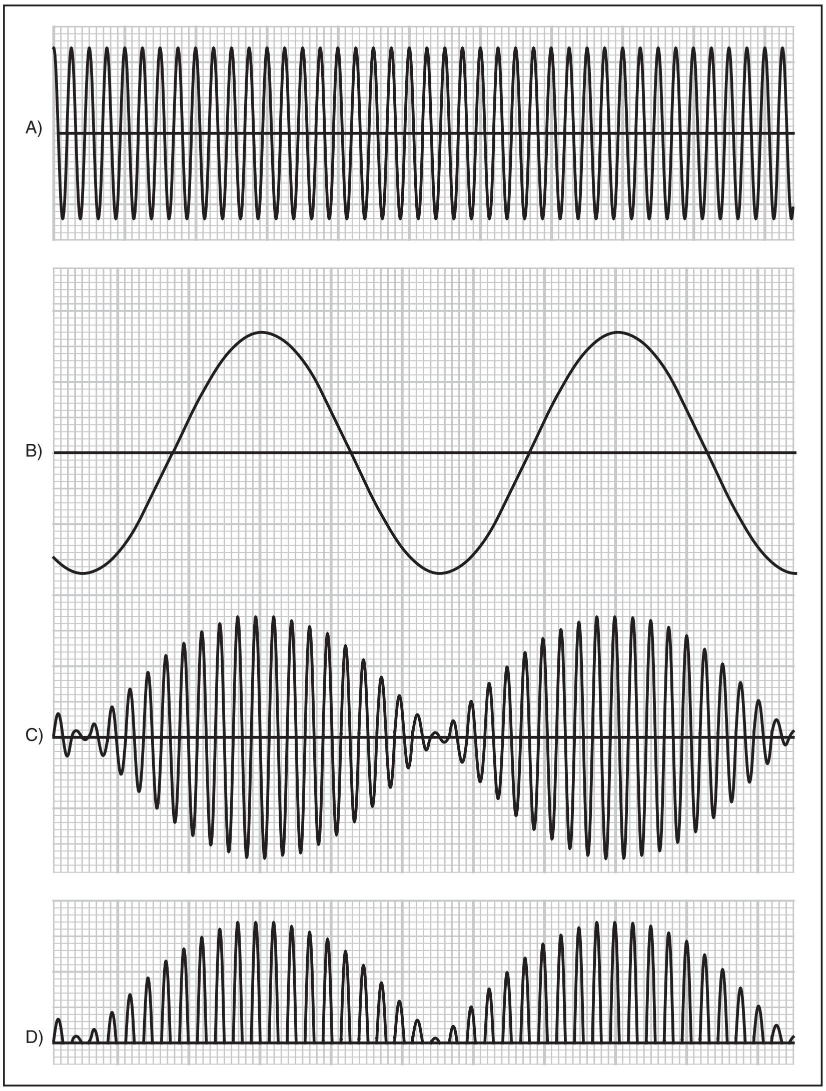

Fig.1.8. Principle of amplitude modulation (AM), (a) the carrier signal, (b) modulating signal, (c) the effect of modulating a *by* b*, (d) half-wave rectification of* c.

Hence the arrangement shown in Fig.1.6 is sometimes used. The diode will be "invisible" when the battery is connected correctly, but if the supply is reversed, the diode will short-circuit the current and the fuse will blow. A blown fuse is a much better option than a destroyed circuit.

Steering

Steering applications probably account for the greatest use of diodes, particularly in logic circuits. An example will illustrate the point:

The circuit in Fig.1.7 show two lamps A and B controlled by means of two pushbutton switches, S1 and S2. We require button S1 to light lamp A, and button S2 to light both lamps. The wiring for dedicated lamp switching is shown in Fig.1.7a.

However, when S2 is connected to both lamps (Fig.1.7b), we find that S1 lights both lamps as well. The solution is shown in Fig.1.7c. A diode is used to steer the current so that S2 can light lamps A and B, but S1 can only light lamp A.

Radio detection

A full description of radio is beyond the scope of this article, but the principle of Amplitude Modulation (AM) is easily explained.

A radio wave can carry audio information (e.g. speech or music) by superimposing or modulating the radio wave (known as the carrier) with the audio signal. The graphs in Fig.1.8 illustrate the point.

