Physics

Teachers' guide **Unit 6**

# Electronics and reactive circuits

Nuffield Advanced Science

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# Electronics and reactive circuits



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Nuffield Advanced Science

**Nuffield Advanced Physics team**

**Joint organizers**

Dr P. J. Black, Reader in Crystal Physics, University of Birmingham

Jon Ogborn, Worcester College of Education; formerly of Roan School, London SE3

**Team members**

W. Bolton, formerly of High Wycombe College of Technology and Art

R. W. Fairbrother, Centre for Science Education, Chelsea College; formerly of Hinckley Grammar School

G. E. Foxcroft, Rugby School

Martin Harrap, formerly of Whitgift School, Croydon

Dr John Harris, Centre for Science Education, Chelsea College; formerly of Harvard Project Physics

Dr A. L. Mansell, Centre for Science Education, Chelsea College; formerly of Hatfield College of Technology

A. W. Trotter, North London Science Centre; formerly of Elliott School, Putney

*Evaluation*

P. R. Lawton, Garnett College, London

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Physics Teachers' guide Unit 6

# Electronics and reactive circuits

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# Foreword

It is almost a decade since the Trustees of the Nuffield Foundation decided to sponsor curriculum development programmes in science. Over the past few years a succession of materials and aids appropriate to teaching and learning over a wide variety of age and ability ranges has been published. We hope that they may have made a small contribution to the renewal of the science curriculum which is currently so evident in the schools.

The strength of the development has unquestionably lain in the most valuable part that has been played in the work by practising teachers and the guidance and help that have been received from the consultative committees to each Project.

The stage has now been reached for the publication of materials suitable for Advanced courses in the sciences. In many ways the task has been a more difficult one to accomplish. The sixth form has received more than its fair share of study in recent years and there is now an increasing acceptance that an attempt should be made to preserve breadth in studies in the 16–19 year age range. This is no easy task in a system which by virtue of its pattern of tertiary education requires standards for the sixth form which in many other countries might well be found in first year university courses.

Advanced courses are therefore at once both a difficult and an interesting venture. They have been designed to be of value to teacher and student, be they in sixth forms or other forms of education in a similar age range. Furthermore, it is expected that teachers in universities, polytechnics, and colleges of education may find some of the ideas of value in their own work.

If the Advanced Physics course meets with the success and appreciation I believe it deserves, it will be in no small measure due to a very large number of people, in the team so ably led by Jon Ogborn and Dr Paul Black, in the consultative committee, and in the schools in which trials have been held. The programme could not have been brought to a successful conclusion without their help and that of the examination boards, local authorities, the universities, and the professional associations of science teachers.

Finally, the Project materials could not have reached successful publication without the expert assistance that has been received from William Anderson and his editorial staff in the Nuffield Science Publications Unit and from the editorial and production teams of Penguin Education.

K. W. Keohane
*Co-ordinator of the Nuffield Foundation Science Teaching Project*

## The Teachers' guide

This volume is intended to contain whatever information and ideas are required for the day to day teaching of the Unit. Not every teacher will need all of it all of the time: sometimes the summary and the list of experiments will come nearer to meeting the need.

In Parts One to Three, the main text contains, on the righthand pages, a detailed suggested teaching sequence, which teachers can adopt or adapt. The facing lefthand pages carry practical details, suggested questions, references, and other information for teachers, in the form of a commentary on the text.

Part Four consists of a long series of suggested practical problems, and is printed, as in a conventional book, on successive right- and lefthand pages.

# Introduction

It is not hard to make a case for leaving electronics out of a sixth form physics course. We include some electronics for two reasons.

**1** It could be useful in the future. Students will find themselves using electronic devices in many courses of further education, and in a very wide variety of future careers, including medicine and jobs directly to do with computers, as well as work in pure and applied physical science. Whatever their careers will be, electronics looks likely to play an important role in their lives over the next quarter of a century or more.

**2** It gives an opportunity for a new style of work, reflecting the tastes and problems of the engineer rather than those of the physicist. In much of the course, students have analysed things, taking them apart in the manner of the pure scientist. Here we shall ask them to synthesize, to put things together to serve a purpose, in the manner of the engineer. We hope that they can be 'engineers for the day' as a change from being 'scientists for the day'.

### A systems approach

The designer of electronic circuits and the inventor of electronic devices need more than we shall offer in this course. Their needs will have to be met in later, more specialized courses. We reject a 'fundamental' approach through the physics of electrons in solids or in vacuum tubes, not because it is uninteresting, but because it would leave too little time to show electronics in action. We believe that the user of electronics has a greater need to grasp what electronics can do than to understand the working of particular devices. Housewives arranging baby alarms, people buying high fidelity record players, engineers monitoring the vibrations in a tower or the flow of chemicals in a pipe-line, chemists following reactions electrically, physicists counting particles from an accelerator, telephone engineers trying to pass signals on without distorting them, and many others, all need to be able to choose devices that will do the necessary job if combined in the right way. Designing the devices is a different, more specialized, profession.

If the components available to the designer were going to stay the same for the foreseeable future, there might be a better case for learning more about how they work. But they are not going to stay the same. What will change less quickly is the range of jobs that electronic devices are useful for: electronics will go on being about combining switches, amplifiers, pulse formers, counters, and oscillators to perform desired functions.

We may note, in passing, that in so far as electronics affects and will affect the daily lives of men and women, their need will be to understand the system they are dealing with, rather than the working of parts of the system. When the central heating fails to come on, finding the fault is a matter of knowing how the system works; of understanding the function of the parts in the whole. Computerized bank accounts, automatic telephone exchanges, or thermostatically and time-controlled electric ovens are all systems: to 'understand' them is primarily to know how they work as systems.

In this Unit, therefore, little or no stress is laid on what each building brick is made of, or on how it works. Instead, students are invited to find out what some simple building bricks do, and to put them together to invent others.

The Unit presents electronics, then, as the creative putting together of systems to do useful and interesting jobs. Each building brick has a part to play in the system, most serving to modify a signal sent through them in some way. Out of only a few such building bricks, a whole host of systems can be built: systems that amplify, oscillate, detect radio signals, count, add, perform mathematical operations, flash warning lights, control other operations, play tunes, and so on. In this view of electronics, the block diagram (see figures 1 to 4) is more fundamental than the circuit. Even within the practice of electronics in the electronics industry, this is becoming increasingly true, with the growing use of integrated circuits. Almost before one has mastered the working of one device, another takes its place; but both fit in similar ways into similar systems.

For the purpose of this course, a simple unit containing a transistor and some resistors and capacitors has been developed. It can be used in several ways to do most of the important elementary electronic jobs; as a flexible building brick, in fact. A number of these units, together with *RC*, *RL*, or *LC* circuits, can be put together by students to do a whole variety of jobs. In addition, the device is used as a source of signals with which to investigate simple networks containing resistors, capacitors, and inductors.

In this Unit, circuits containing capacitors, resistors, and inductors are treated mainly as building bricks for making larger systems. Previous work on capacitors and resistors (Units 2 and 3) is, however, used to pursue an understanding of *RC* circuits that goes a little beyond simply 'seeing what they do to a signal'. The treatment is not very mathematical, however.

Inductors, which enter the course for the first time in this Unit, are treated substantially as black-box-like objects which do things to signals. The analogies between inductors and masses, and between capacitors and springs, are used freely, to aid students' thinking about what these things do in a circuit, to make theoretical analysis simpler by capitalizing on previous knowledge (especially from Unit 4, *Waves and oscillations*), and to illustrate the general value to engineers and physicists of analogical thinking.

The work on inductors, and on *LC* circuits, is placed on its own in Part Three. It can be removed from this Unit with little loss to the Unit as a whole. Some teachers may prefer to take the work with Unit 7, and this may have advantages. The introduction of inductors would then go with the introduction of the fundamental ideas of electromagnetic induction which govern their working, though this is not necessarily better than the method suggested in this Unit, of first studying what an inductor does. An advantage of deferring Part Three to Unit 7 is that some practical work would be transferred to a later stage in the course. This may help the balance of such work in the course as a whole, which tends to lack practical work in the last few Units, and would somewhat shorten the first year, which may be a useful feature.

Unit 6 seems to us to offer something to many other courses besides this one. If it is to be used in a course where time is even more constrained than it is here, we would suggest that the omission of Part Three might be considered.

The suggested treatment of most theoretical matters in Unit 6 is largely non-mathematical, so that time is available for work of a different, no less valuable kind: inventive, practical, creative use of devices to make useful systems. Some students may feel happier with more theory, more formally expressed, and the cost in time may not be great for them. So Appendix C offers an additional, optional treatment using rotating vectors or 'phasors', which may suit some students. This treatment is not recommended for the majority of students, and nothing in the examination will require the use of phasors, but it may assist those who can use this method in discussing the problems of the superposition of light passing through slits, in Unit 8, *Electromagnetic waves*.

# Summary of Unit 6

*Time:* 5 weeks, or a little less.

(Numbers in brackets refer to suggested experiments, listed on page 7.)

## Part One
## Electronic building bricks

*Time:* rather more than a week.

This Part starts by suggesting that all electronic systems, though complex, are made out of a small number of components arranged in a small number of ways. The whole system can be thought of as being built from smaller parts like amplifiers, switches, and so on, each part doing a specific job in the system as a whole. The electronics kit is then used to explore the behaviour of a simple device, and knowledge of this behaviour is used in building up some of the simpler systems to be found inside electronic systems.

*Suggested sequence*

Electronic systems, illustrated by circuit and block diagrams; looking inside well known devices, and building a simple radio (6.1). Investigation of the behaviour of the basic unit from the kit (6.2, 6.3): the unit as a squarer, inverter, *nor*-gate, and pulse producer. Combinations of basic units to make other systems (6.4): including the *and*-gate, astable, bistable, and amplifier. Many other simple systems can be made. Attention is drawn to the above systems (6.5) and to the importance of feedback, especially, but not only, in amplifiers (6.6).

## Part Two
## Circuits containing capacitance

*Time:* rather more than a week.

This Part examines, and tries to understand, the action of *RC* circuits on signals, considering such circuits, like other parts of electronic systems, as making some desired change to a signal. Pulses are given as much prominence as sinusoidal variations, and are used to introduce the idea of circuits which perform mathematical operations, preparing for a brief episode concerning operational amplifiers. A capacitor is compared with a spring.

Power in alternating current circuits receives a mention, as do root mean square values of current or voltage.

*Suggested sequence*

Square pulses into *RC* circuits (6.7); integration and differentiation by *RC* circuits. Phase differences in *RC* circuits (6.8, 6.9). Power and root mean square values (6.10). Operational amplifiers (6.11).

## Part Three
## Circuits containing inductance

*Time:* about a week.

This Part could be transferred as a whole to Unit 7, *Magnetic fields*. It introduces inductors empirically, with no detailed explanation of their behaviour. The response of an *LR* circuit to pulses and to sinusoidal changes is investigated. If a capacitor is like a spring, the analogue of an inductor is seen to be a mass. The value of such analogues is emphasized, and they are used here to circumvent theory, so that more time can be spent in other Parts actually doing electronics.

Finally, a return to previous work on electronics is effected by looking at capacitors and inductors together, comparing the *LC* circuit with a mass and spring system, observing its resonance, and using the resonance for the tuning circuit of a radio set.

*Suggested sequence*

The behaviour of an inductor in 'slow motion' (6.12). The effect of an *LR* circuit on pulses (6.13) and on the phase of sinusoidal voltages (6.14). Currents adding up inside *LC* circuits (6.15); oscillations in *LC* circuits (6.16); resonance and its use in tuning a radio (6.17, 6.18).

## Part Four
## Building electronic systems

*Time:* up to a week.

In this Part each student is invited to use the electronic building bricks discussed previously, including the reactive circuits, to build up electronic systems to do a wide variety of different jobs (6.19). The *Guide* contains a large number of suggested problems, most with at least one possible solution given.

# Choosing one's own path

We hope and expect that teachers will find their own ways of using the material in this Unit. The detailed teaching programme laid out in the following pages represents as good a way of handling the material as we have been able to find in the light of experience in the trials, but should not be thought of as more than a possible, fairly well tested way of achieving the aims we decided upon. No doubt others can and will do better.

But teachers will know that it is the detail that counts in successful teaching, and so the *Guide* is full of particular teaching suggestions and practical details. We hope that these will help those who are uncertain how to handle either new material, or old material taught in a new way for unfamiliar aims.

The summary and list of experiments will, it is hoped, assist those who have taught the course a few times and no longer need to refer to all of the detailed teaching suggestions, as well as those who feel confident that they can make up their own teaching programme out of their previous experience. We also hope that the summary will provide an overall view of the work suggested. Such a view is necessary for keeping a sense of perspective and direction, both when one is immersed in particular detailed teaching suggestions and comments, and when students lead the teaching off in an unpredictable direction by contributing their own ideas.

It seems fair to add that the summary, taken on its own, could mislead. It cannot easily indicate the aims of pieces of work in any precise way, or find words to express the relative seriousness or lightness of particular episodes. Nor should a phrase one might find in a current examination syllabus always be taken here to imply the same work as it would imply there.

# Experiments suggested for Unit 6

Part One

# Electronic building bricks

*Time:* rather more than a week.

### *Students' book*

The article 'Systems and feedback' in the *Students' book* discusses how electronic devices can be regarded as systems, each made of a number of building bricks connected together so as to do a useful job. Figures 1 to 4 also appear in this article at the beginning, together with another example (part of an audio amplifier). The article then goes on to discuss systems of many kinds, biological and mechanical as well as electronic, and to emphasize the importance of feedback in understanding many of them.

Overhead projector transparencies prepared from figures 1 to 4 would be convenient aids, but the figures in the *Students' book* may do just as well.

Questions 1 to 4 are about systems in general.

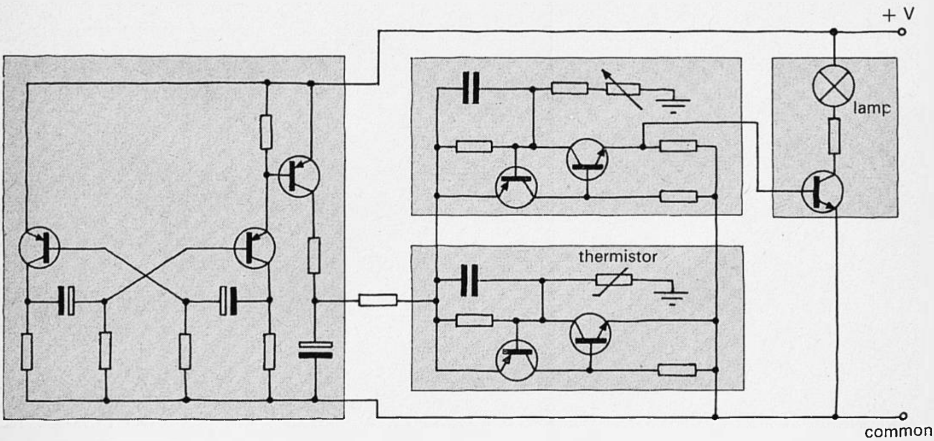



**Figure 1**
Low temperature warning device.
*Adapted from RCA (1970)* Solid-state hobby circuits manual HM-91, *RCA Solid-State Division.*

### Opening up electronic devices

Some of the electronic tools already used in the course are quite easy to open. Some makes are easier than others. The following are not too difficult.

#### *Oscilloscopes*

Advance class oscilloscope OS12. Remove two screws in each side and take off the top.

Telequipment Serviscope Minor. Remove righthand side panel (four screws) and lift off the top (one screw).

Telequipment demonstration oscilloscope S51 E. Put face down on suitable blocks, remove two screws in the back, and lift off the casing.

#### *Ratemeter*

Panax RM202. Remove four screws in the front panel and lift off the case.

#### *Stroboscope*

Griffin & George L 15–740. Remove four screws from the base and two from the side panels.

## Electronic systems

Students have already used a number of electronic instruments, and these make a good starting point. The inside of one or two such instruments can be shown, together with circuit diagrams of these or other devices.

The insides of most electronic devices look baffling, and so do their circuit diagrams. They contain large numbers of resistors, capacitors, transistors, and other components connected in intricate patterns.

Behind this complexity lies a kind of simplicity. Each device contains not very many different kinds of component, so that an oscilloscope does its job with much the same components as a scaler, but with these components connected differently.

Another kind of simplicity can be brought out by showing how to regard such devices as *systems*. The idea can be introduced by showing circuit diagrams like those of figures 1 to 4, each circuit being overlaid with shaded boxes which distinguish the functions of distinct sections of the device.

Thus, figure 1 shows a temperature warning circuit. It looks, and it is, quite complicated. But, as figure 2 shows, it is made up of two switches, a lamp indicator, and a section which produces one pulse every second. One switch controls the lamp, turning it on when a pulse goes to the switch. The other switch can short circuit the first one and its lamp, and it does so if it comes on first. It is arranged to come on first when one resistor (a thermistor) in it is warm and has a low resistance. Thus the whole system, made of these four parts, flashes the lamp when the temperature is low. The system was designed as a warning device for motorists, telling them when icy conditions exist.

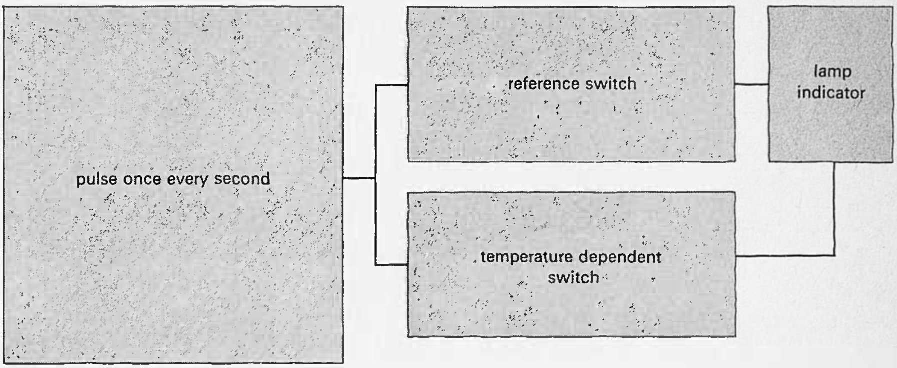



**Figure 2**
Block diagram of a low temperature warning device.

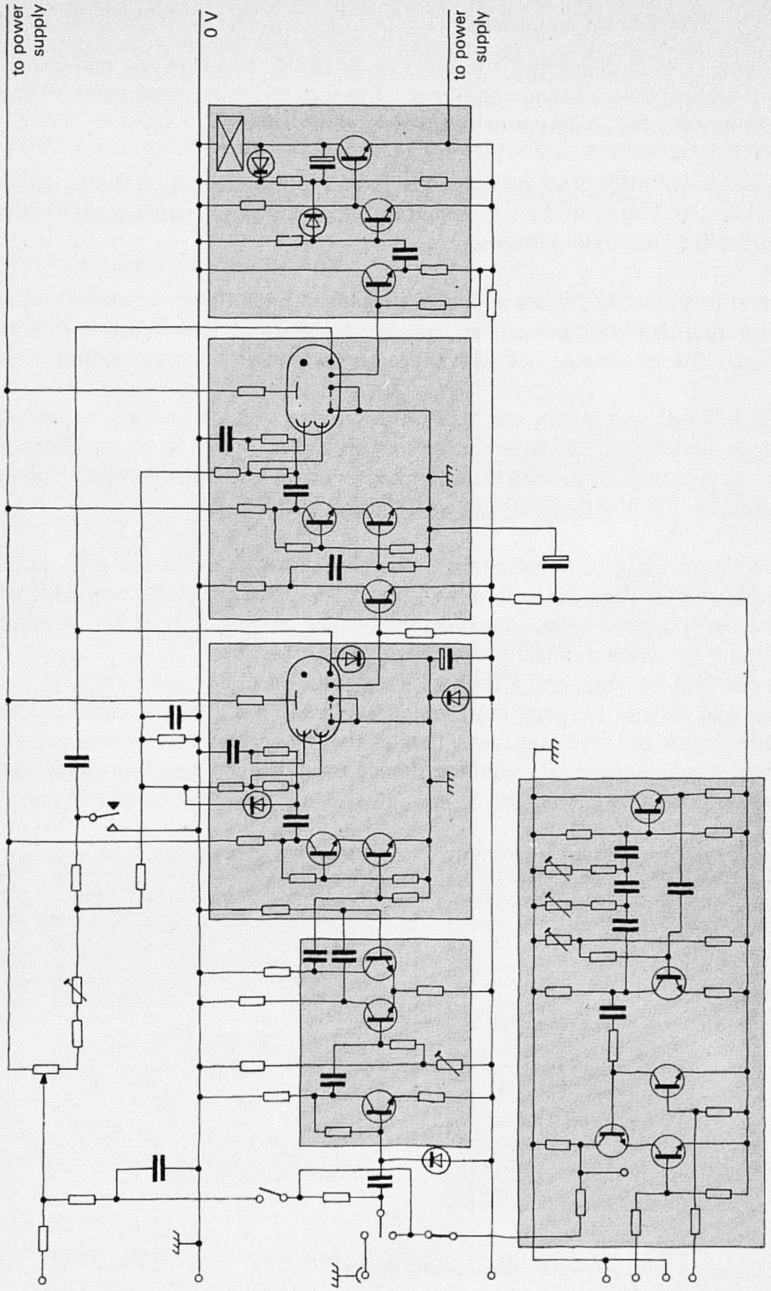



**Figure 3**
Circuit diagram of a scaler–timer (omitting power supply circuits).
*By courtesy of Edwards Scientific International Ltd.*