An example radio wave is shown in Fig.1.8a. This is simply a sinewave oscillating at high frequency. Fig.1.8b shows an audio signal – in this case a sinewave of much lower frequency than the radio wave. Fig.1.8c shows the radio wave modulated by the audio signal – its amplitude pulses up and down in synchronisation with the audio signal.

When the modulated radio wave is received by a radio set, the audio signal is recovered by removing all the waves below the centre line, i.e. removing the negative part of the signal. This is the part played by the diode in the "detection" circuit.

We now have the signal as shown in Fig.1.8d – which resembles quite closely the original audio signal. The high frequency radio signal is ignored by your headphones or loudspeaker, which responds to the "tops" of the signal. In practice, the high frequency radio signal can be removed by a capacitor, leaving the audio signal, which is similar to that shown in Fig.1.8b.

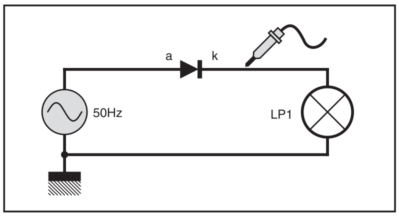

Fig.1.9. Experiment illustrating half-wave rectification.

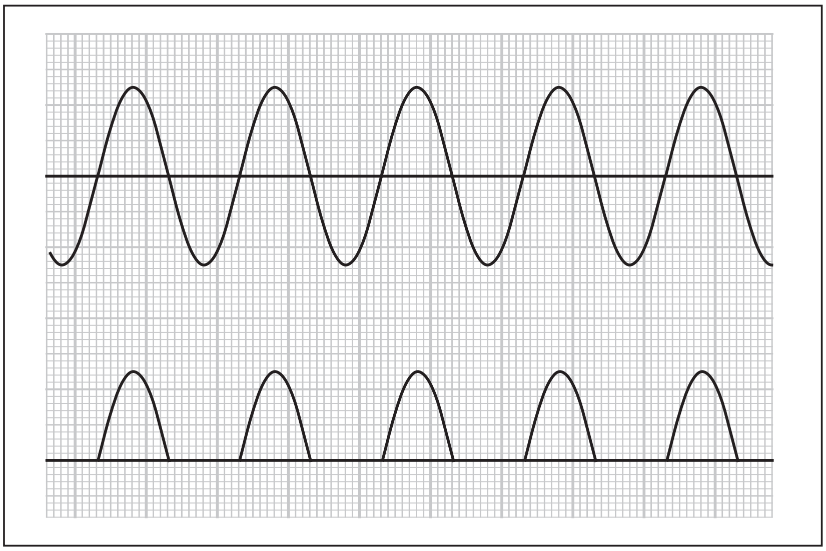

Fig.1.10. Sinewave before (top) and after half-wave rectification.

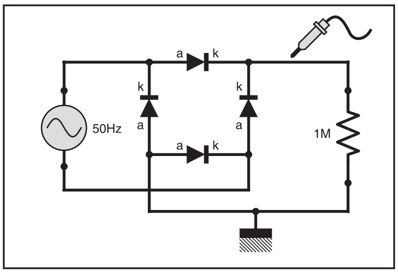

Fig.1.11. Experiment illustrating full-wave rectification.

Rectification

In the previous example, the diode removes the negative parts of the radio signal. In other words we are changing the signal, which pulses above and below 0V, into a signal that pulses only above 0V. This is illustrated in Fig.1.9 and Fig.1.10.

In Fig.1.9 an a.c. generator is shown connected via a diode to a lamp. The upper graph in Fig.1.10 shows the a.c. waveform, and the lower graph shows the effect of the diode, which removes the negative parts of the waveform. Hence, we are left only with the positive part of the waveform i.e. a half-wave.

A single diode can therefore be used as a half-wave rectifier. Note that the half-wave is d.c., i.e. it always flows in the same direction, even though it is pulsing. This type of d.c. is inefficient, and full-wave rectified d.c. is generally preferred.

Full-wave d.c.

There is more than one way of converting a.c. into full-wave d.c., but since diodes cost just a few pence, a useful method is by wiring the diodes into a "bridge" formation, hence the term *bridge rectifier*.

The four diodes are connected as shown in Fig.1.11, and the resulting graph is shown in Fig.1.12. Notice that unlike the previous graph, the gaps have been filled to make full-wave d.c. Full-wave d.c. still wobbles up and down, but is much more efficient than half-wave d.c. Also, with smaller gaps, it is much easier to smooth into a steady flow of d.c.

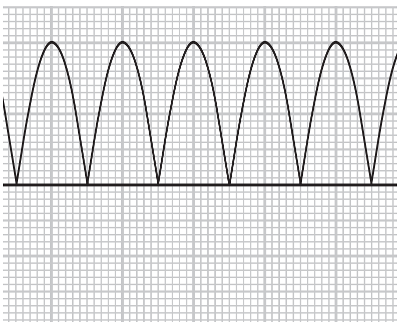

Fig.1.12. Full-wave rectification converts an a.c. signal into d.c. but retains the "ripples" of the a.c. waveform.

WARNING: When experimenting with diodes, ensure that current is able to flow through the diodes by using a lamp (as in the half-wave circuit) or a resistor to provide a "load", as shown in Fig.1.11. Also, with the full-wave circuit, if you are using an oscilloscope (see Panel 1.3 later) to view the waveform, the oscilloscope ground (0V) must be connected only to the d.c. side of the bridge. You cannot, for example, use a double beam oscilloscope to monitor the a.c. and d.c. sides of the circuit at the same time.

The 4-diode bridge circuit is so often required that bridge rectifiers are available as single packages containing the four diodes, as shown in Photo 1.11. Notice that the positive and negative connections are marked on the top of each rectifier. The larger device can handle several amps, the smaller is rated at just over 1A.

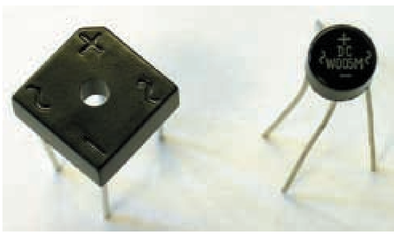

Photo 1.11. Examples of bridge rectifiers.

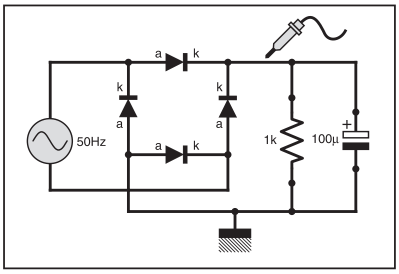

Fig.1.13. Smoothing a full-wave rectified signal.

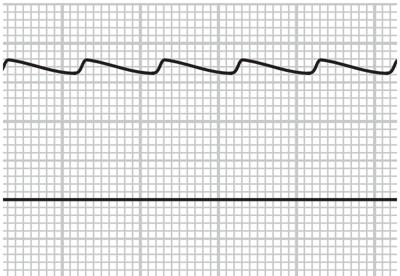

Fig.1.14. A ripple signal remains if inadequate smoothing is given to a full-wave rectified signal.

Smoothing

Electronic circuits require a smooth d.c. supply – the type provided by a battery. With rectified d.c. this is achieved by means of a capacitor as shown in Fig.1.13.

If a capacitor value of $100\mu F$ is used and the load is $1M\Omega$, then the graph will be a perfectly straight line, since very little current flows through the $1M\Omega$ resistor. However, if the resistor value is reduced to $1k\Omega$, then several milliamps flow through the resistor and noticeable ripple occurs. The difference is illustrated in Fig.1.14.

A larger capacitor value will reduce the ripple, but if the amount of current required by your circuit (as represented by the resistor) is 1A or more, then very large value capacitors are required. Hence the capacitors inside your hi-fi power amplifier will be very large indeed.

Back-e.m.f. protection

Many output devices produce a high voltage spike when they switch off. This includes all magnetic devices such as

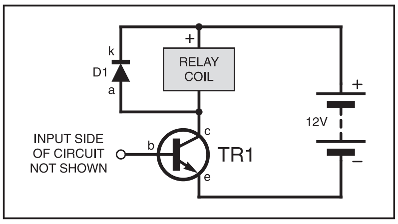

Fig.1.15. Using a diode to eliminate back-e.m.f.

motors, relays and solenoids. The high voltage spike, known as back-e.m.f. (e.m.f. = electromotive force), can damage sensitive components such as transistors and integrated circuits (i.c.s).

The circuit shown in Fig.1.15 illustrates the point. Here a transistor is used to switch a relay on and off. We won't worry about the input side of the circuit. When the transistor turns on, current flows through the relay coil. When the transistor turns off, the current through the relay coil stops, but the magnetism remains for a moment.