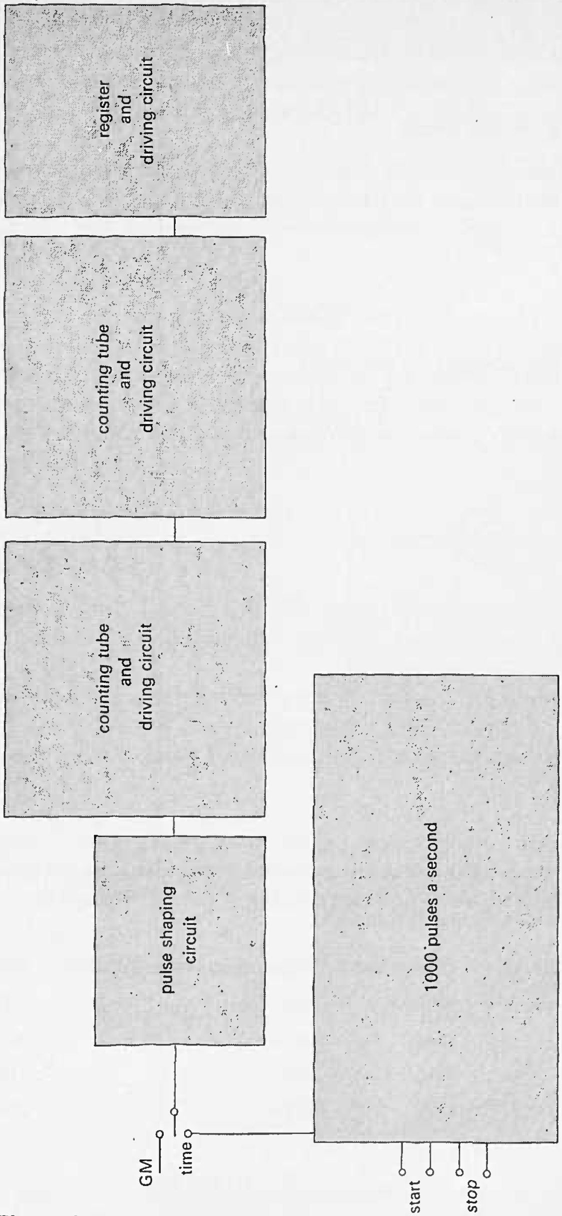



**Figure 4**
Block diagram of a scaler.

Demonstration
## 6.1 Simple radio

1051 tuning capacitor, 365 pF or 500 pF maximum

1037 set of solenoids
*or*
improvised tuning coil (see below)

1051 diode, OA 81 or 1 GP 5

181 general purpose amplifier
*and*
183 loudspeaker (if not in 181)
*or*
1059 earpiece

64 oscilloscope

92X reel of 26 s.w.g. PVC covered wire (for aerial)

1000 leads

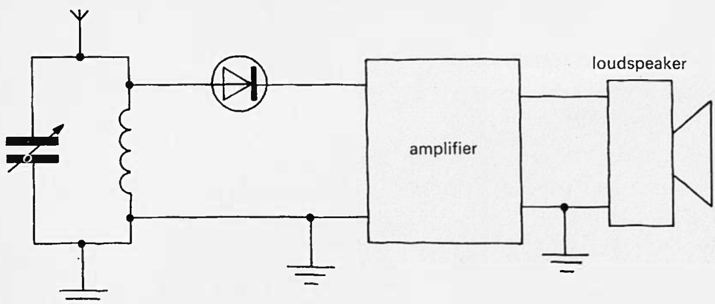



**Figure 5**
Simple radio.

The tuned circuit should be designed to receive the strongest local transmission. The simplest coil is a single layer of turns of enamelled or covered wire wound on a cylindrical former. The self-inductance required for various circumstances is shown in table 1.

| Tuning capacitor/pF | Wave-band | Maximum wavelength/m | Inductance/$\mu$H |
|---|---|---|---|
| 365 | medium | 500 | 200 |
| 365 | long | 2000 | 3000 |
| 500 | medium | 500 | 150 |
| 500 | long | 2000 | 2200 |

**Table 1**

For long wave transmissions, the closely wound solenoids from item 1037 have suitable inductance. A medium wave coil is not hard to improvise from 40 to 50 turns of 24 s.w.g. enamelled wire wound on a cardboard or plastic tube about 70 mm in diameter (a scouring powder carton does well). The tuned circuit should be connected to as long and as high an aerial as possible, and to a good earth such as a water tap. To show the effect of each stage, join the earth connection of the oscilloscope to the earthed side of the circuit, and connect the other oscilloscope input terminal in turn to the outputs of

Figure 3 shows the circuit diagram of one scaler–timer designed for school use, and is even more complicated than the temperature warning device. Like that device, it can be understood by not looking too closely at the detail, but by looking at the functions of various parts. Figure 4 is a block diagram of the scaler. Like the warning device, it contains a part, enclosed in one of the boxes in the figure, which emits a regular train of pulses, but one that does so a thousand times a second instead of once a second.

The remainder of the scaler consists of circuits that count pulses, together with one that enlarges and sharpens pulses from an outside source such as a Geiger-Müller tube, so that they will operate the counters reliably. (There is also, of course, a power supply.)

Electronics can be regarded as being about combinations of building bricks, each of which has a specific job to do. Generally, the job is to do something to a signal; to amplify it, reshape it, pass or block it, count it, and so on. There are not very many different kinds of electronic building bricks, but such amplifiers, pulse shapers, switches, counters, etc., can be arranged into very many different systems to do a whole host of practical jobs.

Demonstration

## 6.1 Simple radio

A simple radio set made out of parts that students have mostly met before in the course can now be used to illustrate the systems story, besides being interesting in itself.

The radio can be laid out along the bench, or better, put together in front of the class. It is made of a row of parts. The aerial brings a signal first to a coil and a capacitor, which passes it on to a diode. From the diode the signal goes through an amplifier to a loudspeaker.

With the tuning circuit set to select a strong signal, it is possible to use an oscilloscope to show how each part of the radio modifies the signal coming to it from an earlier part, looking in turn at the four main parts. Figure 6 shows the block diagram, and the signals at each place.

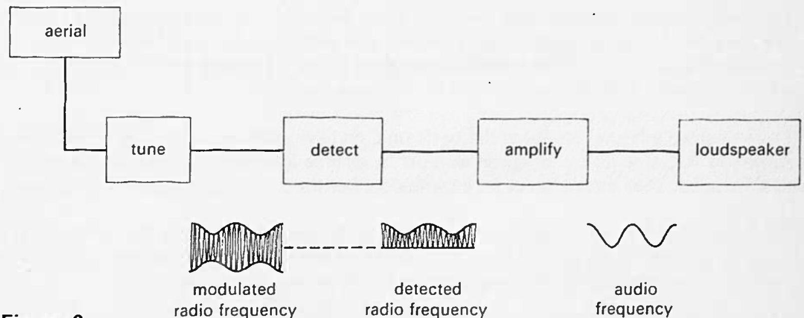


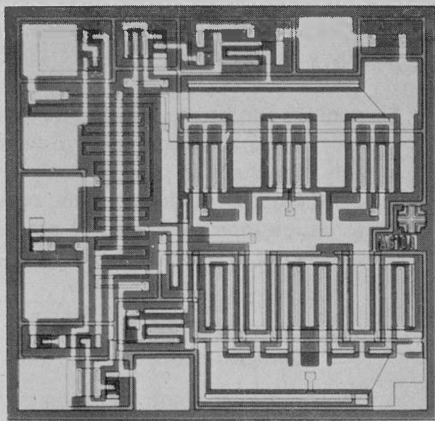

**Figure 6**
Block diagram of simple radio.

the tuned circuit, the diode, and the amplifier. A timebase speed of about 1 ms $cm^{-1}$ is suitable. Some retuning will be needed when the oscilloscope connection is moved from the output of the tuning circuit to the output of the diode.

### Sources of integrated circuits

Complete integrated circuits can be bought from suppliers of radio parts, such as Radiospares Ltd. Griffin & George Ltd sell an integrated circuit which can be put under the microscope for inspection. The article 'Microelectronics' in the *Students' book* contains photographs of the inside of an integrated circuit.

b



a

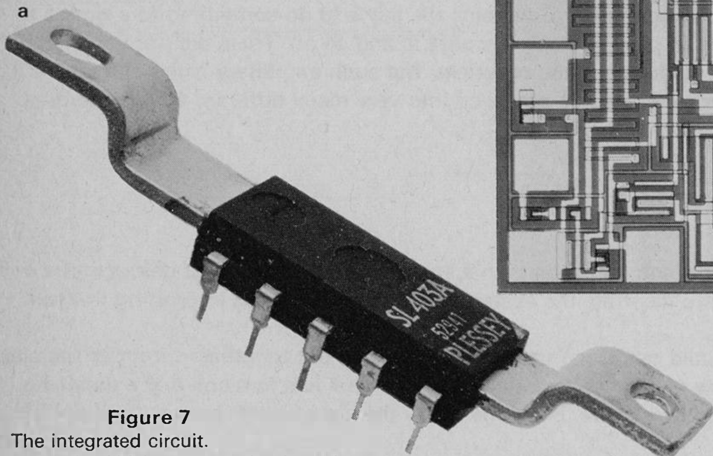



**Figure 7**
The integrated circuit.
**a** The SL 403 integrated circuit package.
*Photograph, Michael Plomer.*
**b** An enlargement of the silicon chip inside the package. The chip is only 1.25 mm × 1.25 mm × 0.2 mm.
*Photograph, The Microelectronics Division, The Plessey Company Ltd.*

### The basic unit used in the electronics kit

The many purpose building brick provided in the electronics kit contains – in the present form of the kit – one *npn* silicon transistor, three resistors, and two capacitors, in the circuit shown in figure 8. It is connected to its power supply either by plugging it into a baseboard or by plugging it together with other units, one of which is connected to the power supply.

More detailed information about the basic unit, and the other modules used in the kit is given in Appendix A. Students can be given as much or as little information about the contents of the basic unit as they want. They *need* little or no information, but they may be happier if they have some.

We have called it a 'basic unit' because it has to have some name, and that name reflects the role it plays in the electronics kit. No electronics engineer would recognize the term, and students should be warned not to expect to find 'basic units' in books about electronics.

The radio is a system of parts, each part with a job to do, which together take a rapidly oscillating signal whose amplitude is changing more slowly, and produce the slow amplitude changes as audible oscillations.

Incidentally, listening with one's ear near the loudspeaker adds several other parts to the total system. The ear converts the sound wave oscillations into electrical impulses again, and the brain interprets these signals.

Some parts of the system are quite complicated inside: the tuning circuit contains two components, but the amplifier contains many. It is convenient and simple to treat the amplifier as a box which makes a signal bigger if that signal has not too high or low a frequency.

### Integrated circuits

An integrated circuit is worth showing, under a microscope if possible, as a sample of modern electronic technology. It illustrates the possibility of packing many components into one module that does a definite job. It may be pointed out that ready-made circuits may well be very important in the future, and are likely to replace devices such as transistors in many of their present applications.

### An electronic building brick

The introduction to the Unit can be completed by saying that students are going to be given a basic electronic building brick (much simpler than the integrated circuit) which can do many of the jobs electronics engineers have found useful. When they know some of the things that it will do, they will be asked to put several units together, as in the radio, to do more complicated and more useful things. An example may help: they could be told that they will be able to build oscillators and counters, as well as some of the units that form part of modern computers and do electronic arithmetic.

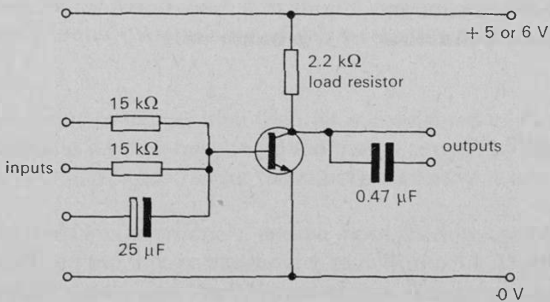



**Figure 8**
Circuit of the basic unit.

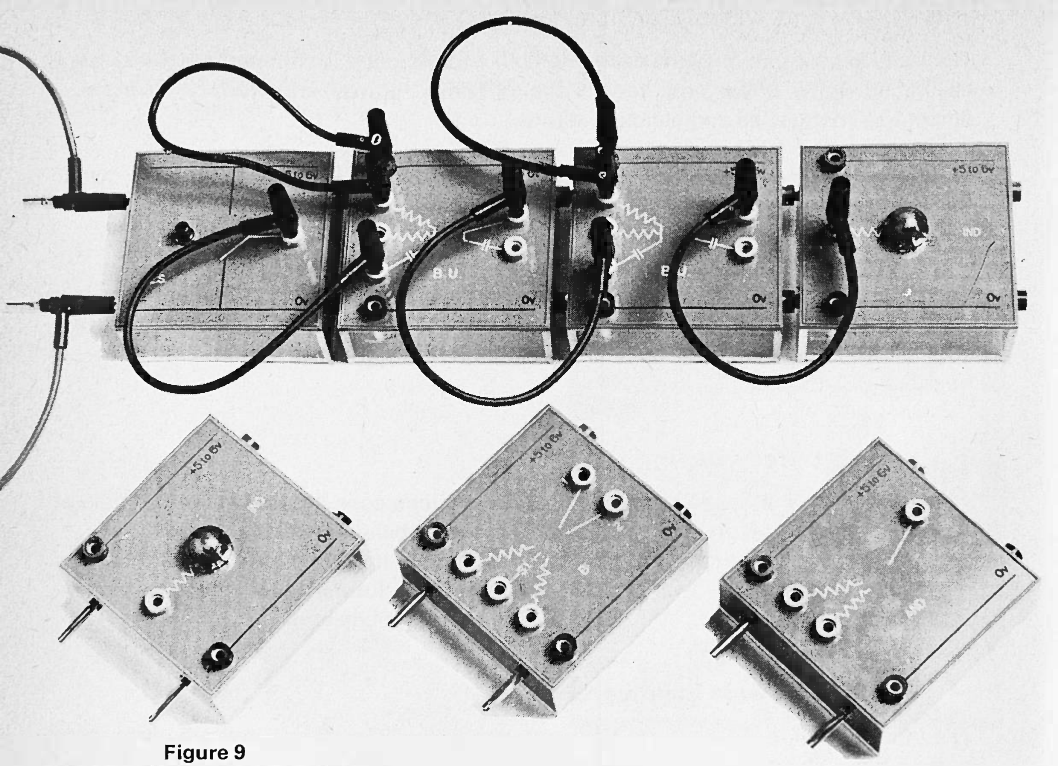



**Figure 9**
Two forms of the electronics kit.
*Photograph, Michael Plomer.*

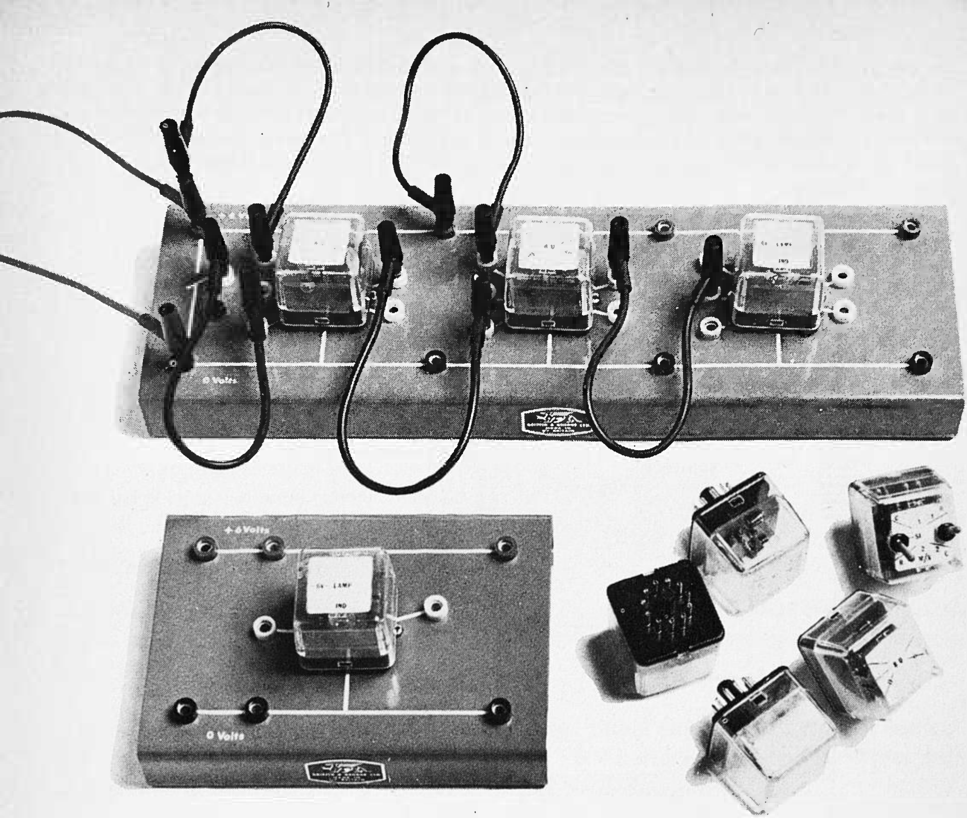
**Time**

Using a combination of demonstration and experiment, experiment 6.2 should take not much more than two or three periods.

Experiment and demonstration

## 6.2 Input and output behaviour of the basic unit

| | |
|---|---|
| 1075 | electronics kit |
| 158 | class oscilloscope |
| 1033 | cell holder with four U2 cells |
| 104 | low voltage power unit<br>*or* |
| 27 | transformer |
| 1041 | potentiometer holder<br>*with* |
| 1051 | 5 kΩ linear potentiometer |
| 1004/2 | voltmeter (10 V d.c.) *2* |
| 1017 | resistance substitution box |
| 1081 | decade capacitance unit (1–10 μF) |
| 1000 | leads |




Experiment and demonstration

## 6.2 Input and output behaviour of the basic unit

The first thing is to find out what the basic unit will do to a signal. Students can do most of the work for themselves, and should certainly start off by themselves, but it may be helpful to mix experiment and demonstration until they have become used to the unit.

It will be necessary to explain that the unit is connected to a low voltage d.c. supply either by plugging it into a baseboard fed from a supply, or by connecting a supply directly to the unit. The top rail for the supply is *positive.*

The unit has three input terminals, and an input is connected to one of them and to the 0 V connection on the unit or baseboard, as in figure 11. The output is taken from one of the output terminals, and the 0 V connection. One input has a capacitor in series with it, inside the unit, while the other two are connected inside to resistors. One output comes direct from the unit, the other output has a capacitor connected to it.

The basic unit has been designed so that no connection a student will normally make to it will harm it, though it may be best to avoid connecting both the direct output and an input to the positive rail at the same time. If the units plug into a baseboard, it is best to have a rule that the supply to the baseboard is to be disconnected while units are being plugged in or taken out. The only other rule is that the top supply rail must be *positive,* using a 5 or 6 V d.c. supply. Four U2 cells in a cell holder makes a convenient supply.

### 6.2a **2 V a.c. input**

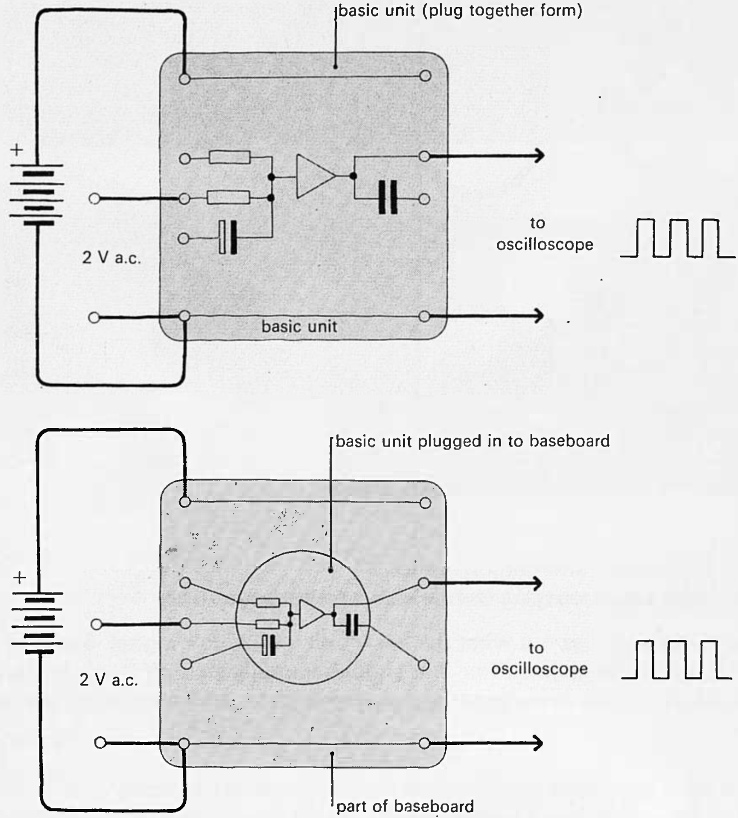



**Figure 10**
2 V a.c. input to a basic unit, showing connections in both forms of the kit.

If the kit in which the modules plug into a baseboard rather than into each other is being used, it will save explanation at this early stage to use the smaller baseboard. This has only one input and one output connection, and when a basic unit is plugged into it, the input is automatically to one resistive input of the unit, and the output is from the direct output of the unit. Otherwise, students will need to be shown where to make the connections. A diagram on the blackboard should be enough.

The 2 V a.c. supply can come from the low voltage power unit (item 104) or a transformer (item 27).

All should be distinguished by markings on the unit so that it is easy to make any desired connection. Inputs are on the left, outputs on the right.

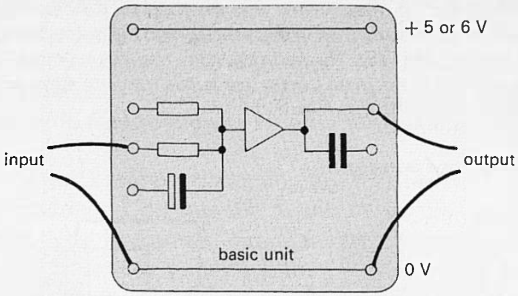



**Figure 11**
Example of input and output connections to basic unit.

### 6.2a **2 V a.c. input**

A good way to start is to try connecting an input of 2 V a.c. to one of the two resistive input connections, and to see what comes out, using an oscilloscope across the direct (not the capacitative) output.