As the magnetic field collapses it is like pulling a magnet out of a coil at high speed – and this induces a voltage (e.m.f.) across the coil. Most transistors can only tolerate voltages of 30V or so but the e.m.f. (which is in the opposite direction to the normal supply voltage – hence "back-e.m.f.") may be 50V or more, so the transistor is destroyed.

Diode D1 acts as a short-circuit to the back-e.m.f. and so removes the danger. However, the diode faces the wrong way for the normal supply voltage, and so does not affect the circuit in any other way.

It is possible to detect the high voltage produced when a relay switches off by placing your finger across the contacts connected to its coil. Connect one side of a power supply (e.g. 12V) to one side of the coil, connect a second lead to the other side of the power supply, and touch its end against the spare side of the relay coil.

Each time you brush the lead against the coil connection you should feel a small current. It helps if you use a large old-fashioned relay such as that shown in Photo 1.12.

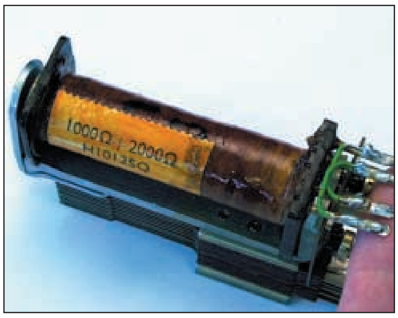

Photo 1.12. An old-fashioned relay, suitable for a back-e.m.f. experiment.

SELECTING A DIODE

When selecting a diode the following considerations apply:

Forward voltage drop (V_F)

When current flows through a diode, there is a voltage drop across it. In other words, some of the voltage is lost. The figure of 0·7V quoted earlier applies to silicon diodes. If this is too large a value, and you are dealing with small currents, you can employ a germanium diode such as type OA91, whose voltage drop is about 0·3V. Hence this type is more appropriate for simple radio receivers.

Forward current (I_F)

Diodes are rated according to the current they can pass. For example, type 1N4001 can carry up to 1A. Type 1N4148 can carry 150mA.

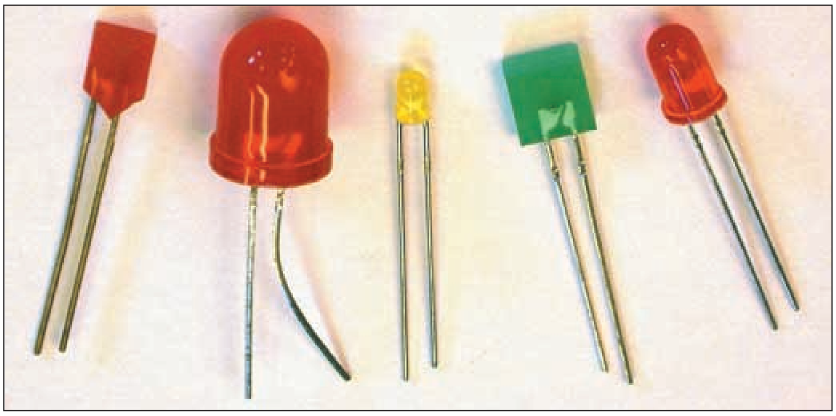

Photo 1.13. Examples of l.e.d. types.

Peak Inverse Voltage (PIV)

The peak inverse voltage is the maximum voltage a diode can withstand in the reverse direction. For example, the 1N4001 diode can tolerate up to 50V. Type 1N4002 has a PIV of 100V, type 1N4003, 200V, and type 1N4004 has a PIV of 400V – making it useful for mains voltages. The popular 1N4148 has a PIV of 75V.

LIGHT EMITTING DIODES

A light emitting diode (l.e.d.) is a special type of diode that emits light when current flows through it. L.E.D.s can be obtained in a range of colours and sizes, as illustrated in Photo 1.13. Note that the longer lead indicates the anode (positive) side of the l.e.d.

Most general purpose l.e.d.s require a current of around 10mA to 20mA, though special "low-current" l.e.d.s are available. The PIV is typically 5V (something to watch as it is much lower than an ordinary diode) and the forward voltage drop is around 1·7V for red l.e.d.s, 2.3V for yellow and green, and over 4V for blue.

A diode provides a low-resistance path in its forward direction. Hence if you connect a diode, including an l.e.d., across a power supply in the forward direction, a short-circuit current will flow, destroying the l.e.d. in the process. So a resistor is required as shown in Fig.1.16.