The result may well be a surprise. The sinusoidal signal emerges as a train of square pulses. If the oscilloscope is calibrated with a 1.5 V battery, it will be found that the pulses swing from 0 V to +6 V and back (using a 6 V supply).

It is convenient to have a symbol to represent the effect of the basic unit on a signal, which is quick to draw, and contains enough, but not too much, information. Figure 12 *a* shows one possible symbol, which leaves it understood that the second leads of inputs and outputs always go to the 0 V line. This symbol will be convenient for drawing block diagrams of more complicated systems later on. To save time, only those input and output connections actually in use need be drawn in, as in figure 12 *b*, which records the outcome of the experiment.

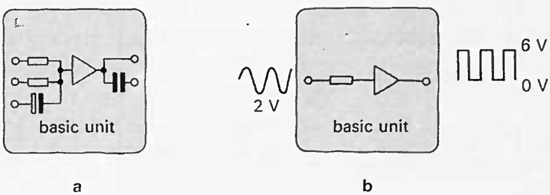



**Figure 12**
**a** Symbol for a basic unit, for use in block diagrams.
**b** Example of a simplified symbol, when only one input and output are in use.
*Note.* The triangle is the usual symbol for an amplifier, which is near enough to the way the transistor and its load function in all the uses of the basic unit to be a fair symbol for them.

*Why the output is squared*

Students are about to find out why the output comes out square. Teachers may want to know earlier. When the input voltage is zero, the output voltage is 6 V, because little current flows in the load resistor (shown in figure 8) that joins the output terminal to the supply rail. As soon as the input voltage rises over half a volt or so, a large current flows in this resistor, and the output voltage drops to near zero, there being nearly 6 V across the load. The output voltage can vary no more than this, so it swings sharply between 0 V and 6 V as the input passes just above zero, but stays constant while the input makes the rest of its sinusoidal changes. See figure 14.

### 6.2b Input and output voltages

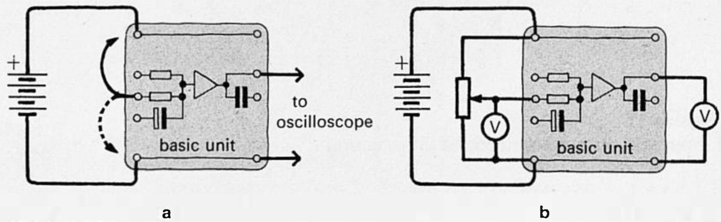



**Figure 13**
**a** Input +6 V or 0 V d.c.
**b** Input varied from 0 V to +6 V.

First, as in figure 13 *a*, one resistive input can be joined to the +6 V rail and then to the 0 V rail. The output goes from 0 V (6 V input) to 6 V (0 V input). If there is a switch module, or a switch on the baseboard, it can be used to make these input connections, but its use is hardly worth the time.

Next, as in figure 13 *b*, the input voltage is varied continuously from 0 V to 6 V using a potentiometer connected across the supply, with voltmeters to indicate the input and output voltages. High resistance voltmeters (100 µA movement) are essential. It would be convenient to have a potentiometer module as part of the kit, but item 1041 (potentiometer holder) serves perfectly well.

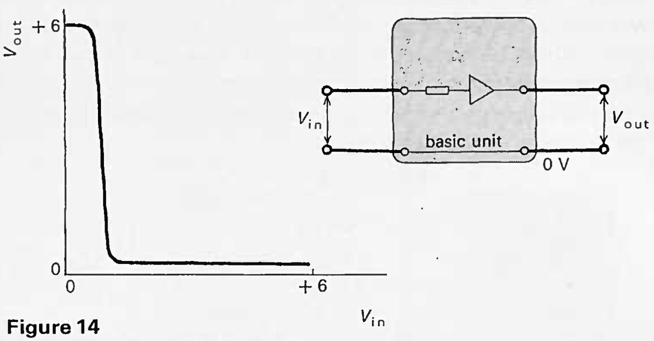



**Figure 14**
Input–output characteristic of the basic unit.

#### Pace of teaching

The experiments (6.2) on the basic unit serve as much as anything to get students used to it, though the results are needed later. But it would be a mistake to let them drag, for there will be many later opportunities to handle the unit. Slow, timid workers might be encouraged by being given some form of data sheet to complete, which shows a suggested circuit and indicates what to do.

### 6.2b **Input and output voltages**

Now that students have seen the unit doing something to a signal (and the ability to produce square pulses will be very useful later on) it should be natural to look in greater detail at just how the output voltage changes when the input voltage is varied. The alternating signal is changing rapidly. How could the input voltage be varied more slowly, to see what happens at each stage? The use of a d.c. voltage, and a potentiometer to vary it, may emerge as suitable suggestions.

It is useful to try the quick test of connecting one resistive input to the 6 V and 0 V rails, with an oscilloscope to indicate the output. When the input is high, the output is low, and vice versa. What happens in between these extreme voltages? Some students will be able to deduce something from the trial with a 2 V a.c. input. Offer a potentiometer to vary the input slowly over the range 0 V to 6 V. Figure 13 *b* shows a suitable circuit.

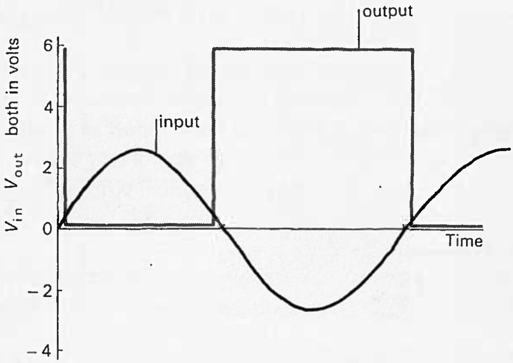



**Figure 15**
Almost square output from sinusoidal input.

A graph of output voltage against input voltage should be plotted, giving the input–output characteristic of the basic unit (using the resistive input). It looks like figure 14. The output voltage swings sharply from nearly +6 V to nearly 0 V as the input rises by a small amount just above 0 V. For all input voltages larger than the one for which the changeover is complete, the output voltage is low. If desired, small, negative input voltages can be tried: the output stays steady at +6 V.

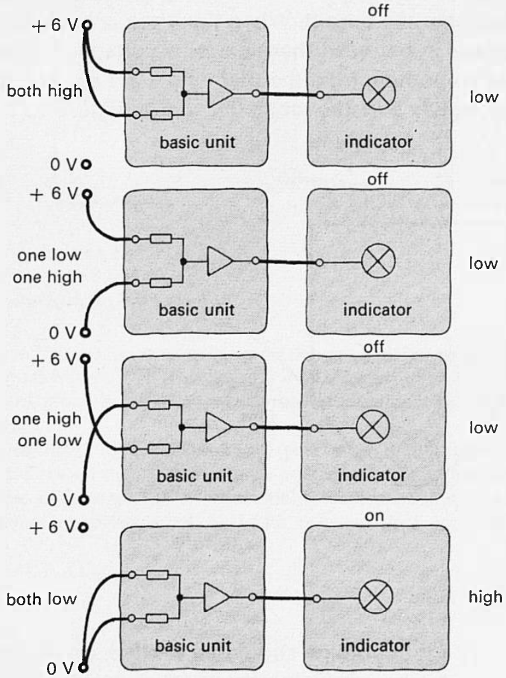
It is worth making sure that students realize that the two resistive inputs are identical, perhaps simply by allowing them to use either.

The graph may now be used to explain how the sinusoidal input in 6.2a comes out square, as shown in figure 15. It may be worth checking that, as expected, the 'high' part of the square output lasts a little longer than the 'low' part, and that the 'walls' of the square pulses are not quite vertical, but tilt because the changeovers from 6 V to 0 V and vice versa occur over a narrow but finite range of input voltages.

Others, especially the electronics experts to be found in most classes, will be impatient for more ambitious undertakings. They might be asked now, for example, to set up an arrangement with an oscilloscope so that it displays the graph of output voltage against input voltage on the screen. (Turn off the time base, connect $V_{in}$ to the X-input of the oscilloscope, connect $V_{out}$ to the Y-input, and vary $V_{in}$ slowly, perhaps using the low frequency a.c. generator, item 170.)

### *Students' book*

See questions 9 and 10, which are about the input–output behaviour of a basic unit. Questions 14 and 15 follow up the idea of using the unit as an amplifier.




| Input 1 | Input 2 | Output |
|---|---|---|
| high | high | low |
| high | low | low |
| low | high | low |
| low | low | high |

| Input 1 | Input 2 | Output |
|---|---|---|
| 1 | 1 | 0 |
| 1 | 0 | 0 |
| 0 | 1 | 0 |
| 0 | 0 | 1 |

**Figure 16**
The basic unit as a *nor*-gate, showing two forms of 'truth table'.

### Truth tables

Truth tables were invented by a philosopher. They first appeared in Ludwig Wittgenstein's beautiful, intensely difficult, and influential book, *Tractatus logico-philosophicus.* Wittgenstein used truth tables as a way of displaying the logical relations of the truth or falsity of compound propositions ('so-and-so or such-and-such', for example) and the various possibilities for the truth or falsity of their constituent propositions.

There is no need to explain any of this, unless the class wonders what 'truth' has to do with switches.

### *Students' book*

See questions 5 to 8, which use and develop the idea of a truth table.

What might be the possible use of a unit that squares a sinusoidal input? Maybe sharp square pulses would be easier to count; in fact computers do their arithmetic on square pulses representing digits. Indeed the pulse-shaping part of the scaler, figure 4, discussed previously, has a very similar function.

Because the output swings through nearly 6 V while the input changes by much less than this, the unit is potentially an amplifier of voltage changes. Students will use it as such later on.

### 6.2c **The basic unit as a switch with two inputs**

If they have not already done it of their own accord, students can now try connecting each of the two resistive inputs to either +6 V or 0 V, to see what the output does. It is convenient to introduce the lamp indicator module here, as a quick way of observing whether the output is high or low. (Show that the lamp lights when its input is +6 V – high – but not when its input is 0 V – low.)

The result of trying both inputs is simple enough. Only when both of the inputs are low is the output high and the lamp alight. The output is high when *neither* one *nor* the other input is high. Used as a switch, the device might be able to light a lamp in a room when the room was neither in daylight (signal from a photocell) nor locked up for the night (signal from a contact in the door lock). Then one would never need to put the lights on – they would come on when needed.

Such a switch is called a *nor*-switch or *nor*-gate. Students will be exploring what can be done with them in various combinations, in *experiment* 6.4.

Figure 16 shows the four possible circuit combinations, and also shows ways of tabulating the results. It is clearer, as in the first table, to write 'high' or 'low' for the various possibilities; it is quicker to write 1 or 0 instead, as in the second table. Besides being quicker, the second way has the advantage that such methods are used in computers where pulses represent digits or decisions – such as, 'Yes, there is a number greater than zero in the store.'

Such 'truth tables', as they are called, are an economical way of writing down what a switching circuit does, or is meant to do. They are helpful, but not absolutely essential, for this course.

### Demonstration of experiment 6.2d

The effect of adding capacitance or resistance in series with the two inputs (shortening or lengthening the pulse) is the kind of thing that can profitably be argued out quickly with the class as a whole, with demonstrations of the effects confirming rough expectations, but which would eat up time if students had to be told what to do so as to try it individually. The treatment can be brief to the point of brusqueness: Part Two is the place for a longer discussion of *RC* circuits.

The action of the circuit is explained in Appendix A.

### 6.2d The basic unit as a pulse producer

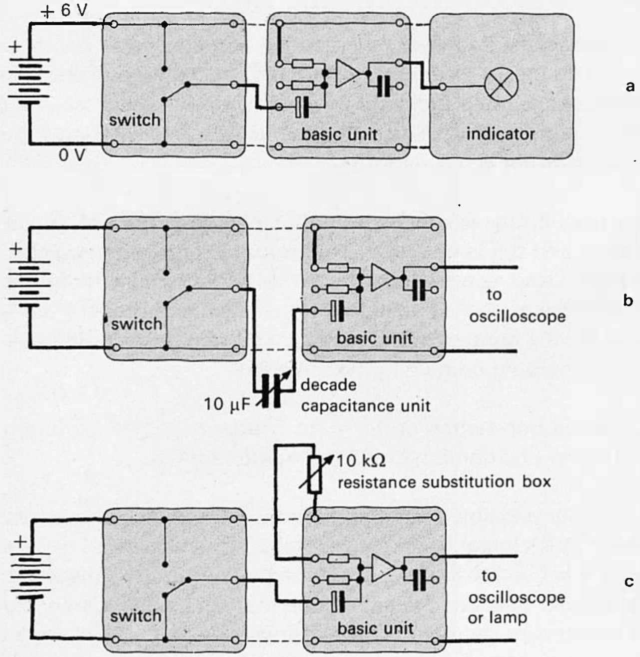



**Figure 17**
Circuits for using the basic unit as a pulse producer.
**a** Single pulse.
**b** Shorter pulse.
**c** Longer pulse.

Figure 17 shows circuits for showing the basic unit as a pulse producer, using items from the list of apparatus on page 18. It is best to start by using a flying lead to the capacitative input, touched in turn to +6 V and 0 V, changing later to the switch method shown. All three trials (figure 17 *a, b, c*) can be shown both with the lamp indicator (as in *a*) and with an oscilloscope (as in *b* and *c*).

The switch is either in a switch module, as shown in figure 17, or is part of the baseboard into which the basic unit and other modules are plugged.

#### *Students' book*

See questions 12 and 13.

### 6.2d The capacitative input: the basic unit as a pulse producer

The basic unit will play another interesting, perhaps surprising trick. As shown in figure 17, connect one resistive input to +6 V, when a lamp indicator connected to the basic unit will be off. Then take a lead from the capacitative input, which has been ignored so far, and touch it onto the +6 V rail. Nothing happens. *Then* touch this lead onto the 0 V rail. The lamp comes on for a moment, and then goes off again.

Instead of using a flying lead, a switch in the lead to the capacitative input can be switched first to +6 V, and then to 0 V. When the lamp has been seen to light, an oscilloscope can be used in its place; then it can be seen that the unit emits a positive going 6 V square pulse when its capacitative input swings from +6 V to 0 V.

The effect is the result of the changes in charge on the input capacitor, which is connected to +6 V through the input resistor which was joined to the +6 V rail. It would be unwise to go into detail now, and it is what the unit does rather than how it does it which is important for the moment. *RC* circuits can be discussed more fully later on. But students know enough about the rate of change of charge on a capacitor (from Unit 2), to be able to predict that making the capacitance smaller should decrease the time taken for its charge to change, while raising the resistance connected to it should increase the time. Both can be tried, the first by putting a capacitance in series with the capacitative input (two capacitors in series have a lower capacitance than either alone), the second by putting extra resistance in series with the resistive input which is joined to the +6 V rail. The pulse can be made to last for perhaps five seconds, or can be reduced to a very brief time.

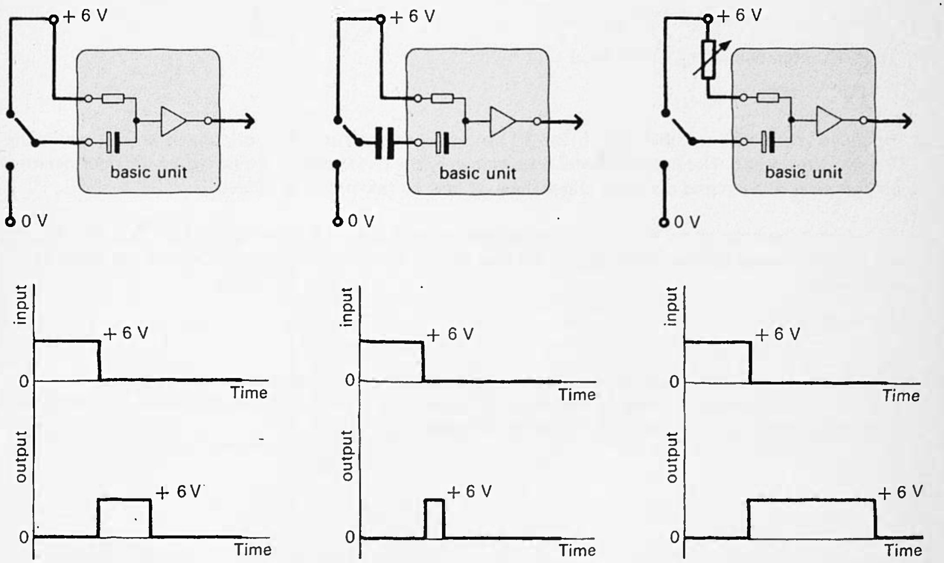



**Figure 18**
Changing the length of the output pulse.

### Action of the basic unit circuit, and action of a transistor

There is, of course, nothing wrong with knowing how the basic unit works, or with hearing simplified stories about how transistors work. But if time is spent on these matters, it will have to be taken from things we regard as more important and, in the long run, more valuable: namely, using the kit to construct interesting and useful systems.

Most physics teachers will want to include experiment 6.3 at least, recognizing it as closely related to basic physics. In this context, that may be a bad reason, for this Unit is not about the basic physics of the devices but about using them. If the basic unit contained a complicated integrated circuit amplifier, one would have no more of a bad conscience if one treated it as a 'black box' than one does in handing out stop watches to younger students without a previous discussion of balance wheels, hair springs, and escapements.

A good reason for including the experiment is that it may make students happier, and readier to go on and use the basic unit with confidence. If they want to hear about how transistors work, they can and should be given whatever information they want (with the caution that most of the stories told are partly fictional). The best way, rather than to use up good class time, is to refer interested students to one of the many books which discuss the transistor. A list appears on page 154. It should also be made clear that transistors are far from being the latest word in electronic technology, and what students learn about them now may be of only limited use in a few years' time.

Optional experiment

## 6.3 Input and output currents in the basic unit

1075 electronics kit

1033 cell holder with four U2 cells

1041 potentiometer holder
*with*
1051 preset potentiometer, 5 kΩ

1002 microammeter (100 μA d.c.)

1003/2 milliammeter (10 mA d.c.)

1000 leads

Figure 19 *d* shows a suitable circuit. The 10 mA meter (resistance 10 Ω) effectively short-circuits the 2.2 kΩ load resistor. The potentiometer is used to vary the base current, measured by the microammeter, so that pairs of base and collector current values may be taken, and graphed.

As an extra, one can show that if the base current is set to one of its previous values (say 80 μA), after the supply voltage has been reduced to 4.5 V or to 3 V, the collector current is almost the same as it was before.

*Limitation of collector current*

Note that in the circuit of figure 19 *a*, the collector current cannot be larger than the ratio *supply voltage/load resistance*. In the circuit of figure 19 *d*, it can rise above this value, since the meter shunts the load. This difference may need to be mentioned.

Optional experiment

## 6.3 Input and output currents in the basic unit

Many students will want to know why the output of the basic unit goes down, rather than up, when its input goes to a high voltage. They do not *need* to know, but many will feel happier if something is said about this curious property.

A simple experiment can show part of the reason. Figure 19 *a* shows the circuit inside the basic unit. When either resistive input is connected to +6 V, a current flows down it to point B, the 'base' of the transistor, and thence via E, the 'emitter', to the 0 V rail. This current $I_B$ is measured in the experiment.

When the box is connected to a 6 V supply, another current flows down the 'load resistor' (2.2 kΩ) to point C, the 'collector', and thence via E to the 0 V rail. This current $I_C$ is also measured: it turns out to be a good deal bigger than $I$ .

$I_B$ can be varied by taking the input voltage from a potentiometer. $I_C$ increases as $I_B$ increases, but the base current $I_B$ is only of the order of 10–100 μA, while $I_C$ is of the order 1–10 mA. A small current controls a larger one. How it does it is not so simple to explain.

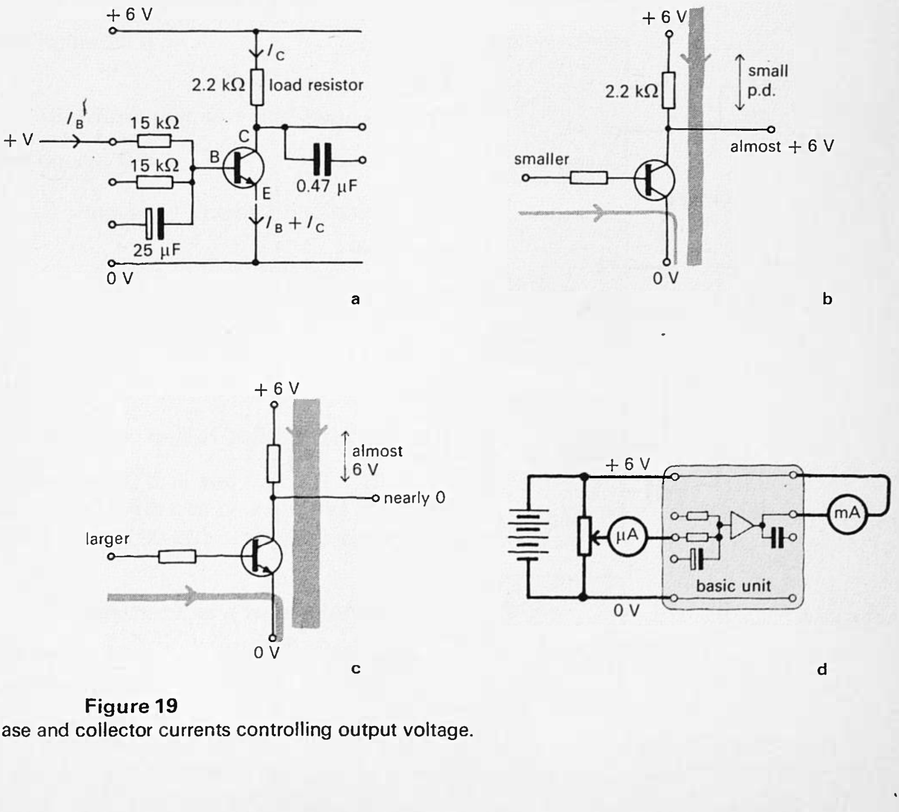



**Figure 19**
Base and collector currents controlling output voltage.

*Students' book*

The list of things the basic unit can do appears in the *Students' book* on page 75.