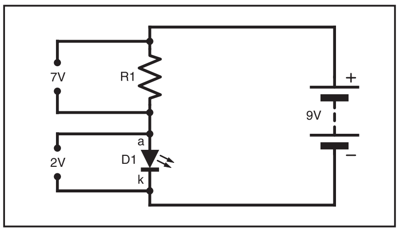

Fig.1.16. A resistor must be used in series with an l.e.d. to prevent excessive current flow.

Calculating the resistor value

We calculate the resistor value by means of Ohm's Law, namely,

Voltage = Current × Resistance

where Voltage is the voltage across the resistor, and Current is the current flowing through the resistor (and the l.e.d.).

A catalogue itemising the l.e.d. might tell us that the forward voltage drop across the l.e.d. is 2V (probably about 1·8V, but we will call it 2V). Assuming a 9V supply, this leaves 7V across the resistor.

We know from the catalogue that a suitable current through the l.e.d. is about 10mA. The same current flows through the resistor. So we have 7V across the resistor, and 10mA (i.e. 0·01A) flowing through it.

From Ohm's Law:

R = V/I, so R = 7/0·01 = 700 ohms.

The nearest conventional resistor value available is 680 ohms.

The calculation can be reduced to a single formula:

$$R = \frac{V_s - V_d}{I}$$

where

R = resistor value
V_s = supply voltage
V_d = l.e.d. voltage drop
I = current through l.e.d.

The assumption of 2V forward voltage drop is adequate for red, green and yellow l.e.d.s, but if you use white or blue the forward voltage is much higher.

Remember that the series resistor is required because the l.e.d. has little forward resistance. Virtually all other output devices such as buzzers, bulbs, motors etc., have their own resistance and do not require a series resistor.

Photo 1.14. Examples of l.d.r.s, left a "standard" type, e.g. ORP12, and right a more responsive miniature version.

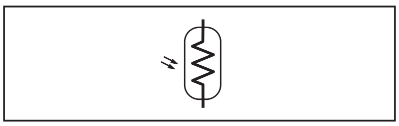

Fig.1.17. Symbol for an l.d.r.

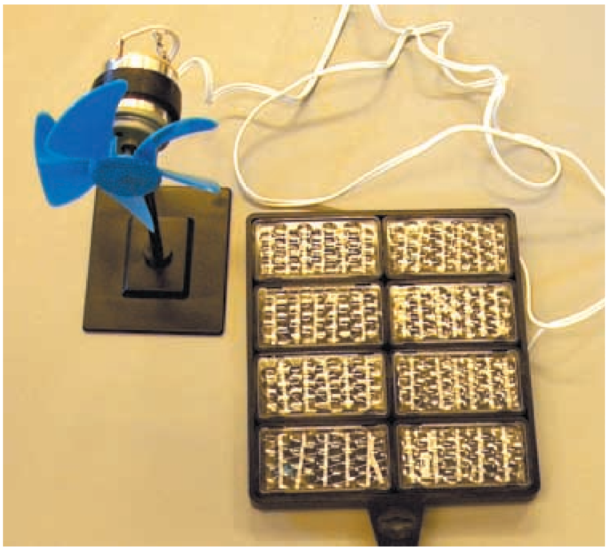

Photo 1.15 (above). A set of solar cells capable of powering a small fan.

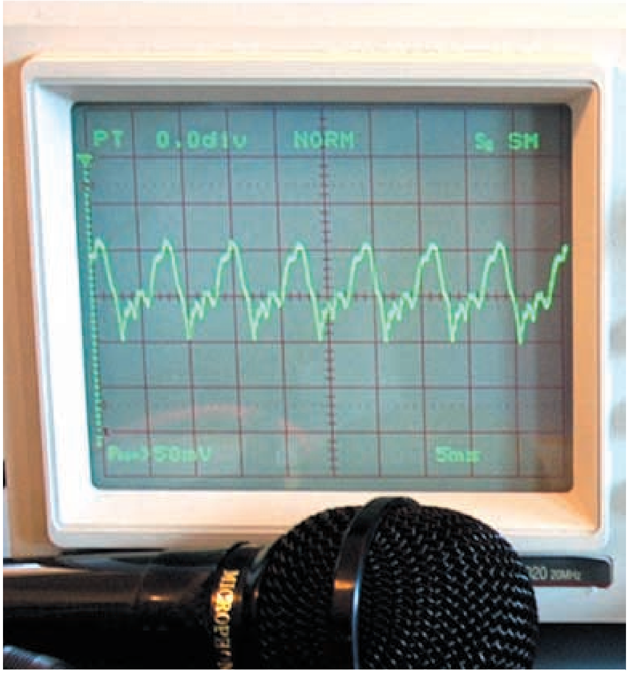

Photo 1.18 (right). Oscilloscope display of the signal output from a dynamic microphone.