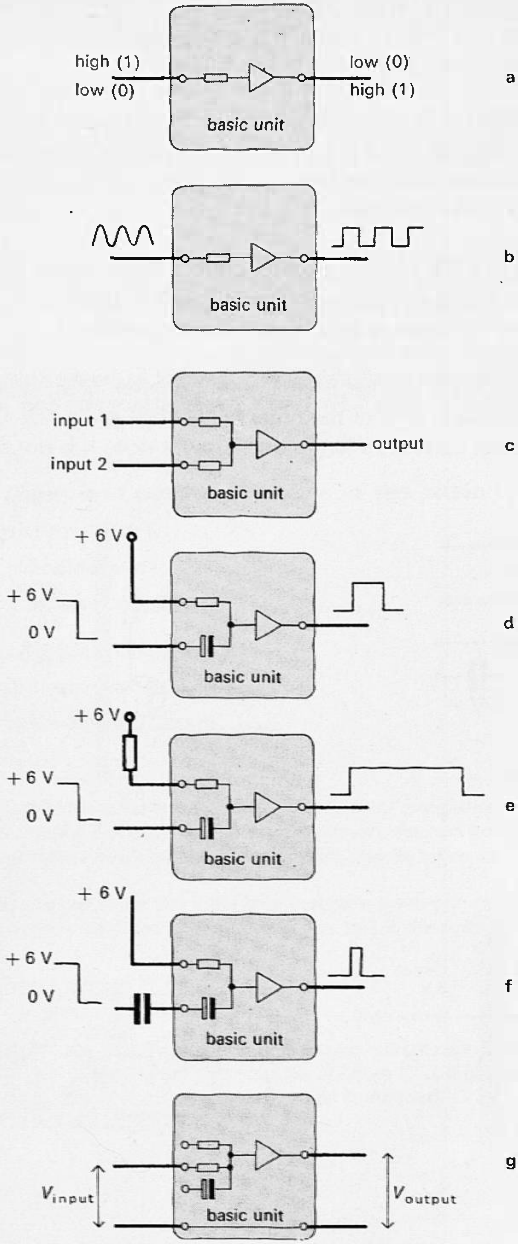



**Figure 20**
Uses of the basic unit.

In figures 19 *b* and *c*, the size of the currents $I_B$ and $I_C$ is represented by the width of the shading beside the wires they flow in. In *b* a low input voltage across the input resistor gives a small base current and a modest collector current. The p.d. across the load resistor through which $I_C$ flows is small, so the output terminal connected to the resistor is nearly at +6 V. But when $I_C$ is bigger, as in *c*, the p.d. across the load resistor can rise to almost 6 V, when the output must be down to 0 V, approximately. Thus the output can swing between the limits +6 V and 0 V, and is high when the input voltage is low.

## Review: the basic unit as a many purpose building brick

Students are now ready to start some electronic engineering, putting basic units together into simple systems to do new things. It should be helpful, before they start, to summarize the various jobs the basic unit can do on its own.

1 *Basic unit as a switch or inverter*

See figure 20 *a*.

2 *Basic unit as a squarer*

See figure 20 *b*.

3 *Basic unit as a two-input* nor*-gate*

See figure 20 *c*.

| Input 1 | Input 2 | Output |
|---|---|---|
| 1 | 1 | 0 |
| 1 | 0 | 0 |
| 0 | 1 | 0 |
| 0 | 0 | 1 |

4 *Basic unit as a pulse producer or timer*

See figures 20 *d*, *e*, and *f*.
The pulse length can be extended or shortened using an extra resistor (about 10 to 20 kΩ, up to 100 kΩ) or an extra capacitor (about 10 μF).

5 *Basic unit as a voltage amplifier*

See figure 20 *g*. See also figure 38 (page 39), for a more developed version of an amplifier circuit.

Over a narrow range of input voltages (0.5 to 1.0 V roughly), the change of output voltage is proportional to the change of input voltage, but is larger.

### First group of electronic jobs

At the end of the Unit, there will be another group of tasks, more complicated than those suggested here. These two groups of tasks are the heart of the Unit. They are not luxury extras: an aside from the serious business of learning electronics, for in this Unit learning about electronics *is* doing things with electronic devices, and inventing new systems.

Students will need hints and oblique help, but not recipes. If they have recipes given them, they will work faster and do more, no doubt, but will have little opportunity to use their own initiative and inventiveness. Since an important lesson from this Unit is that engineering is a matter of being inventive, it would be a pity to lose that lesson.

We suggest that each student should try two jobs or so in this group. It is necessary to allow one or two double periods of practical work for it; at this point the benefit of having saved time earlier will show. Not all the suggested jobs need be tried. The important ones, used a lot later on, are the bistable, the astable, the *and*-gate, and the amplifier. Some can be held over until experiment 6.19, in Part Four.

Experiment
## 6.4 Jobs to do, using simple combinations of modules

1075 electronics kit

1033 cell holder with four U2 cells

158 class oscilloscope

1017 resistance substitution box

1018 capacitance substitution box

1047 two-terminal box with cadmium sulphide resistor

1047 two-terminal box with diode

1009 signal generator

104 low voltage power unit
*or*
27 transformer

1040 clip component holder (with assorted components)

1041 potentiometer holder
*with*
1051 preset potentiometer, 5 kΩ

1021 aerosol freezer

157 microphone

1059 earpiece

132N thermistor (TH3)

1000 leads

***Students' book***

The jobs suggested below are set out in the *Students' book*.

Experiment
## 6.4 Jobs to do, using simple combinations of modules

At this point, in an important sense, the real work begins. The task of an engineer is to see how inventive he or she can be, using the materials that are available. He or she has to know what the materials are capable of doing, and that is what the work so far has been about, so far as the basic unit is concerned.

Any useful electronic device contains several such parts, arranged so as to achieve a particular purpose. At this stage, students are invited to see what they can achieve by putting basic units together into simple systems.

There follows a list of suggested jobs to do. Given some help, they need not prove to be very difficult. Nor need they be tackled too solemnly, and there is no reason to prevent students playing a little with combinations they fancy. Many of the systems that they will make in that way are interesting and some are surprising.

The first group of jobs, 6.4a to 6.4g, are intentionally rather simple ones. For each job, a suggested brief is given, which will need to be varied according to the ability and confidence of the group trying it. One solution is suggested; sometimes more than one. Most jobs have more than one solution. For some jobs, possible extensions are also indicated.

### 6.4a Make a lamp go out for five seconds

Use two basic units and extra resistors or capacitors to make an indicator lamp go out for five seconds.

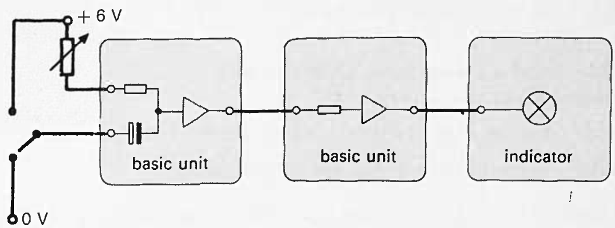



Figure 21

### 6.4b Make a lamp go on from a +6 V input

Use two basic units to make an indicator come on when the input goes to +6 V.

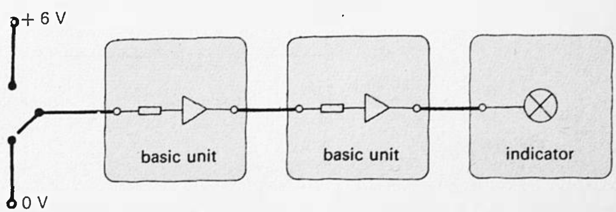



Figure 22

### 6.4a Make a lamp go out for five seconds

*In addition to the electronics kit:*

1017 resistance substitution box.

Capacitors are not essential, but it is helpful if they are available. The second basic unit acts as an inverter.

### 6.4b Make a lamp go on from a +6 V input

This relatively trivial job could be linked to the next, 6.4c. Although it is trivial, it is the basis of the *or*-gate, which has some importance.

### 6.4c Make a lamp flash from an input rising to +6 V

Extensions: vary the length of the pulse; see if using both resistive inputs to the pulse-producing basic unit connected in parallel to +6 V halves the pulse length.

### 6.4d Making spikes

*In addition to the electronics kit:*

158 class oscilloscope

1017 capacitance substitution box

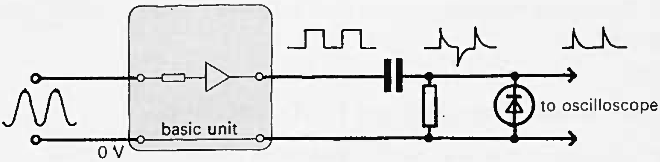



**Figure 23**

The capacitative output of the first basic unit could be used in place of an extra capacitor. An alternative solution uses an *RC* circuit and a diode (figure 23).

### 6.4e Make a lamp come on in the dark

*In addition to the electronics kit:*

1047 two-terminal box with cadmium sulphide cell

1017 resistance substitution box may be needed

It is better to feed the system from a potential divider containing the cadmium sulphide cell, than to use the cell alone. The cell should always have at least 200 Ω in series with it. An alternative solution is shown in figure 24.

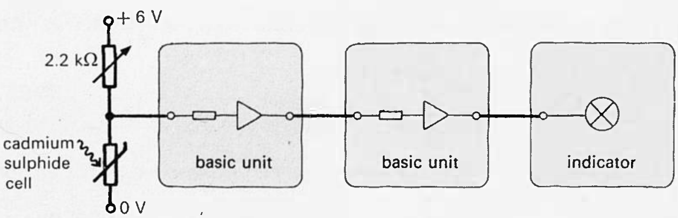



**Figure 24**

## 6.4c Make a lamp flash from an input rising to +6 V

Use two basic units to make an indicator flash on for a moment when the input goes to +6 V, and stays there.

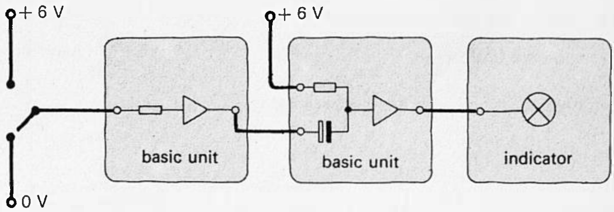



Figure 25

## 6.4d Making spikes

Turn an alternating supply into short, sharp spikes. It helps to square the alternating input first.

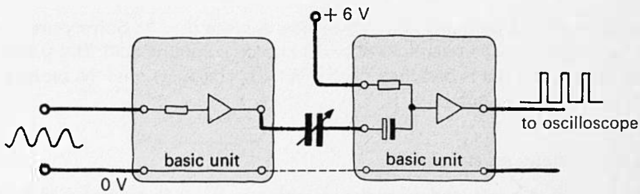



Figure 26

## 6.4e Make a lamp come on in the dark

The resistance of a cadmium sulphide cell decreases when light shines on it. Use one of these cells to make an indicator lamp come on when the cell is in darkness.

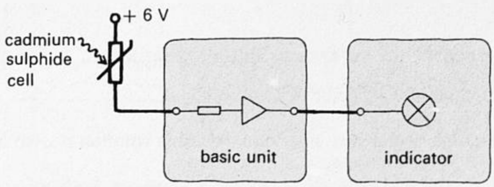



Figure 27

6.4f **Make an icing-up warning device**

*In addition to the electronics kit:*

132N thermistor (TH 3)

1040 clip component holder

1017 resistance substitution box

1021 aerosol freezer

An alternative solution is shown in figure 28.

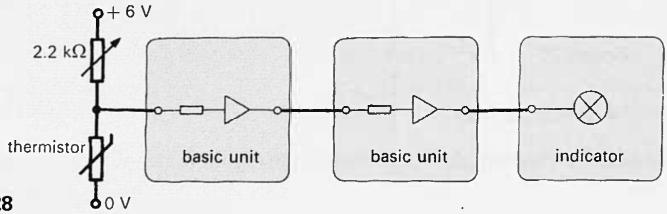



**Figure 28**

Extension: make a humidity warning device. A piece of solid polystyrene (from a bottle, not expanded polystyrene) is soaked overnight in concentrated sulphuric acid. The surface molecules become sulphonated, and if it is breathed on, the surface conducts until the moisture evaporates, because ions are liberated by the moisture.

6.4g **Make an *or*-gate**

This is easy, but could lead on to the bistable system, 6.4h, with the addition of only one more wire (the feedback wire from the output of the second unit to the input of the first). See question 16.

6.4h **Make a bistable circuit**

This circuit is particularly important, and this job should not be omitted. Note that it introduces the first feedback loop used so far, and, as so often, the introduction of feedback produces novel and perhaps unexpected results. See question 17.

6.4i **Make a circuit that pulses continually (astable)**

This is an important circuit and should not be omitted.

Extension: make the pulse beat a very slow one. Possible solution shown in figure 29.

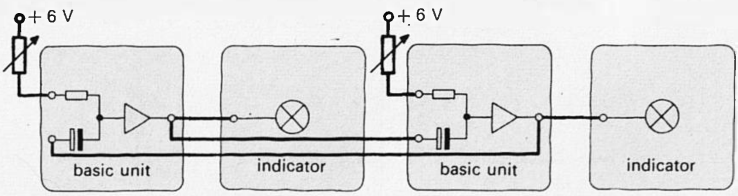



**Figure 29**

### 6.4f Make an icing-up warning device

The resistance of a thermistor rises when it gets colder. Use one to make a system that lights a lamp when icy conditions exist. (Cool the thermistor with an aerosol freezer.)

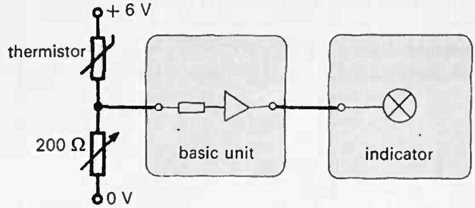



Figure 30

### 6.4g Make an *or*-gate

Make a system of two basic units so that the output of one is high when either or both of two inputs to the system are high.

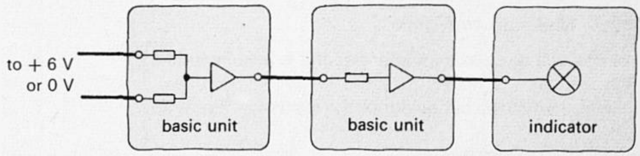



Figure 31

### 6.4h Make a bistable circuit

Interconnect two units so that only one of them can have a high input at any one time, and if the one that is low is made to go high, the other at once goes low.

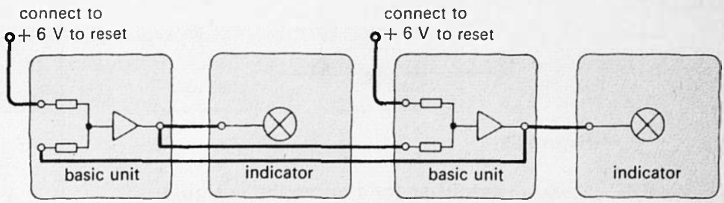



Figure 32

### 6.4i Make a circuit that pulses continually (astable)

Connect two units so that each sends short pulses to the other, and the system produces a steady train of pulses.

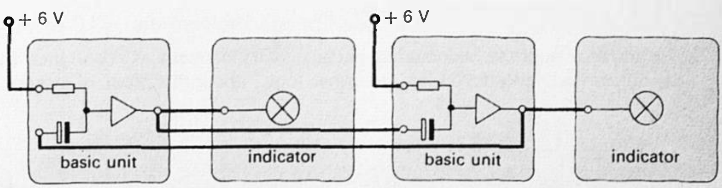



Figure 33

### 6.4j Make an astable that produces an audible tone

*In addition to the electronics kit:*

1018 capacitance substitution box *2*

The extra capacitors could both be of the order of 0.1 μF.

Extension: switch the system from a push button, to make a Morse sender. An earpiece must be connected via the capacitative output. Possible solution shown in figure 34.

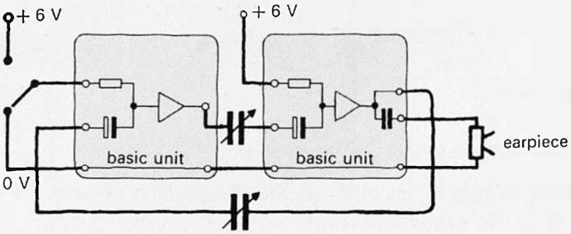



**Figure 34**

### 6.4k Make an *and*-gate

This circuit will be used a lot later on, and is best included.

Extension: predict the behaviour of the system in figure 35.

***Students' book***

See question 8.

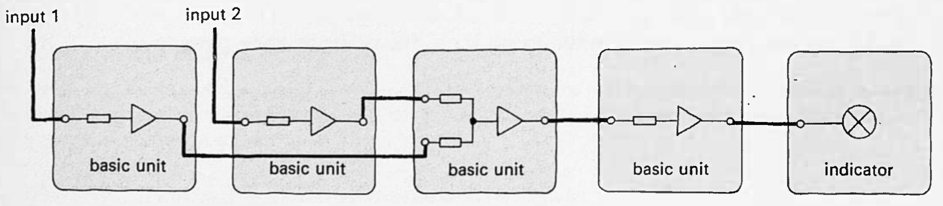



**Figure 35**

### 6.4l Make an amplifier for a microphone signal

*In addition to the electronics kit:*

157 microphone

158 class oscilloscope

1041 potentiometer holder
*with*
1051 preset potentiometer, 5 kΩ

The amplifier ought to be included, because of its interest and importance, but also because it offsets the otherwise strong flavour of 'electronic logic' about this group of tasks.

## 6.4j Make an astable that produces an audible tone

Speed up the astable (6.4i) and make it produce a tone in an earpiece.

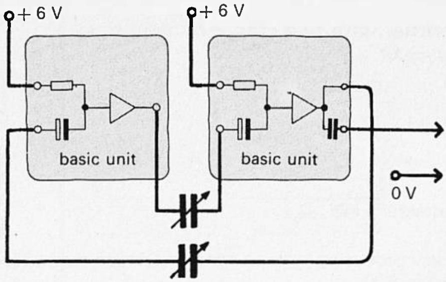



Figure 36

## 6.4k Make an *and*-gate

Use three basic units to make a system with two inputs, and one output which is high only when both inputs are high together.

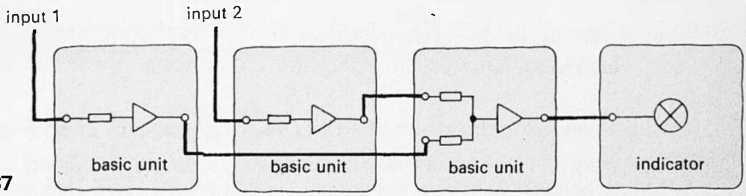



Figure 37

## 6.4l Make an amplifier for a microphone signal

A microphone connected to the capacitative input of a basic unit gives the unit a small input. A magnified signal can be obtained if the output is allowed to vary over the right range by controlling the current in another input. (Recall the graph of input voltage against output voltage.)

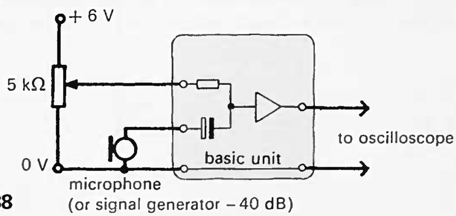



Figure 38

The following jobs, 6.4m to 6.4p, are harder ones to keep fast-working students busy.

### 6.4m Make a monostable circuit

The monostable circuit can be used to flip over and back after a +6 V signal arrives at one input, putting out a square pulse of preset length.

### 6.4n Make an amplifier with two stages of amplification

*In addition to the electronics kit:*

| | |
|---|---|
| 157 | microphone |
| 158 | class oscilloscope |
| 1041 | potentiometer holder *2* *with* |
| 1051 | preset potentiometer 5 kΩ *2* |

The two-stage amplifier is worth using with an earpiece, which draws too much current to be effective with the one-stage amplifier, 6.4l.

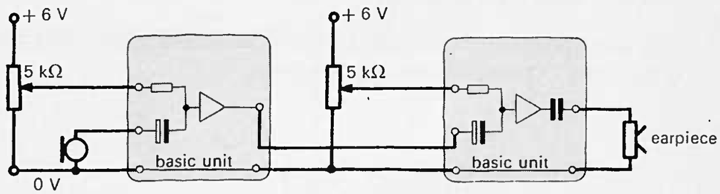



**Figure 39**

### 6.4o Investigate the effect of strong negative feedback on an amplifier

See experiment 6.11. The arrangement is a crude integrator, so that if the input rises sharply from 0 V to +6 V, the output rises more or less linearly, and falls linearly again when the input steps back from +6 V to 0 V. The circuit stops 'integrating' when the output reaches about +6 V or 0 V, and will not handle negative going inputs.

It is the sort of circuit one can use to puzzle the knowledgeable student, not one to give to inexperienced people.

### 6.4p Make a *parity*-gate

This demands some hard thought. It best follows previous use of the *and*-gate. The *and*-gate module should be given out, unless the students want to work with six basic units at once.

***Students' book***

See question 18, which nearly gives the answer.

## 6.4m Make a monostable circuit

Half way between the bistable (6.4h) and the astable (6.4i) is a system that has one of two units on whenever the system is undisturbed, though the other unit can be switched on for a time.

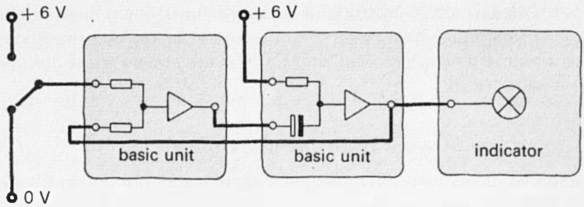



Figure 40

## 6.4n Make an amplifier with two stages of amplification

Add another stage to the amplifier (6.4l).

## 6.4o Investigate the effect of strong negative feedback on an amplifier

See what the system in figure 41 does when it is given step-like inputs. Try square and sinusoidal inputs too. It is the 'poor man's integrating operational amplifier'.

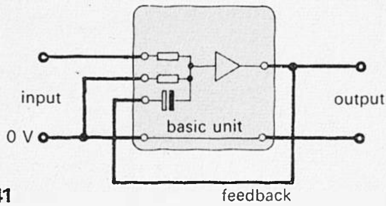



Figure 41

## 6.4p Make a *parity*-gate

Make a system using an *and*-gate and three basic units to give a high output only when both of two inputs are high or both are low.

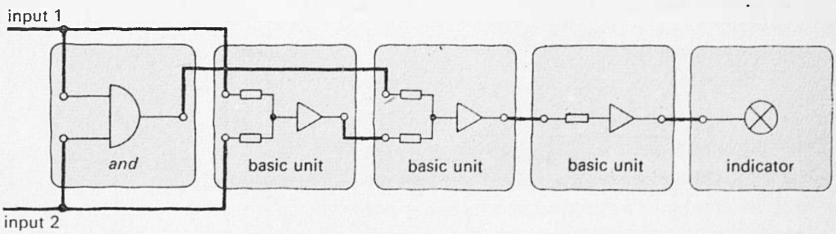



Figure 42

### Further modules in the electronics kit

Students have now built an *and*-gate, a bistable circuit, and an astable circuit, using the basic unit. These are wanted often enough for it to be helpful to have them put, ready made, into modules so that ambitious projects are practicable which would otherwise use up many basic units and much time connecting them.

This Part concludes by showing students these modules, using them to ensure that every student has seen these three circuits, which have so far been seen by only a proportion of the class. The amplifier, as one other important electronic building brick, is then given some attention. A new idea – that of feedback – is introduced.

### Reporting of work from experiment 6.4

Demonstration 6.5 deals with the *and*-gate, bistable, and multivibrator modules. (The latter combines astable, bistable, and monostable circuits.) Demonstration 6.6 deals with amplification. As far as possible, these should be done, or introduced, by those students who worked on the relevant tasks in experiment 6.4. The teacher will need to add comments about and demonstration of ways in which the new modules differ from the circuits made so far.

Other reports, of less important tasks, will need to be kept brief.

## Demonstration
## 6.5 Bistable module; multivibrator module; *and*-gate module

1075 electronics kit

1033 cell holder with four U2 cells

1007 double-beam oscilloscope

1017 resistance substitution box

1000 leads

104 low voltage power unit

181 general purpose amplifier

183 loudspeaker

### 6.5a Bistable circuits

Students can first demonstrate the effect of adding a feedback connection to two basic units, joined via their resistive inputs and direct outputs, as in figure 43. Both units should have lamp indicators. connected to them.

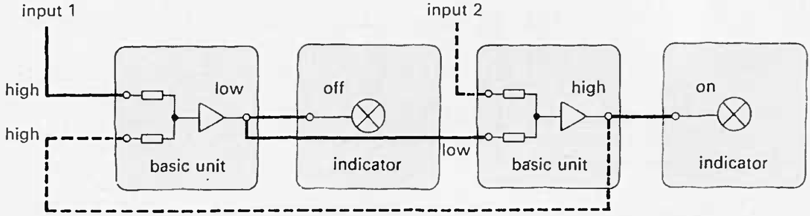



**Figure 43**
Building up a bistable circuit.

## The building bricks of electronics

Out of the basic unit, students have now built most of the building bricks of electronics: amplifiers, gates, bistable and astable circuits. There are others, but not so very many, and most are developments of these parts so as to fit them for more specialized uses. (For example, there are trigger circuits that are gates which open when the input voltage reaches a preset level.) A good sinusoidal oscillator is yet to come, but the astable circuit will serve as an oscillator for many purposes.

These circuits are enough to build most of the widely used electronic systems: computers, calculators, electronic switchgear, oscilloscope amplifiers, record player amplifiers, tape recorders, scalers, ratemeters, electronic clocks, electronic voltmeters, radio receivers, radio transmitters, and many other things.

In the rest of this Unit, students will use these building bricks. At the end, they will be invited to try one or two out of a whole host of possible applications. Before that, they will use them to investigate some of the circuits, made of resistors, capacitors, and inductors, that play as big a part in electronics as do devices such as transistors or integrated circuits.

Demonstration

### 6.5 Bistable module; multivibrator module; *and*-gate module

#### 6.5a Bistable circuits

Students who tried any of 6.4b, 'Make a lamp go on from a +6 V input', 6.4g, 'Make an *or*-gate', and 6.4h, 'Make a bistable circuit', can all contribute. The following are the points to bring out.

Figure 43 shows two basic units in a row. If the input to the first is high, its output and therefore the input to the second are low, as the first lamp indicator shows. The output of the second is high, because of the way the basic unit works when its resistive inputs are used.

Now suppose that the output of the second unit is fed back to the input of the first (the broken line in figure 43). The new input is high, like the original input to the first unit. So the new input makes sure that the system stays where it started; indeed the original input can now be taken away.

How can the system be made to do anything else? If a high input is sent for a moment to the second unit (input 2, figure 43), its output goes low, and is fed back to the first unit, whose output goes high. This output now goes to the second unit, and the system has provided just what is needed to keep the system in its new state. The input to the second unit which switched the system over can now be taken away. This new behaviour has been produced by *feedback*. It is *positive* feedback; that is, a change at one input is fed back to that input in the same sense as itself, so that the system 'confirms' any change made to it. The circuit has two stable states, so it is called a bistable circuit.

The bistable module, each output connected to a lamp indicator, is first switched to and fro by +6 V pulses applied alternately to the two inputs, as in figure 44 *a*. A series of +6 V impulses sent to the trigger input, as in figure 44 *b*, will also switch the bistable.

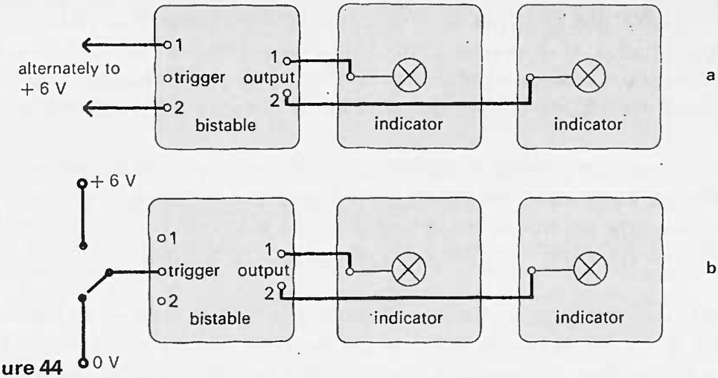



**Figure 44**
Switching the bistable module.
**a** Two inputs.
**b** Trigger input.

To show the pulses on the double-beam oscilloscope, feed the trigger input of the bistable from a basic unit which is squaring a 2 V a.c. supply from a low voltage power unit, as in experiment 6.2a. The earthed side of the oscilloscope goes to the 0 V rail, as in figure 45 *a*; the input to the trigger can be shown on one beam and one of the two outputs on the other beam. Finally, the two outputs can be displayed together. Figure 45 *b* shows the waveforms. The circuit is described in Appendix A.

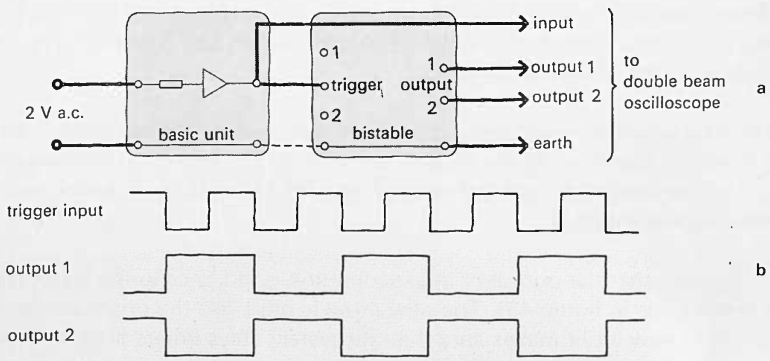



**Figure 45**
Rapid pulses sent to the bistable trigger input.

### *Students' book*

Feedback, introduced at this point in the course, is discussed with reference to its many applications in electronics and elsewhere in the article 'Systems and feedback' in the *Students' book.* See questions 16 and 17.

### 6.5b The multivibrator module

It is worth while showing that the multivibrator module does exactly the same as the bistable module, if its switches are set to R, interconnecting the two basic units inside it resistively.

The bistable system is very useful, because it remembers what happened to it last. It is so useful that two of the modules in the electronics kit contain this circuit, each built into a single box. Show the bistable module driving two lamp indicators, switched to and fro by momentary +6 V signals to inputs 1 and 2, as in figure 44 *a*.

This module has an extra facility. It is a nuisance sometimes to have to use two inputs to switch it over, and a third, trigger, input is provided. Diodes inside the module guide successive +6 V signals sent in here to the input which was not used last time the module switched over. It is easy to show that this happens, though not so easy to say how.

The system does arithmetic, in a sense. Half as many pulses come out of one output as go in to the trigger input, so it can be used to divide by two. Later, several of these modules will be used to make counters such as are used in computers.

### *A bistable game*

It may help to play a simple game. Make two students face each other, each being told to stand if the other is sitting, and vice versa. Seat both and say 'go'. The faster moving one will end up on his feet, with the other sitting down. Delays may introduce oscillation. Pushing one into his seat brings the other to his feet.

## 6.5b **The multivibrator module**

Students who tried 6.4i, 'Make a circuit that pulses continually (astable)', and 6.4j, 'Make an astable that produces an audible tone', can start the discussion off. Any who tried 6.4n, 'Make an amplifier with two stages of amplification', may have hit on acoustic feedback by accident. The following are the points to bring out.

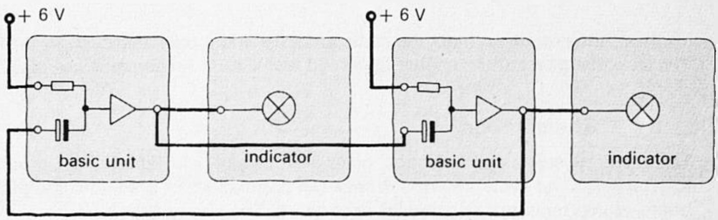



**Figure 46**
Astable made from two basic units.

In figure 46, the two basic units are connected as 'pulse producers' as in experiment 6.2d. If the input of the first goes from high to low, its output goes from low to high, stays there for a bit, and then drops again. This output is the input to the second unit. The rise does nothing, but the drop from high to low, arriving at the end of the first unit's pulse, has an effect. The second unit repeats the behaviour of the first. When the second unit's pulse ends, its output goes to the input of the first along a feedback path, and the first emits another pulse. (Like a pair of quarrelsome men, they are both busy giving each other a punch on the nose in payment for the last punch received – a process which is notoriously difficult to stop.)

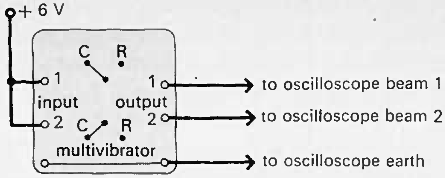



**Figure 47**
Astable multivibrator.

Figure 47 shows the connections for making the multivibrator into an astable. The switches or links are set to C, and the two inputs are both connected to +6 V. In this circuit, these inputs exactly correspond to the two resistive inputs of the basic units in figure 46, which are also connected to +6 V. The trigger input is not used.

Where the basic units have 25 μF capacitors in their inputs, the corresponding capacitors in the multivibrator are only 0.047 μF, as shown in figure 148 in Appendix A, which describes the circuit. The resistors in the inputs are also lower, and so the pulse repetition rate is much higher, being about 2.5 kHz instead of about 1 Hz.

An oscilloscope connected across one output and the 0 V rail shows the output waveform. It may be worth showing both outputs, out of step, on two beams. The waveform is not square, but has a curved leading edge, as shown in figure 48. The same figure shows how to square it off with a basic unit.

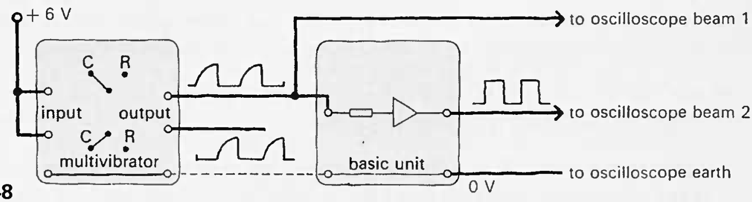



**Figure 48**
Squaring the astable output.

10 kΩ resistors in one, and then in both leads from the inputs to +6 V lengthen first one, then both trains of pulses, reducing the repetition rate.

To 'hear' the output, connect the audio amplifier and loudspeaker across the 0 V rail and one output. The amplifier gain control should be turned well down. An earpiece can also be used.

***Students book***

The article 'Systems and feedback' gives examples of delayed feedback producing oscillation, including the Canadian 'fur cycle' (feedback between populations of predators and prey), and the cyclic boom–slump tendency in capitalist economies. See also question 12.

### 6.5c The *and*-gate module

Figure 49 *a* shows the three-basic-unit *and*-gate. Demonstrate how the single *and*-gate module performs the same function, as in figure 49 *b*. The system in figure 50 is made of a bistable, an astable, and an *and*-gate. The bistable is switched to and fro by a series of pulses from a press switch. In only one condition is the output going to the *and*-gate high, and only then will the rapid pulses from the astable appear at the *and*-gate output. The amplifier gain must be turned low, or leakage signals of a small fraction of a volt will drive it all the time, giving a continuous sound.

***Students' book***

See question 8.

Once again the feedback is positive, for, if the input of one unit drops from +6 V to 0 V, the feedback to that input does the same again. The new feature is the delay. Instead of finding a stable state, the system switches back and forth by itself. It is said to be *astable* – lacking a stable state.

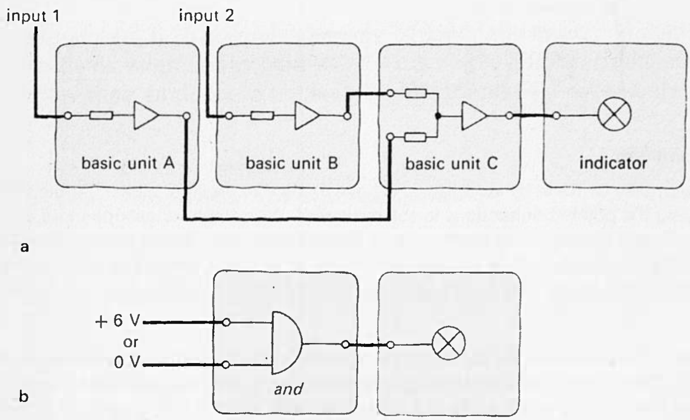
A device which produces a steady train of pulses is so useful that a module in the electronics kit contains two basic units that can be interconnected as an astable. The multivibrator module, to be as flexible as possible, is astable when its switches are at C (the interconnections being via capacitors), but can also be made bistable (with a trigger) by having the switches at R, when the circuit is that of figure 43 (with the trigger steering circuit added). Show the astable multivibrator output on the oscilloscope, and hear it on a loudspeaker. The capacitors in it are smaller than those in the basic unit, so that it switches more frequently, and the output produces an audible tone. This circuit is widely used in electronic organs.

*An astable game*

The bistable game suggested previously may have produced oscillations due to delayed feedback. If delay is built into the rules, the game goes astable. Stand two students opposite each other. Tell each to stand up, count five, and sit again whenever the other makes the action of sitting down. Press one into his seat, when the astable action should start.

### 6.5c The *and*-gate module

Students who tried 6.4k can show the rest how three basic units can function as an *and*-gate; that is, the output is high only when both of two inputs are high. Figure 49 shows the circuit, using basic units.




| input 1 | input 2 | output |
|---|---|---|
| 0 | 0 | 0 |
| 0 | 1 | 0 |
| 1 | 0 | 0 |
| 1 | 1 | 1 |

**Figure 49**
**a** *And*-gate from basic units with a truth table.
**b** Combined *and*-gate module.

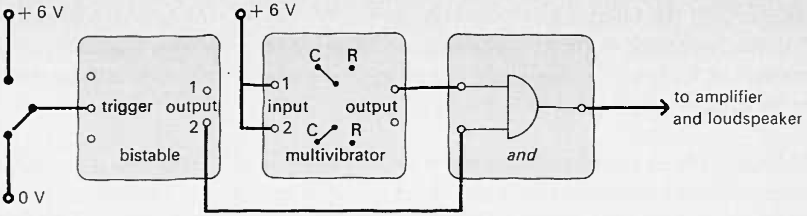



**Figure 50**
A system using three modules, equivalent to seven basic units.

Demonstration
## 6.6 Amplification and feedback

| | |
|---|---|
| 1075 | electronics kit |
| 1033 | cell holder with four U2 cells |
| 64 | oscilloscope |
| 1041 | potentiometer holder with 5 kΩ potentiometer *2* |
| 1041 | potentiometer holder with 100 kΩ potentiometer |
| 1018 | capacitance substitution box *2* |
| 1059 | earpiece |
| 183 | loudspeaker |
| 157 | microphone |
| 1009 | signal generator |
| 1000 | leads |

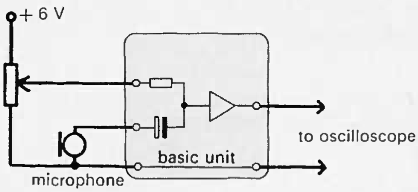



**Figure 51**
Single-stage amplifier.

*Single-stage amplifier*

This demonstration will normally be done by students who have made the amplifier earlier. Figure 51 shows the circuit, excluding the power connections to the basic unit. With the oscilloscope input at d.c., sensitivity at 1 V $cm^{-1}$, and the time base running, raise the input voltage using the potentiometer so that the trace suddenly moves down from its upper limit (+6 V) to its lower limit (0 V), as in figure 53. Then adjust the potentiometer until the trace lies midway between these extremes (output about +3 V.)

If a sound is now made in the microphone, the oscilloscope trace shows oscillations around ıne steady level just selected. Replace the microphone by a signal generator, using it at a low output level such that the amplified trace on the oscilloscope is perhaps 2 V peak to peak. Insert a capacitance of about 0.22 μF in series with the signal generator if the output is distorted. Show, by taking the oscilloscope input to the signal generator, that the signal is indeed amplified.

The explanation is easiest backwards. Unit C gives a high output only when both its inputs are low, for this is what the basic unit does. The outputs of units A and B will be low if their inputs are high. So if their outputs are fed to unit C, its output is high only if the inputs to A and B are high.

The *and*-gate module is useful enough for it to be worth putting in one box, especially as it takes three basic units. It is useful for combining signals together in building systems, as when a burglar alarm is allowed to sound if the safe is opened only when it is also after shop or office hours.

It may help to show the new modules combined together, as in the system shown in figure 50, where a bistable remembers whether to pass pulses from an astable or not.

### Amplifiers

An amplifier is the most important part of a record player, and is a vital part of a radio set. Amplifiers have been in use throughout the course, for there are amplifiers inside the oscilloscope, audio amplifier, and electrometer. In the electrometer, the amplifier's job is to magnify a tiny current flowing through the input into a bigger current, proportional to the input current, which will drive a meter.

The audio amplifier, also much used, does two jobs. It magnifies small alternating voltages at its input into bigger, but proportionate, voltages inside it, and then magnifies the power delivered until it is big enough to drive a loudspeaker.

Work on amplifiers in this Unit will concentrate on amplifiers which do the same job as those in an oscilloscope, whose task is to magnify the *voltage* (perhaps 100 mV) at the input until it is large enough to deflect an electron beam when applied to a pair of deflection plates in the cathode ray tube of the oscilloscope (perhaps 100 V).

Experiment 6.2b suggested a way in which the basic unit might amplify a voltage. Students who tried experiment 6.4l, a simple amplifier, can say what they did and show their amplifier to the rest. Demonstration 6.6 follows the idea further.

Demonstration

### 6.6 Amplification and feedback

In experiment 6.2b it was found that a small change in input voltage to the basic unit produced a big swing of output voltage, as long as the input voltage varied between narrow limits. Figure 53 shows how the two voltages varied (see figure 14).

A small alternating signal sent to the capacitative input of the unit can now raise or lower the input current to the unit above or below the steady current flowing through the resistive input, provided this current is such as to bring the output voltage to somewhere in between its two extreme values of +6 V or 0 V. Such a current is found by varying the voltage applied to the resistive input using a potentiometer, as in figure 51. The current *biases* the amplifier.

Vary the potentiometer, so that the mean level of the input is no longer +3 V. As the peaks or troughs of the output signal approach the +6 V or 0 V levels, they are clipped off. Both peaks and troughs are clipped if the mean level is +3 V, and the input is raised so that the output tries to exceed 6 V peak to peak.

It is best not to try to show that the microphone signal is amplified, as it very likely is not, since the microphone's impedance is high and it delivers very little current to the unit.