INPUT DEVICES

Input devices are often referred to as transducers or sensors. The flow of current through the transducer depends upon an external influence such as light or temperature. Some transducers are passive, i.e. they do not generate electricity; others are active, i.e. they *do* generate electricity. We will examine the most common examples.

Light dependent resistor (passive)

A light dependent resistor (l.d.r.) is simply a variable resistor whose resistance changes according to the light intensity hitting its surface. Its resistance changes from about 200 ohms in bright sunlight, to over 1M ohms in total darkness. A "standard" l.d.r. is shown in Photo 1.14, together with a miniature type that is more responsive and cheaper. The schematic symbol is shown in Fig.1.17.

You can watch the resistance of an l.d.r. change if you connect it to a multimeter set to ohms (or k-ohms or M-ohms).

Note that an l.d.r. reacts quite slowly to a change of light; for example, it may take several seconds to fully change to its new value. This is of no consequence in automatic dusk triggered projects, since daylight changes very slowly anyway, but it can be a problem in some circuits, and so faster devices such as photo-diodes or photo-transistors should be considered.

Solar cell (active)

A solar cell generates electricity when exposed to light. Its cost makes it less suitable as a sensor, but if you require power in remote locations a solar cell may provide an answer. The set of cells shown in Photo 1.15 generate enough electricity to power a very small motor when exposed to strong direct sunlight.

Thermistor (passive)

A thermistor is a variable resistor whose resistance changes according to its temperature. The "-t" notation shown in Fig.1.18, indicates a negative temperature coefficient (n.t.c.). In other words, as the temperature rises the resistance of the thermistor falls. The opposite is a positive temperature coefficient (p.t.c.) type.

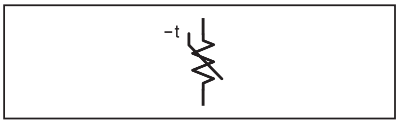

Fig.1.18. Symbol for an n.t.c. thermistor.

Thermistors are generally given a resistance rating according to their resistance at about 25°C.

Try connecting a 5kΩ thermistor (n.t.c.) to a multimeter set to a range of 20k ohms. When you touch the thermistor, the warmth of your fingers will make its resistance fall a little.

When choosing a temperature sensor, also consider the range of "integrated circuit sensors" (i.e. complete circuits inside the sensor package) now available, which provide an exact voltage change per degree Celsius. These make accurate calibration of your circuit very easy.

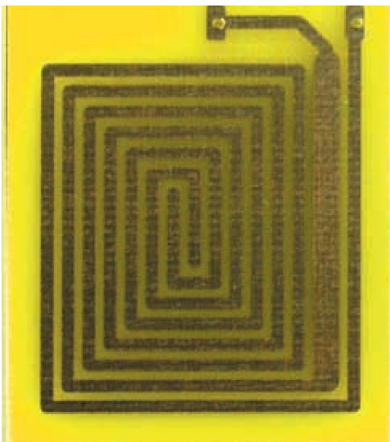

Photo 1.16. P.C.B. tracking used as a moisture sensor.

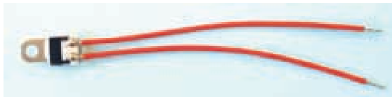

Photo 1.17. Commercial moisture sensor.

Moisture sensor (passive)

A pair of bare wires, or the tracks of a piece of stripboard or p.c.b. can be used as an adequate moisture sensor. The p.c.b. shown in Photo 1.16 has a sensor made of two tracks close together but not touching each other. When you breathe on the sensor the moisture in your breath causes the resistance between the tracks to fall from over 10MΩ to less than 100kΩ. In a later part we will look at a transistor circuit that will cause a warning buzzer to sound with your breathe on a moisture sensor.

A more professional moisture sensor is shown Photo 1.17. It works the opposite way in that moisture causes the resistance between the wires to increase. This is useful in applications where the sensor is normally wet, since less current is wasted.