### Two-stage amplifier

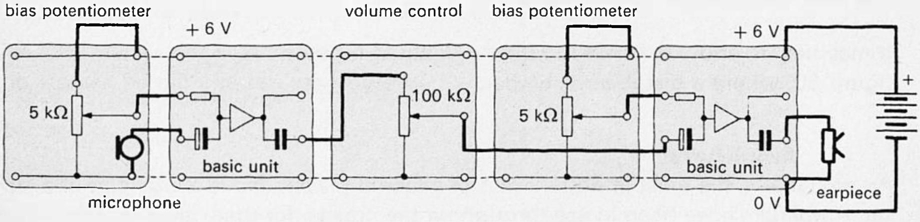



**Figure 52**
Two-stage amplifier, with volume control.

Figure 52 shows the two-stage amplifier circuit. Because this is one of the occasions on which it would be convenient to have them in that form, the potentiometers are shown mounted in modules that fit with the rest of the kit. Such potentiometer modules are suggested as a possible extension to the electronics kit in the *Teachers' handbook,* in the chapter, 'Guide to apparatus'. The potentiometer holders, item 1041, containing preset potentiometers, as detailed in the list of apparatus for this experiment, are, of course, perfectly satisfactory.

The 100 kΩ volume control may be omitted. Without it, the second stage may be overloaded and clip the waveform at large input signals.

Adjust the two bias potentiometers, using an oscilloscope connected to each basic unit's direct output in turn, so that each is biased to the middle of its possible output voltage swing, as in the previous part of the experiment.

The earpiece *must* be connected to the capacitative output of the second stage, or it will offer a d.c. path across the output of the second unit, and prevent it from working.

### Matching

Replace the earpiece in the amplifier by a loudspeaker of a few ohms' impedance. The sound produced should be much fainter.

An additional demonstration of the same effect can be done with a signal generator which has high and low impedance outputs. Use an oscilloscope across the two outputs in turn to show that they produce similar amplitudes of alternating voltage. A loudspeaker will, however, only give an audible output across the low impedance output.

The above experiments show only that there is a matching problem: no more is intended. As with a cell having internal resistance, where the maximum power is delivered to a load of equal resistance, so in a.c. circuits for maximum power transfer, the impedances of source and load must be matched. Although matching is an important problem both in system design and in the design of components, time is too short to do more than show that a problem exists.

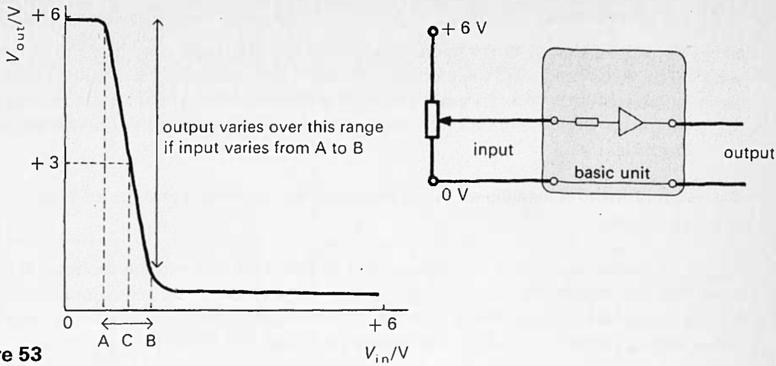



**Figure 53**
Variation of input and output voltage for the basic unit (resistive input).

The capacitative input is used for inputs from a microphone or signal generator for two reasons. First, no steady current passes the capacitor, so that once the steady current in the resistive input has been fixed at the required size, connecting something else makes no difference to that steady current. Second, the flow of alternating current via the capacitor, for a given alternating voltage produced by the source, can be bigger than it would be if it had to pass through an input resistor. (Part Two will explore the amount of alternating current passing a capacitor, in greater detail.)

The output cannot swing above +6 V or below 0 V, so the input cannot be made large without cropping the top and bottom of the output signal. (The +6 V and 0 V levels on the oscilloscope screen act like invisible barriers.) There is a best value for the mean output: midway between these extremes, so that neither top nor bottom of the output is chopped off before it need be. These two features – proper bias, and an upper limit on gain – are two things every amplifier designer has to bear in mind.

*Two-stage amplifier*

How could the gain be increased? Amplifying the output of one unit with another is an obvious thing to try. The two-stage amplifier, figure 52, will produce an audible sound in an earpiece if the microphone is used as input.

### Matching

If the earpiece of the two-stage amplifier is replaced by an ostensibly 'more powerful' loudspeaker, less sound emerges, not more. The loudspeaker contains but few turns of wire, while the earpiece contains many, and needs a smaller current to drive it. Presumably the unit cannot deliver enough current to drive the loudspeaker effectively. It is important to 'match' the voltage and current from an amplifier, or from one stage of it to the next, to the effective resistance of the next part, be it a loudspeaker or another stage. Matching is an important problem, but there is no time to pursue it further.

### Feedback

Bring the earpiece close to the microphone, with the volume control high. The circuit should oscillate, with a whistle coming from the earpiece. An oscilloscope across the output shows that the circuit is switching backwards and forwards, but if the gain round the whole loop is reduced, by holding the earpiece further from the microphone or by using the volume control, the oscillations become more or less sinusoidal.

The pitch of the note usually makes at least one discontinuous change as microphone and earpiece are brought together.

Figure 55 shows essentially the same circuit as figure 52, without microphone or earpiece, but with a wire from the second-stage output to the first-stage input. The oscilloscope should show that the circuit is oscillating. As an optional extra, capacitance substitution boxes can be inserted between the wires linking the two outputs to the other inputs, and this alters the frequency.

### Negative feedback

Figure 54 shows a basic unit set up as a one-stage amplifier, as in the first part of this experiment, but with a feedback wire from the capacitative output to the spare resistive input.

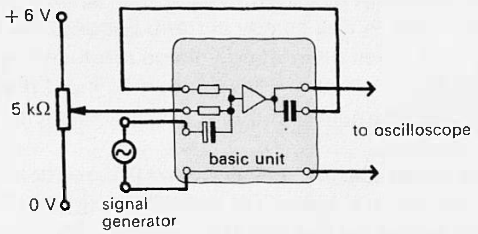



**Figure 54**
Single-stage amplifier with negative feedback.

A frequency of 1 kHz from the signal generator is suitable. Raise the signal generator output until the output from the basic unit amplifier (with feedback) is just not distorted. If the feedback link is now broken, the output is seen to be considerably distorted by clipping. If the signal is reduced until there is no distortion, and the feedback link is restored, the amplifier output can be seen to drop, indicating that the feedback decreases the gain.

### Reasons for using negative feedback

Essentially, negative feedback improves stability. With it, temperature-dependent changes of component parameters have less effect. Variations between individual components, such as are inevitable in solid state devices, matter far less. Frequency variations of the gain of components are reduced, but so is their gain overall. Designers have to 'trade gain for band-width'. See demonstration 6.11 for another use of feedback. It would be possible to do that demonstration at this point.

### *Students' book*

See questions 20 to 25, which are about feedback. Question 25 is long and detailed, and need not be attempted by more than a minority.

## Feedback

If the earpiece is put near the microphone, the system whistles. Why? It is not hard to think of the output sound going back to the input, being amplified, going back again, and so on until the system is going as hard as it can.

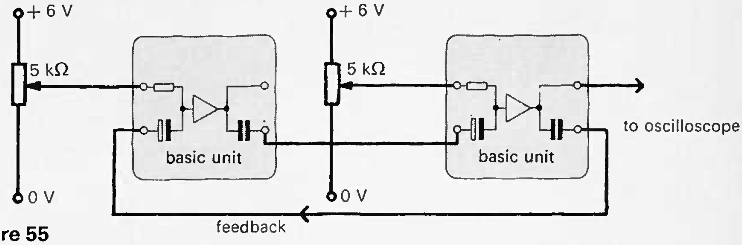



**Figure 55**
Two-stage amplifier with positive feedback along a wire.

What would happen if the signal were taken from output to input along a wire instead of through the air? The oscilloscope connected to the output shows that the system oscillates. Indeed, the circuit, shown in figure 55, is very much like that of the astable oscillator, and it oscillates for the same reason. The feedback is positive.

The feedback is positive because when the input to either stage goes positive, its output goes negative, and vice versa. If the input to the first stage goes positive, that to the second goes negative, and the output of the second goes positive. If this output is taken to the first stage's input, it is in the same sense as the signal that created it.

Any positive going signal therefore amplifies itself until it is too large for the system to amplify any further. The signal then has nowhere to go but down: as soon as it starts to do so the feedback effect helps it on its way, until it has gone as far as it can the other way. The system oscillates between these extremes.

## Negative feedback

The output of one basic unit (or of any odd number) swings in the opposite sense to its input. What effect would feeding such an output back to the input have?

A trial shows that a bigger input gives the same output with less distortion, and that the gain is reduced. Without pursuing an algebraic analysis, it is not hard to see that this result might have been expected. Any change in the input is partially cancelled by having an opposite change fed back on top of it.

This apparently stupid arrangement is called negative feedback. Amplification is reduced but so is distortion, and the amplifier is less sensitive to changes in gain of the transistor. Because the gain of a transistor falls off at high frequencies, negative feedback improves frequency response (keeps the amplification more nearly constant over a wide range of frequencies). All self-respecting, good quality gramophone amplifiers use a lot of negative feedback, and one has to pay more money for the extra transistors needed to get the amplification back again.

**Part Two**

# Circuits containing capacitance

*Time:* rather more than a week.

### *Students' book*

Figures 1 and 3 in this *Guide* (pages 10 and 12) are also figures 1 and 3 in the *Students' book*, appearing in the article 'Systems and feedback'. Figure 5 in that article shows part of an audio amplifier, which very clearly uses *RC* circuits to link amplifiers (for tone control). This use of *RC* circuits is discussed in the text of the article. See questions 26 to 30, about *RC* circuits.

### Link with Unit 2

The four-terminal boxes used in Unit 2 (experiments 2.6, 2.7), were presented as devices which accepted an input and gave a different output, and it may help to point out the parallel.

### Pulses into reactive circuits

It has been usual, at Advanced level, to discuss the behaviour of reactive circuits fed with sinusoidal voltages, while their transient behaviour has usually been neglected. We think that the effect of such circuits on pulses is no less important than their effect on sinusoidal voltages, and is perhaps simpler to understand in a semi-quantitative way.

Experiment

## 6.7 Pulses into *RC* circuits

1075 electronics kit

1033 cell holder with four U2 cells

1017 resistance substitution box
*and*
1018 capacitance substitution box
*or*
1040 clip component holder 2 (with wire ended components)

158 class oscilloscope

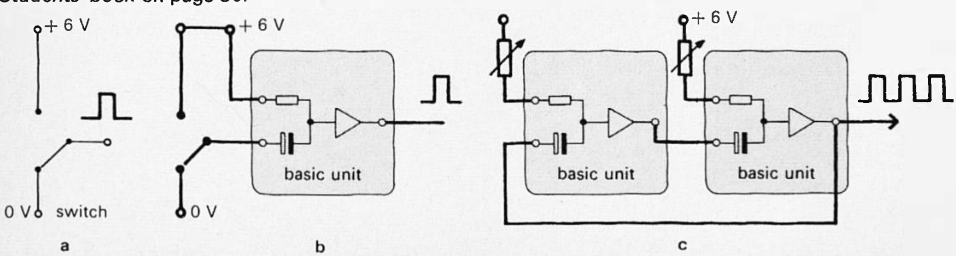
104 low voltage power unit
*or*
27 transformer

1009 signal generator (not essential, see below)

1000 leads

*Sources of square pulses*

Figure 57 shows five ways of making square pulses. Not all need be used, but in the class as a whole, some should try pulses one at a time (figure 57 *a* and *b*, and *c* running slowly), while others should try rapid trains of pulses (figure 57 *d* and *e*, and also a signal generator). Use of a signal generator is also possible, and it has the advantage of having a lower output impedance than the basic unit, as well as a wide and easily varied frequency range. The list of ways of producing square pulses appears in the *Students' book* on page 80.



### *RC* circuits in electronic devices

Figures 1 and 3 (pages 10 and 12), showing circuits for two electronic devices, contain many resistors and capacitors. The networks of resistors and capacitors often link together blocks like amplifiers, passing a signal from one block to the next, having modified it. Like amplifiers, counters, pulse shapers, and so on, *RC* circuits can be regarded as parts of a system which alter the signal passing through them in some desired way. This Part is about what *RC* circuits do to signals.

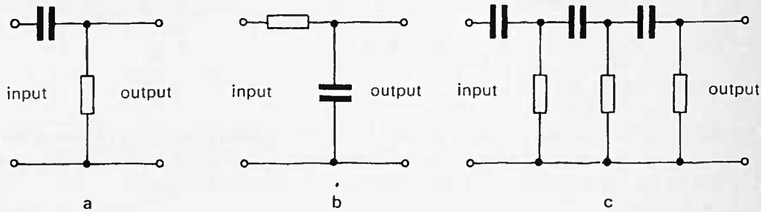



**Figure 56**
*RC* networks. **c** is from the 1 kHz oscillator shown in figure 3 (its function is to alter the phase of a 1 kHz signal by 180°).

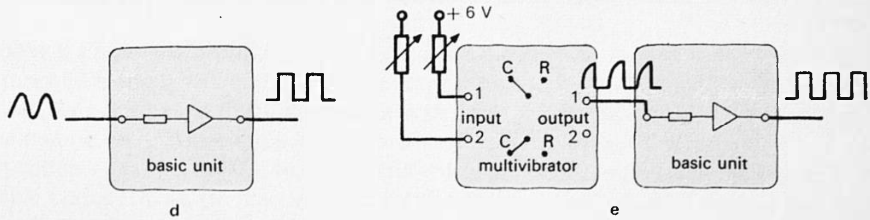
Figures 56 *a* and *b* show two simple circuits which appear several times over in circuits such as those in figures 1 and 3. They are the circuits which will be looked at in this Part. Figure 56 *c* shows a sample of a more complicated *RC* circuit; such complex circuits can often be analysed into several of the simpler circuits of figures 56 *a* and *b* in combination.

## 6.7 Pulses into *RC* circuits

The first step is to discover the effect of an *RC* circuit on the shape of a pulse. Square pulses are worth trying first, because they are much used in systems like computers and counters, and because the electronics kit provides them easily. How many different ways of making square pulses can the class think of?

Figure 57 shows several ways of making square pulses. Some produce pulses in a steady train, others produce them one at a time.

**Figure 57**
Ways of making square pulses.
**a** Switch. **b** Basic unit as pulse producer. **c** Two basic units as an astable. **d** Basic unit as a squarer. **e** Multivibrator as an astable with a basic unit as a squarer.



*Circuits and component values*

The most suitable component values for the two circuits depend on the frequency being used, or on whether the supply delivers single square pulses. Table 2 suggests suitable values.

| **Frequency/Hz** | **Time constant $RC$/s** | **$C/\mu F$** | **$R/k\Omega$** | |
|---|---|---|---|---|
| single pulses | $10^{-2}$ | 0.01 | 1000 | Differentiating |
| 50 | $2 \times 10^{-4}$ | 0.022 | 10 | circuit |
| 1000 | $10^{-5}$ | 0.001 | 10 | (figure 59 *a*) |
| single pulses | 2 | 10 | 200 | Integrating |
| 50 | $2 \times 10^{-2}$ | 0.22 | 100 | circuit |
| 1000 | $2 \times 10^{-3}$ | 0.22 | 10 | (figure 59 *b*) |

**Table 2**

With the differentiating circuit, it is quick and convenient to vary $C$ and $R$ using the switched substitution boxes, so as to keep the time constant the same, by increasing one and decreasing the other by the same factor. The form of the output is then unchanged.

With the integrating circuit, the values in the table are big enough for integration to be observable. The time constant should be reduced from the value suggested, by decreasing $R$ or $C$, to see the output change form, by failing to integrate and becoming more like the input.

Figure 58 illustrates one possible circuit, showing connections to an oscilloscope. Other circuits use others of the ways of producing pulses shown in figure 57.

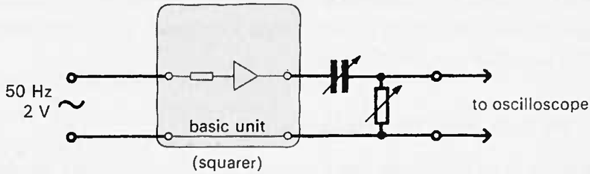



**Figure 58**
One circuit for investigating the effect of an $RC$ circuit on pulses.

Any students who use a signal generator, or who vary the frequency of pulses from the multivibrator module, could try $RC = 10^{-4}$ s ($C = 0.01\ \mu F$, $R = 10\ k\Omega$). For the differentiating circuit, the output is differentiated at about 100 Hz, but emerges square and unchanged above about 10 kHz. The integrating circuit integrates at frequencies above 5 kHz, but the output is unchanged at low frequencies, about 50 Hz.

***Students' book***

To save time giving instructions about component values, page 81 of the *Students' book* gives a number of diagrams showing possible circuits and values to try. Students ought still to be encouraged to calculate $RC$, the 'time the capacitor will take to change its charge appreciably', for any combination they use.

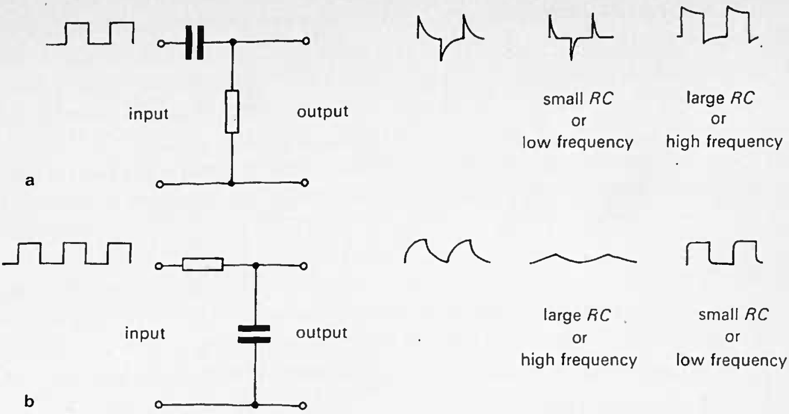



**Figure 59**
**a** Differentiating circuit.
**b** Integrating circuit.

Figure 59 *a* shows one of the circuits some of the class should try. They can show the others what happens. If the time $RC$ (which the capacitor needs to change its charge appreciably) is large compared to the time in which the signal changes (large $RC$ or high frequency) the signal emerges almost unscathed, but if $RC$ is small or the frequency is low, the output is a series of sharp spikes.

Figure 59 *b* shows the other circuit to try. This time, if $RC$ is small or the frequency is low (the capacitor has time to change its charge before the signal changes again), the signal is hardly changed, but if $RC$ is large or the frequency is high, the output is a series of more or less straight sloping ramps.

### Discussion of the two *RC* circuits

Discussion, based on questioning and argument about the experiments, should aim to bring out the following points.

In both circuits, currents from the input will tend to charge or discharge the capacitor. The larger the resistance, the longer any such change will take. The larger the capacitance, the less a given flow of charge will alter the p.d. across the capacitor. Together, the result is that the p.d. across the capacitor takes a time of the order $RC$ to change appreciably. If $C$ is 500 $\mu$F and $R$ is $10^5\ \Omega$, $RC$ is 50 seconds, for example.

Suppose a single +6 V square pulse (figures 60 *c* and *d*) is applied to the two circuits in figures 60 *a* and *b*. In the integrating circuit shown in figure 60 *b* (it will be seen in a moment why it is called that), the output is the p.d. across the capacitor, proportional to the charge on it. This charge has to flow as a current through the resistor. If the input suddenly rises from 0 V to +6 V, and the capacitor is uncharged, the biggest possible current flows (to start with, equal to $6/R$ amperes). Most of the p.d. is across $R$, but the p.d. across $C$ begins building up rapidly. As the p.d. across $C$ rises,

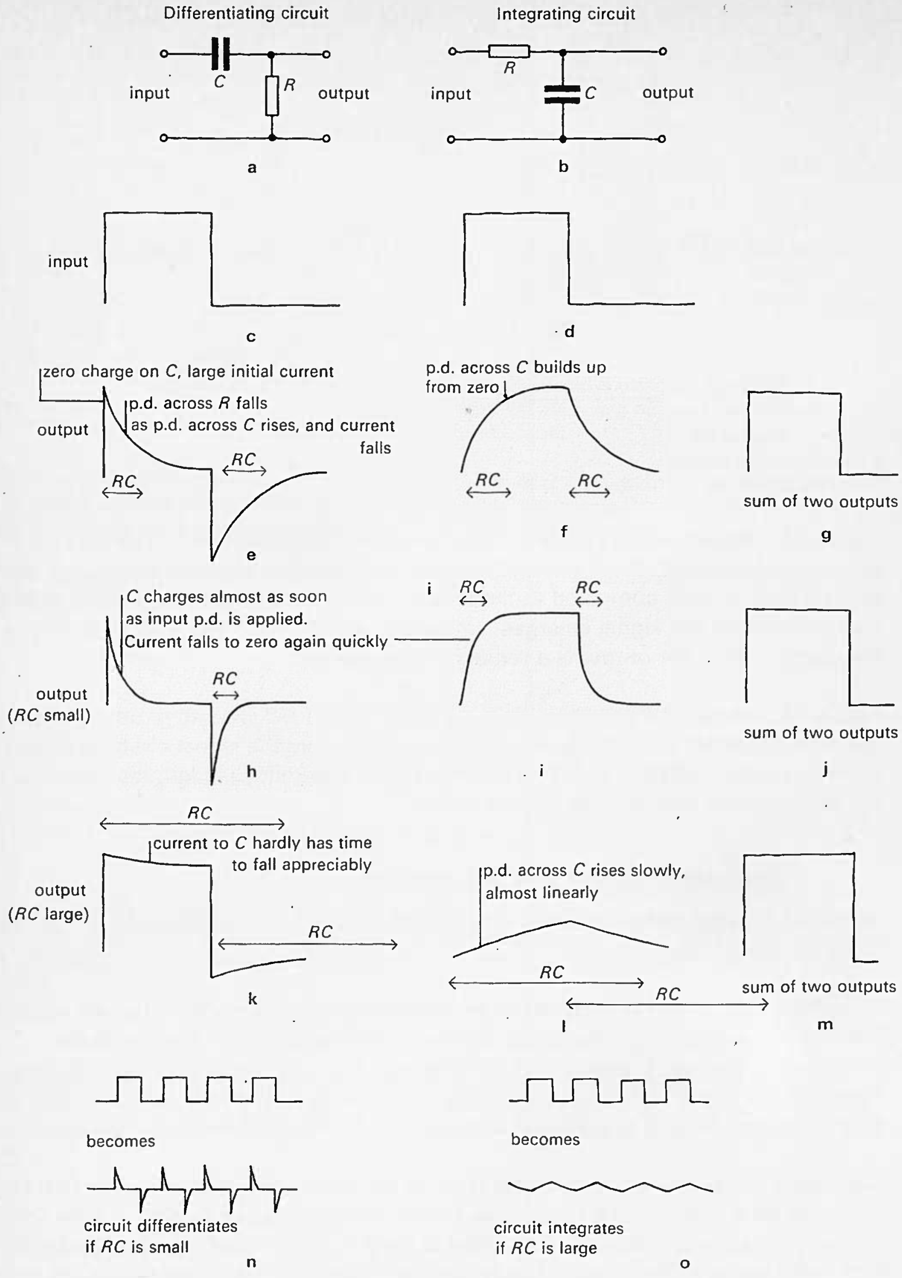



**Figure 60**
Integrating and differentiating circuits.

if the input is steady, the current falls. (When there is 4 V across *C* there is only 2 V across *R* and the current is only $2/R$ amperes.) When the p.d. across the capacitor reaches 6 V, after a time of the order *RC* (actually, up to 5 *RC*) no more current flows and the output stays steady.