Microphone (dynamic = active; electret = passive)

A dynamic microphone senses sound energy, and converts it into electrical energy. You can connect a high-impedance headphone to a microphone and receive sound without a battery or power unit.

The signal from a microphone is very small, and so an amplifier is generally required to boost the signal to an acceptable level. It is possible to connect a dynamic microphone directly to an oscilloscope to display your voice as shown in Photo 1.18.

Photo 1.19. Electret microphone handset.

PANEL 1.3. OSCILLOSCOPE DISPLAYS

Throughout this series we use oscilloscope photographs to display the signals at the input and/or output of a circuit. An oscilloscope can show what is happening when a voltage is quickly rising or falling; it shows the voltage by means of a graph or trace on a screen. Some of the images used in this series are displayed on a "dual beam storage oscilloscope".

A dual beam oscilloscope has two channels, one for each trace. This allows you to compare waveforms. For example, you may wish to check that an amplifier does not distort your sound signal, and so you could display the output signal below the input signal and check that their shapes are identical.

However, a cheaper single beam oscilloscope is almost as useful. The reason that the author used a storage oscilloscope is that photography was made much easier! Some of our displays are also produced by a computer simulation.

A digital multimeter is a much cheaper alternative to any oscilloscope and will cover many of the experiments in this series.

If an oscilloscope is not available, you can use a multimeter set to "a.c. voltage". This will provide a guide to the signal level being generated.

An electret microphone requires a power supply, and the microphone module houses a tiny amplifier. The microphone in Photo 1.19 contains a battery that supplies power to the amplifier module. Hence a signal is produced which is similar to the effect of using a dynamic microphone.

Expensive electret microphones do not contain a battery and so require "phantom power". This is (generally) a 48V supply that is fed down the microphone cable from the main microphone mixer/amplifier.

Dynamic microphones can be bought for as little as £5, though good quality dynamics costing around £100 are often used in stage shows. Electret microphones are often used in professional recording studios. They should be placed above the faces of the performers so that air is not puffed into the microphone, to avoid popping noises.

Microphone Inserts

Dynamic and electret microphones are available as inserts, i.e. the microphone module without the housing. The one shown in Photo 1.20 is an electret type, available for about 50p and ideal for project work.

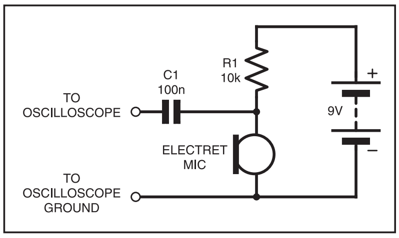

Fig.1.19. Experimental electret microphone circuit.

Try setting up the circuit in Fig.1.19 on a breadboard. Notice that resistor R1 is required in series with the microphone and the power supply. The signal from the microphone is normally connected to an amplifier circuit via a capacitor, C1. This blocks the d.c. supply, so leaving just the a.c. sound signal. The value of the capacitor is not critical and any value above 100nF should work.

If you use an electrolytic type then its positive connection should be nearer the resistor. If you monitor the a.c. signal on an oscilloscope, you may also find that a "load resistor" is necessary – say 100kΩ – connected between the oscilloscope side of C1 and ground (0V). (Note that you can omit the capacitor and set the oscilloscope to "a.c. input".)

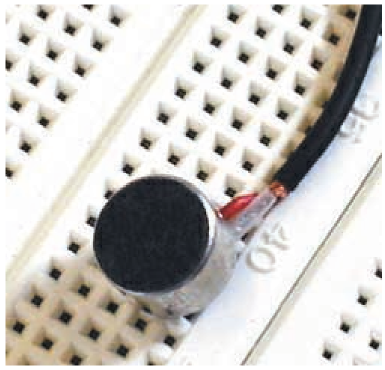
Photo 1.20. Electret microhone insert.

When you speak into the microphone you should see your voice on the oscilloscope screen, in the same way as illustrated in Photo 1.18.

OUTPUT DEVICES

Output devices are best dealt with as their need arises, and we will examine many during this series. They include:

lamps, l.e.d.s, heaters, bells, buzzers, speakers, electromagnets, solenoids, relays and motors.

Many output devices require a significant current and you generally need to amplifier the current available from a sensor before an output device will respond adequately.

NEXT MONTH

Next month we will show how simple transistor circuits can provide the appropriate current and voltage for an output device.