If the input then goes back to zero suddenly, *C* discharges, taking as long about it as it did to charge. In this way, the curved edges of the output pulse shown in figure 60 *f* are produced.

The same effects produce different results in the differentiating circuit, figure 60 *a*. (Again, the reason for the name will appear shortly.) Now the output is equal to the p.d. across *R*, which is proportional not to the charge on the capacitor, but to the current – the rate of change of charge.

When the input suddenly rises, the charging current, as before, starts at a high value, which accounts for the steep leading edge of the output pulse in figure 60 *e*. As the charge builds up, so does the p.d. across the capacitor, and the current and the p.d. across *R* both fall. This accounts for the curved trailing edge of the output pulse in figure 60 *e*.

One circuit's output is the p.d. across *R*; the other's is the p.d. across *C*. Together, these p.d.s add up to the input p.d. at any instant. Their sum is shown in figure 60 *g*, and, for smaller and larger time constants, in figures 60 *h* to *j* and *k* to *m*.

### *Differentiating and integrating circuits*

Suppose the time *RC* is small (compared to the time between changes of the input).

As suggested by figures 60 *h* and *i*, the capacitor charges to +6 V almost as soon as the input goes to +6 V. The output of the integrating circuit (not integrating here) follows the input faithfully. The output of the differentiating circuit is proportional to the rapid surges of current onto and off the capacitor which occur every time the input switches over. If *RC* is very short, the output is almost a series of short, sharp spikes, as in figure 60 *n*, an extreme version of figure 60 *h*. The output is always exactly proportional to the rate of change of charge on the capacitor, but if *RC* is very small, the output is almost proportional to the rate of change of the input. It is in this sense that the circuit in figure 60 *a* might be said to differentiate the input.

Now suppose the time constant *RC* is large. As suggested by figure 60 *l*, the p.d. across the capacitor rises very slowly, and has not got very far before the input switches over and an equally sluggish discharge begins. If *RC* is very big, the rise and fall of the p.d. across *C* is almost linear, the current being almost steady. The p.d. across *C* is always proportional to the integral of the charges last sent to it; if *RC* is large, it is almost proportional to the integral of the input (around its average value). In this (limited) sense, the circuit might be said to integrate the input.

### *Students' book*

While much of the discussion of the differentiating and integrating circuits will best come out of questions and arguments centred on the experiments done and the apparatus in front of the class, questions 28 and 29 in the *Students' book* may also help. They follow through arguments similar to those on page 61, step by step.

### Integration about the mean

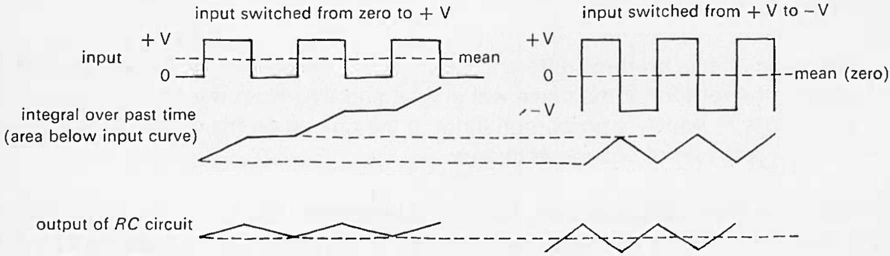



**Figure 61**
Integration about the mean, by an *RC* circuit.

A note of caution is needed in claiming that the integrating circuit, figure 60 *b*, 'integrates' the input. If the square wave input switching between 0 V and +6 V were integrated in the usual sense, the output would be a series of rising ramps, with level shelves in between, as in figure 61. Instead, the output is a series of rising and falling ramps; the integral of the input with its zero taken as half its maximum, if 'on' periods last as long as 'off' periods.

The reason is simple, but need not be explored with the class. The output rises and falls as the charge on the capacitor rises and falls. The charge on the capacitor is the integral of current with respect to time since the charge on it was last zero, and clearly does not include all the charges put on it and taken off again in its past history. If the input switches between equal positive and negative values, the charges are in alternate senses, and, counting one sense as negative, the 'past history' integral is identical with the 'since the last zero' integral. If the input switches from zero to some voltage, the two differ. The circuit integrates the input with respect to a level about which the input fluctuates as much below as above – its mean level, in fact.

### Spring and capacitor analogy

A moment spent on this now should be repaid later, when thinking about *LC* circuits. By analogy with mass (inductance) and spring (capacitor) it will be possible to capitalize on earlier work in Unit 4, *Waves and oscillations*, and write down at once a result for the oscillation time of an *LC* circuit. Such short cuts are not a bad thing: engineers and physicists use them all the time. Indeed, guessing by analogy is an important part of that valuable commodity, intuition.

### *Students' book*

Question 30 discusses the capacitor–spring analogy.

### Making a mechanical analogue

If an *RC* circuit is compared with a mechanical analogue, such an analogue should be displayed. One can be improvised, as in figure 62, from a compression spring (item 1080/1), a test-tube, a cork, and some oil. Use a cork, not a rubber bung, as oil attacks rubber. The tube, containing oil, is held in a clamp, and the spring rests on the clamp, surrounding the tube and projecting over its top. A stout wire fixed to the cork is also fixed to the top of the spring, perhaps by forming a loop in the wire and bending this round a turn of the spring.

## Springs and capacitors

As suggested in Unit 2, a capacitor is not unlike a spring. For the capacitor, $V = (1/C)Q$; for the spring, $F = kx$, where $F$ is the tension in the spring, $x$ the extension, and $k$ the force constant of the spring.

A soft spring, with a small force constant, corresponds to a large capacitance value (little force needed to extend the spring a lot; little p.d. needed for a large charge).

A car's suspension is rather like the integrating circuit, figure 60 *b*. If the car were driven over serried ranks of bricks (square wave input), the car body should rise and fall more gently, as does the output in figure 60 *f*. The car designer tries to make the body's response as much like the integrated output of figure 60 *l* as possible. This means having soft springs (small $k$, analogous to large $C$) and plenty of damping (analogous to large $R$).

## Optional: a mechanical analogue for *RC* circuits

Figure 62 shows a system, like the spring and dampers of a car's suspension, which behaves somewhat like the series *RC* circuit. Table 3 shows how the equations describing them compare.

| ***RC* series circuit** | **Spring and damper (in parallel)** | **Correspondences** |
|---|---|---|
| $V_C = (1/C)Q$ | $F_{spring} = kx$ (sometimes) | $V_C$ and $F_{spring}$ |
| | | $1/C$ and $k$ |
| | | $Q$ and $x$ |
| $V_R = R\,dQ/dt$ | $F_{damper} = \mu\,dx/dt$ (sometimes) | $V_R$ and $F_{damper}$ |
| | | $R$ and $\mu$<br>$I = dQ/dt$ and $dx/dt$ |
| $V_{total} = V_C + V_R$ (in series) | $F_{total} = F_{spring} + F_{damper}$ (in parallel) | |

**Table 3**
Symbols: p.d. across capacitor, $V_C$; p.d. across resistor, $V_R$; capacitance, $C$; resistance, $R$. Force, $F$; displacement, $x$; force constant of spring, $k$; constant of proportionality between damping force and velocity, $\mu$.

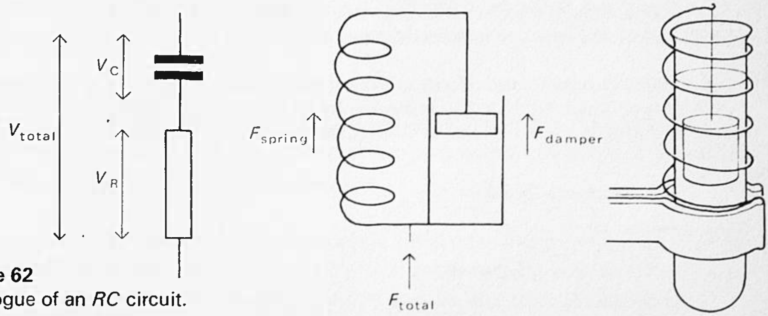



**Figure 62**
Mechanical analogue of an *RC* circuit.

Some trial is needed to obtain the best amount of damping, using corks of varying diameter.

The system is not exactly like either of the electrical circuits, figures 60 *a* and *b*. The input to it is a force applied to the system; the output is its displacement. Since the displacement corresponds to the charge on a capacitor, the closest parallel is with the integrating circuit, whose output is the p.d. across a capacitor. Attempts to sort out in discussion exactly what corresponds to what are likely to take too long to be worth while.

Revision demonstration

## 6.8 Slow alternating current in a circuit containing capacitance

170 low frequency a.c. generator

64 oscilloscope

1033 cell holder with four U2 cells

70 demonstration meter · *2*

71/3 dial for demonstration meter, 5 V d.c. dial

71/4 dial for demonstration meter, 2.5–0–2.5 mA, d.c. dial

1017 resistance substitution box

1051 capacitor, 500 μF
*and*
1040 clip component holder

30 slotted base.

1000 leads

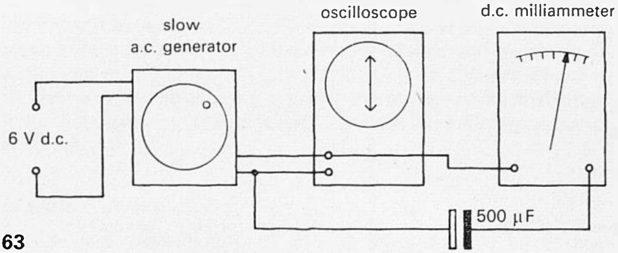



**Figure 63**

Figure 63 shows a suitable circuit, using a 500 μF capacitor. It is best, with electrolytic capacitors, to use two 1000 μF capacitors in series, back to back. A resistance of 1000 Ω can be substituted for the capacitor for comparison. If it would help a demonstration voltmeter can be substituted for the oscilloscope, though the class should see the oscilloscope as well, since they will be using one in a similar way in the next and later experiments.

See Nuffield O-level Physics *Guide to experiments V,* experiments 91a to d for details of similar experiments, which ought to be considered for a class without a Nuffield O-level Physics background. Experiments 92a and b, optional at O-level, are the basis of the capacitor experiment here.

***Students' book***

See question 26.

If a steady force is applied to the junction of spring and damper, and then released (like a voltage pulse that comes on, and then goes off), the junction will move a little way and will then move back again. If the damping is large, the motion is a steady rise and fall, to be compared with the output of the integrating circuit.

If the damping is small, the spring extends quickly whenever the force changes. A speedometer attached to the junction would show sudden pulses of speed, to be compared with the output of the differentiating circuit.

The analogy is more than a mathematical amusement. Electric circuits can be used in preliminary studies of the properties of a proposed mechanical system, which is useful if the mechanical system would be expensive to build. Alternatively, one might use the comparison the other way round, and say what one expected to happen in an electric circuit by analogy with a better understood mechanical device. Engineers often find that this kind of mental bypass route is quicker than the orthodox route.

## Alternating currents in *RC* circuits

Circuits containing resistance and capacitance are to be found in amplifiers such as those used in record players. Their job there is to offer greater or less 'resistance' to the passage of alternating currents of high or low frequency, or to introduce, in effect, delays between signals by shifting the phase of one signal. The next experiments look at such effects.

Revision demonstration

### 6.8 Slow alternating current in a circuit containing capacitance

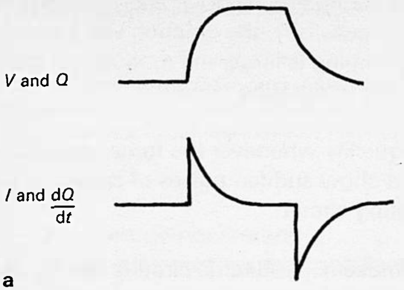
Alternating voltages from the mains or from a signal generator vary rather rapidly. It is easier to understand what is going on in a circuit carrying alternating current if the changes can be seen in slow motion. This experiment revises work from Nuffield O-level Physics, Year V.

An oscilloscope displays the slowly varying voltage, while a direct current meter indicates any slowly changing current. Would a d.c. voltmeter serve in place of the oscilloscope? (Yes.) Would it still serve at 50 Hz? (No.)

A class which has not seen the low frequency a.c. generator can first see it connected to an oscilloscope, and observe the sinusoidal voltage with the time base running slowly.

A large capacitor and a d.c. meter can then be added as in figure 63. A current flows back and forth through the meter. If the generator stops turning, the current drops to zero, whatever the p.d. shown on the oscilloscope.

If the generator is turned backwards and forwards a little near the position where the p.d. is zero (zero deflection on the oscilloscope), the meter needle is deflected. If the p.d. is varied slightly near large positive or negative values, the needle moves less.



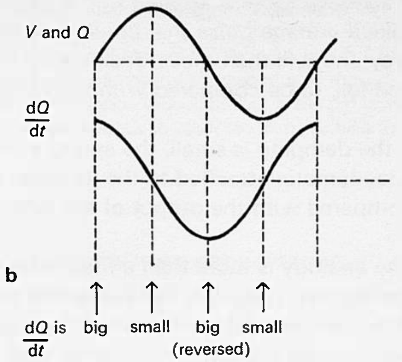




**Figure 64**
Changes of p.d. across and current in a capacitor.

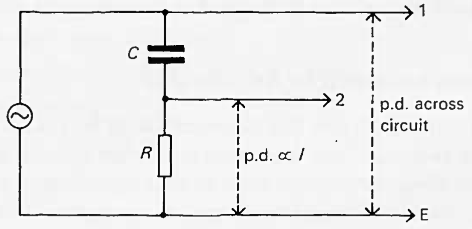



**Figure 65**
P.d. across a resistor to indicate a current.

### Two-beam oscilloscopes for all

The electronics kit contains a module which converts the class oscilloscope into a double-beam oscilloscope by switching the oscilloscope beam to and fro rapidly between two inputs to the module. The switching is done electronically, using a device the class has just met – the astable circuit. In this way, students can do their own phase shift experiments at little extra cost, and see a further use for the electronic systems developed so far, thus helping to integrate the work on electronics and reactive circuits still further.

If in a two-beam display, the junction of resistor and capacitor is common to both beams, the p.d. across the capacitor is not mixed with some p.d. across the resistor in its display, but the phase difference contains an extra 180° shift. We think this introduces more confusion than does the arrangement of figure 65, and the approach to the two-beam display is intended to smooth the path for the use of this circuit.

Experiment
## 6.9 Phase differences in an *RC* circuit (simple two-beam oscilloscope)

1075 electronics kit

1033 cell holder with four U2 cells

158 class oscilloscope

104 low voltage power unit

1017 resistance substitution box

1018 capacitance substitution box

1000 leads

Why do these things happen? Is it true that the meter indicates current *through* the capacitor?

Discussion should bring out that the charge on the capacitor depends on the p.d. If the p.d. changes, charge flows on or off the capacitor. The more quickly the p.d. changes the more quickly charge flows, that is, the bigger the current $I$, since

$$I = \mathrm{d}Q/\mathrm{d}t = C\mathrm{d}V/\mathrm{d}t$$

The current at any instant indicates how quickly the p.d. is changing. By switching the d.c. supply to the generator on and off, with the generator set in various positions, these arguments can be linked with the earlier switching experiments, as illustrated by figure 64 *a*.

If $V$ (and $Q$) vary sinusoidally, how does $I$ vary? Look at the meter and oscilloscope: the current $\mathrm{d}Q/\mathrm{d}t$ is large when $V$ (and $Q$) are small, but changing fast, as illustrated in figure 64 *b*. $\mathrm{d}Q/\mathrm{d}t$ is biggest when $Q$ is zero but climbing, zero when $Q$ is large but not varying much; large but reversed when $Q$ is zero but falling.

If necessary, replace the capacitor by a resistor, to emphasize that the phase change is a property of the capacitor. With a resistor, current and p.d. are in step.

*Approach to a two-beam display of p.d. and current*

It is not easy to watch the meter and oscilloscope together and if the alternating supply were not so artifically slow a meter would be no good for showing how the current varies. The class should realize that the answer to this problem is to use an oscilloscope to display a p.d. that is proportional to the current, using a resistor as in figure 65.

Will the p.d. across the circuit (leads 1 and E, figure 65) be equal to the p.d. across $C$? (No, there is some potential drop across $R$.) Will the current be the same as it would be with no resistor present? (Again, no.) How can these differences be minimized? (Keep $R$ small. This principle was used in the previous demonstration, where the meter resistance was not very big.)

Experiment

## 6.9 Phase differences in an *RC* circuit (simple two-beam oscilloscope)

This experiment will use an oscilloscope to show the voltage across an *RC* circuit, and the current through it, both at the same time. Some oscilloscopes have two beams, which makes the job easy. An oscilloscope with only one beam can be made to do the job by switching the one-beam input rapidly from one signal to the other and back again, taking tiny repeated samples of each.

*For extra supporting demonstration:*

1007 double-beam oscilloscope

1081 decade capacitance unit (1–10 μF)

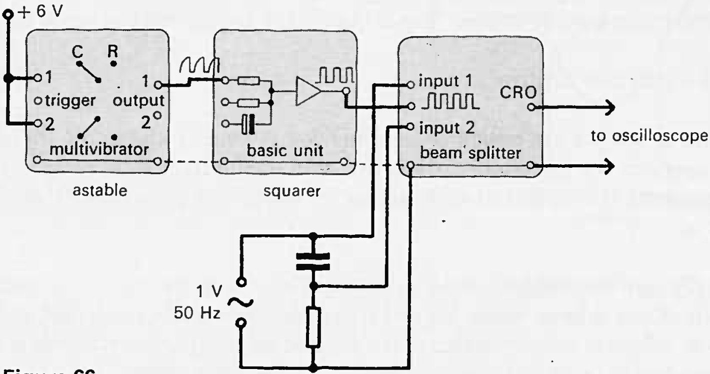



**Figure 66**
Use of beam splitter module to display phase differences in an *RC* circuit.

### *Beam splitter*

The astable produces pulses at about 2.5 kHz, and the basic unit (figure 66) squares these pulses. The pulses go to the beam splitter module. When the pulse is on, any input to input 1 of the beam splitter is steered to the upper oscilloscope trace; when the pulse is off, signals from input 2 appear on the lower trace. If the switching between beams is faster than the changes in the signal, at an appropriate timebase speed both traces appear to be more or less continuous. Appendix A gives the beam splitter circuit, and some more information about how it works.

### *Phase difference display*

A low voltage supply must be used, as the total excursion on the oscilloscope screen cannot exceed 0 to +6 V, so that the two beams must be fitted into this range, with the result that signals greater than about 1 V r.m.s. to either beam will be clipped.

Some difficulty will probably be found in getting the traces stationary on the screen, synchronized with the time base. The trick is to advance the variable timebase control until the traces are almost stationary, but occasionally 'jump', then to advance the control a little more, when they will lock.

Suitable values for $C$ and $R$ are 0.1 to 0.2 μF, and about 5 to 10 kΩ.

### *Extra demonstration*

It will probably help to show the same experiment in a corner of the laboratory using the demonstration double-beam oscilloscope. Because the gain of the two beams in this instrument can be varied, the condition that the p.d. across the resistor ought to be much less than that across the capacitor, if the output across both is to be much the same as that across the capacitor alone, can be more nearly met. Suitable values for $C$ and $R$ are 1 μF and about 500 Ω or less.

### ***Students' book***

Figure 66 of the *Students' book* gives a diagram showing how to connect up the beam splitter module.

With some such introduction, the beam splitter module from the electronics kit can be produced, and the class be invited to set it working, feeding it with rapid square pulses to do the switching. (How are rapid square pulses manufactured with the kit?)

It is best to start by letting them obtain two beams, with no signals going to either input of the beam splitter. At fast time-base speeds, the oscilloscope shows the square pulses emerging from the beam splitter; at low speeds the screen seems to show a double trace. The gap between the two traces keeps the two signals apart on the screen.

Some simple explanation of the beam splitter will be wanted. It contains two diodes, one connected to each input. As the square pulses coming in from the astable and squarer go positive, the diode connected to input 1 conducts, letting a signal from that input through to the output, and so to the oscilloscope. The other diode blocks any signal from input 2. When the square pulses are at 0 V, the first diode stops conducting and the second conducts, letting the signal from input 2 through and blocking that from input 1.

Then the class can try putting an alternating voltage onto each input in turn, and can finally connect up the circuit of figure 66.

Sketches of the traces are worth making, as in figure 67. The main point is that, just as in experiment 6.8, when the voltage across the capacitor, and so the charge on it, is growing fast, the current is large and positive. Thus the voltage trace is zero (growing) when the current trace is at a maximum. As the voltage then grows, it must reach its maximum *after* the current does, to the right of the current trace's maximum in the display, because the electron beam travels from left to right.

Experts say, therefore, that the current 'leads' the voltage, or that the voltage 'lags' the current. These terms are useful ones, but not essential, as long as the physical situation is understood.

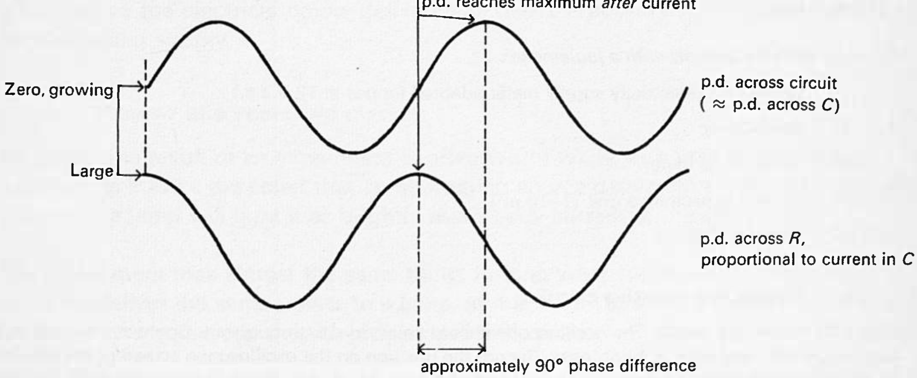



**Figure 67**
Oscilloscope traces from an *RC* circuit.

*Phase difference not 90°*

The phase difference between the traces will not reach 90°, because the current is being compared, not with the p.d. across the capacitor, but with the p.d. across both capacitor and resistor. The demonstration oscilloscope can be used if necessary to show that as $R$ is reduced, the phase difference becomes nearer and nearer to 90°.

### Treatment using phasors

The simple, essentially physical discussion on page 69 is what is suggested for most students. It should provide a good basis for further learning.

Some students may profit by going beyond this minimum treatment, though to do so should be regarded as going beyond the basic needs of the course.

Appendix C contains an outline of a deeper treatment using rotating vectors, perhaps better called phasors. It might be used with students whose mathematical tastes will lead them to enjoy and appreciate the extra security of a fuller discussion. The phasor technique can be used for similar purposes later on, in Unit 8, *Electromagnetic waves,* to extend the discussion of diffraction effects. The use of phasors there, as here, is optional, but if it is likely that the teacher would wish to use the technique there, it would be wise to introduce it now.

Demonstration

## 6.10 Power in alternating current circuits

| | |
|---|---|
| 104 | low voltage power unit |
| | *or* |
| 27 | transformer |
| 1033 | cell holder with two U2 cells |
| 541/1 | rheostat (10–15 Ω) |
| 64 | oscilloscope |
| 52L | mounted bell push 2 |
| 92R | m.e.s. bulb (2.5 V, 0.3 A) |
| 92T | m.e.s. holder |
| 1000 | leads |

*Optional extra for schools with a joulemeter:*

| | |
|---|---|
| | joulemeter (electricity supply meter adapted for use at 12 V a.c.) |
| 27 | transformer |
| 1005 | multi-range meter |
| 1081 | decade capacitance unit (1–10 μF) |
| 541/2 | rheostat (330 Ω) |

### Power in a resistive circuit

Figure 68 shows the circuit. The oscilloscope should be set to d.c. throughout. Connect the lamp to the a.c. supply first, and note its brightness. Record the position on the oscilloscope screen of the maximum of the alternating trace. Switching quickly to and fro from a.c. to d.c., adjust the rheostat until the lamp does not change brightness when switched over. Note the steady p.d. across the lamp shown on the oscilloscope screen. The maximum alternating p.d. should be about 1.4 ($\sqrt{2}$) times greater than the steady p.d.

### Optional: the reactance of a capacitor

Some students will like to have their knowledge made more complete by seeing how to find the reactance offered by a capacitor to alternating current at any frequency. This course does not require the result, but it is the sort of result which it may be convenient for some students to have heard about.

If an alternating voltage $V$ is applied to a capacitor, and

$$V = V_{\max} \sin 2\pi ft$$

the charge on the capacitor is

$$Q = CV_{\max} \sin 2\pi ft.$$

The current, $dQ/dt$, is

$$dQ/dt = 2\pi fCV_{\max} \cos 2\pi ft.$$

The ratio of the largest voltage $V_{\max}$, to the largest current $2\pi fCV_{\max}$ is

$$\text{maximum voltage/maximum current} = 1/2\pi fC.$$

It must be noted that the maximum voltage does *not* occur at the same time as the maximum current. The term *reactance* is reserved for such ratios of out-of-step voltages and currents when the phase angle is $\pi/2$. But the reactance is in ohms, nevertheless. A 10 μF capacitance has a reactance of about 330 Ω at 50 Hz.

Demonstration

## 6.10 Power in alternating current circuits

The fact that a current which is alternating is continually rising and falling makes some difference to the power it delivers, compared with a steady current. The fact that current and voltage for a capacitor are not in step makes a very important difference. This experiment explores these differences, which are of vital importance in practical affairs, since the electrical power delivered all over the country from power stations is an alternating supply.

### Power in a resistive circuit

Guessing the result of an experiment is often worth while, as a way of developing intuition. Is it to be expected that an alternating source delivering a certain maximum current to a lamp will light it as brightly as a steady current of the same value?

The experiment tries almost the same thing, finding what steady and alternating voltages deliver the same power to a lamp, as it is easier to see if a lamp is equally bright on two occasions than to judge small differences.

The circuit used is shown in figure 68. The class is invited to note the brightness of the lamp run from an alternating supply, and then to say when a steady supply has been adjusted to give the same brightness.

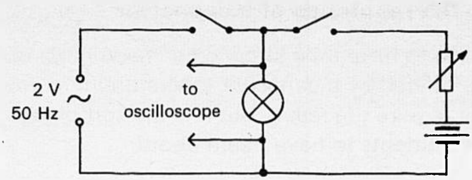



**Figure 68**
Comparing the brightness of a lamp lit from a.c. and d.c.

This experiment is taken from Nuffield O-level Physics *Guide to experiments V,* page 153.

***Students' book***

Questions 31 to 36 are about energy in alternating current circuits. Question 31 is about root mean square values.

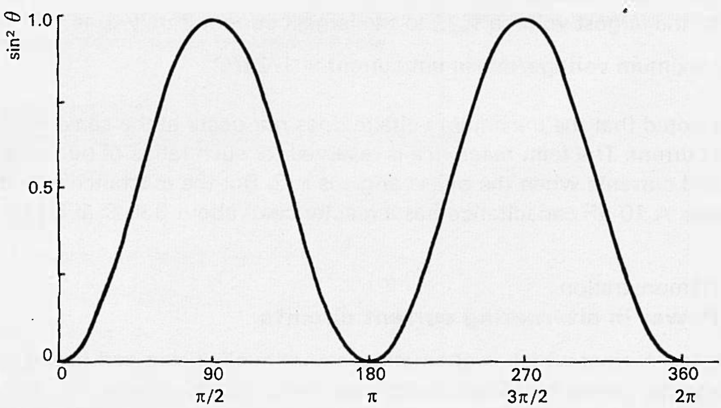



**Figure 69**
$\sin^2 \theta$ against $\theta$ over one cycle.

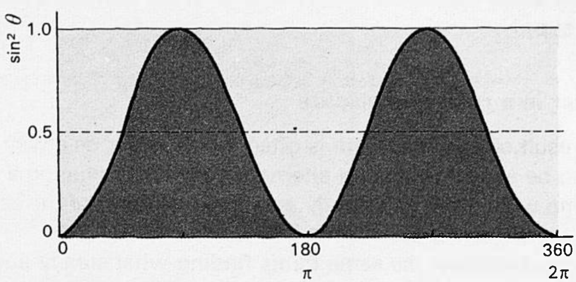



**Figure 70**
Average value of $\sin^2 \theta$.

The p.d. across the lamp is noted on each occasion, the maximum p.d. being observed when the supply alternates. Figure 71 shows what may be expected. The steady d.c. voltage is less than the peak alternating voltage for the same rate of supply of power to the lamp. Why should this be so? (The alternating supply has values less than maximum.) The average alternating voltage is zero – why does this supply light the lamp at all? (The lamp does not care which *way* the current flows.)

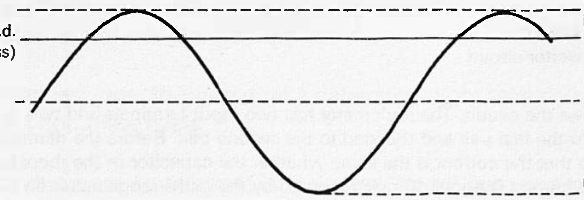



**Figure 71**
Steady and alternating p.d.s across a lamp lit equally by both.

### *Root mean square values*

The power dissipated by a steady current $I$ flowing in a lamp with a p.d. $V$ across it is $IV$, equal to $V^2/R$. How much power will an alternating supply (maximum p.d. $V_{max}$) deliver to the same resistor?

The alternating p.d. varies sinusoidally, say $V = V_{max} \sin 2\pi ft$, where $f$ is the frequency and $t$ is time. It is easiest to lump $2\pi ft$ into an 'angle' $\theta$, where $\theta$ goes through the range 0° to 360° every cycle. Then the power varies like $\sin^2 \theta$.

How often is the p.d., and so the power, large in each cycle? (Twice.) How often is $\sin^2 \theta$ at a maximum in one cycle? (Twice.) A large graph of $\sin^2 \theta$ can be displayed. (Figure 69 shows such a graph.) If an overhead transparency is used, it is easy to make an overlay to show that the areas shaded differently in figure 70 are equal, so that each is equal to half the area below the line $\sin^2 \theta = 1$. Therefore, the maximum value of $\sin^2 \theta$ is just twice its average value over one or more cycles.

The steady voltage which lights the lamp as brightly as the alternating voltage must deliver the same power on average.

$$V^2_{average} = \tfrac{1}{2} V^2_{max}$$

$$V_{average} = \frac{1}{\sqrt{2}} V_{max}$$

The experiment gives a check on this result, though not a very precise one. The steady p.d. should be equal to the square root of the average of the square of the alternating voltage. This mouthful is usually contracted to 'r.m.s. voltage' for 'root mean square voltage'. For sinusoidal supplies, it is $1/\sqrt{2}$ of the maximum voltage; for square, triangular, or other waveforms, it is not. Most alternating current ammeters and voltmeters indicate r.m.s. values, and only give a good guide to the current flowing if it varies sinusoidally, as it most often does.

### Power in a capacitor circuit – optional demonstration

If the school has a 'joulemeter' (an electricity supply meter adapted for use at 12 V a.c. and calibrated in joules) a further, very pretty demonstration can be done.

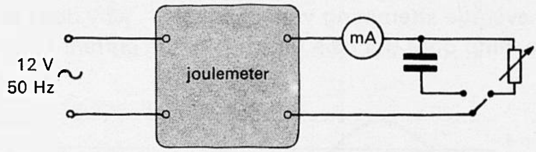



**Figure 72**
Power in a capacitor circuit.

Figure 72 shows the circuit. The joulemeter has two input terminals and two output terminals, the supply going to the first pair and the load to the second pair. Before the demonstration is done, adjust the rheostat so that the current is the same whether the capacitor or the rheostat is in circuit. If $C = 10\ \mu F$, the current is about 40 mA, recorded by the multi-range meter on an a.c. range.

For demonstration, start with the rheostat in circuit. The joulemeter rotates as expected, about 5 joules every ten seconds. Then switch to the capacitor. Although it passes the same current, the joulemeter stays virtually still.

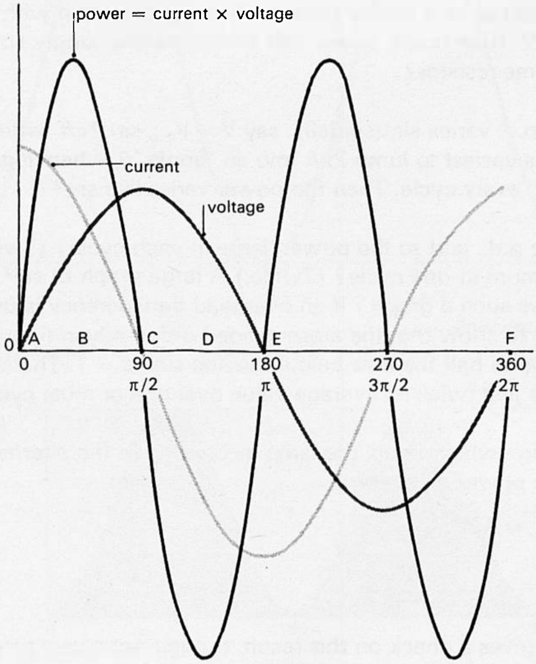



**Figure 73**
Variation with time of current, voltage, and power in a capacitor circuit.

### Power in a capacitor circuit

Guessing the power dissipated in a capacitor carrying alternating current (zero) is harder than guessing the result of the previous experiment. Some questions may help. What current flows when the capacitor happens to be fully charged? (Zero.) Is energy being delivered at that moment? (No.) Has energy been delivered in charging the capacitor? (Yes.) When it is uncharged again, at the next moment the p.d. is zero, has it energy? (No.) Where has the energy gone? (Back to the supply, perhaps.) If a good steel spring is squashed in and out, is energy dissipated, perhaps making the spring warmer? (Little or none is dissipated.)

Then maybe a student will dare to guess that a capacitor might take no net energy from a supply, over a complete cycle.

Figure 73 shows how current *I*, voltage *V*, and power *IV* vary over one cycle. Such a graph can be prepared in advance on an overhead projector transparency. (Time ought not to be spent plotting it in class.) The power graph has loops of equal size above and below the axis, which leads us to the conclusion that the mean power dissipated over a whole cycle is zero.

For most classes, a more physical argument is preferable. At point A (figure 73) the capacitor is uncharged, and has no energy stored in it. When point C is reached, the charge is at a maximum because the voltage is at a maximum, and there is no current flowing, so no energy being delivered, and the power graph goes through zero. But energy has been delivered between A and C. The rate of delivery reaches a maximum half way through the charging period, because to start with there is little or no p.d. across the capacitor, so that putting the first bit of charge on is easy, while at the end no current flows, as already indicated. This point about the maximum power is not worth labouring.

Between C and E, the p.d. falls to zero again, and the capacitor ends up uncharged, with no energy. The energy it had at C has gone away. If the source had been a very special sort of accumulator, maybe one could imagine it being charged up again, having got all its energy back once more. If the source has resistance, power will be dissipated there, but *not* in the capacitor. Like an oscillating spring, a capacitor gives back on discharge what it got in the charging process. The remainder of the cycle, E to F, sees the capacitor charged and discharged in the opposite sense, the energy flows being identical.

### Time

This piece about operational amplifiers should, so far as the Advanced Physics course is concerned, be offered for interest and entertainment, and be carried off as smoothly as possible, without any pursuit of matters of detail.

The subject is large enough to occupy an electronics course by itself. It can certainly provide material for any students who wish to take electronics beyond the limits of this course. The intention here is merely to make a beginning: to show students that the field exists, and might be interesting and useful.

It ought not to be allowed to occupy more than one lesson, and could be omitted.

### An operational amplifier module

Integrated circuit operational amplifiers can be bought at modest cost, and a school which wishes to pursue the matter should have three or four. One would be a good investment in any case. The experiments suggested here all use the basic unit as a 'poor man's operational amplifier'. It does not do the job very well, and this ought to be openly admitted to the class. We hope that a module containing an operational amplifier will be added to the electronics kit in the future, as one of a number of extra modules in an extension kit. Such extra modules would be optional, and would not be needed for the Advanced Physics course, but could add to the interest and value of the kit. Appendix B gives some further details of the use of an operational amplifier. The use of such an amplifier in place of basic units in experiment 6.11 is strongly advised.

Demonstration or experiment

## 6.11 Operational amplifiers and analogue computing

1075 electronics kit

1033 cell holder with four U2 cells

1017 resistance substitution box *3*

1007 double-beam oscilloscope
*or*
64 oscilloscope
*or*
158 class oscilloscope

1000 leads

The basic unit is a bad operational amplifier, and its deficiencies have to be concealed by some mild trickery. The less said about these deficiencies to the class the better. It is better still to use a good operational amplifier (see Appendix B).

## Operational amplifiers: a new use of circuits containing resistors and capacitors

Earlier in this Part, it was suggested that an electric circuit might be thought of as a model of some other thing, like a spring system, which behaved like the circuit in some ways.

In Part One, amplifiers with feedback were investigated, and it seemed that feedback could produce interesting new effects.

Recently in this Part, the behaviour of capacitors in a circuit was understood by thinking of the current in them being proportional to the rate of change of the voltage across them. Such circuits could 'integrate'.

These things now come together. Amplifiers with feedback, which may be through capacitors or resistors, can be used to do mathematical operations, like integration. They are called operational amplifiers. They can be used to solve equations, and can be used as models or analogues of any system that obeys the same equations. Using operational amplifiers in this way is called analogue computing.

Demonstration or experiment

### 6.11 Operational amplifiers and analogue computing

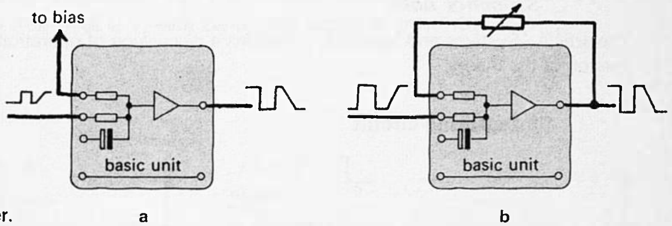



**Figure 74**
The basic unit as an amplifier.

The basic unit turns signals 'upside down', and can make them bigger. If some of the output is taken back to the input, as in figure 74, the gain is reduced, and because what happens depends partly on the values of the resistors which settle how much signal is fed back, it depends less on how much the basic unit amplifies. Indeed, enough signal can be fed back for the system to have a gain of one, so that it is like an electrical see-saw, the output going down (from +6 V) as much as the input goes up (from 0 V).

The input to the basic unit draws very little current compared to that at the output. Nearly all the current in the circuit in figure 74 *b* flows in the resistors. If this is so, the voltages across parts of the circuit depend on Ohm's Law more than on the behaviour of the basic unit. By choosing the resistances, the gain can be made $-1$, $-2$, $-\frac{1}{2}$ or whatever one wants. (The minus sign represents the see-saw effect: the output going down when the input goes up.)

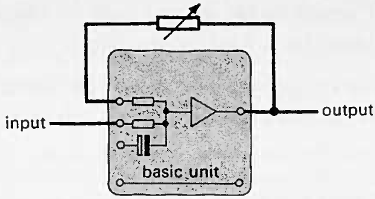



**Figure 75**
See-saw (inverting amplifier) using a basic unit.

Figure 75 shows the basic unit as an inverting amplifier (see-saw) with a resistor from the direct output to one resistive input. The resistor can be adjusted from 10 kΩ to 200 kΩ to vary the gain. If the resistive input had been joined directly to the output, then although the circuit would be like figure 77, with $R_F = R_I$, the gain is *not* $-1$, as the transistor gain is only modest. The base of the transistor is also at a more or less constant half a volt or so above zero, not at zero. The amplifier will 'see-saw' if the input goes positive, but not if it goes negative to any extent. It is not very linear.

### Theory of the operational amplifier

The theoretical discussion opposite is not difficult, but should be omitted if it makes this piece of teaching drag. It is provided to keep students happy, not to keep them busy. An alternative, quick, and simple treatment would be empirical, stopping short at the point of showing that a see-saw circuit can be made, and testing it. The integrating circuit can then also be treated empirically, with the comment that, as the basic unit itself draws little current, a steady current in the resistor will give the capacitor a steadily rising charge.

### *Students' book*

The article, 'Systems and feedback', contains a discussion of operational amplifiers, including a simple version of the theory.

### Integrating circuit

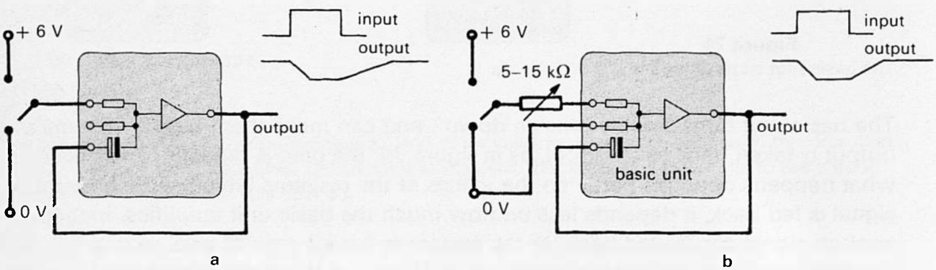



**Figure 76**
The basic unit as an integrator.
**a** An unsatisfactory simple circuit.
**b** A better circuit.

Figure 76 *a* shows a simple circuit. When the input steps from +6 V back to 0 V the output rises much more slowly than it fell when the input stepped from 0 V to +6 V. Figure 76 *b* shows a partial remedy: connection of the spare resistive input to 0 V and the insertion of a resistor in series with the input, adjusted so that the two ramps produced by a square on–off pulse slope about equally. The time base of the oscilloscope should be running very slowly, and its input be switched to d.c.

Circuit *b* is the one to use, without drawing attention to the fact.

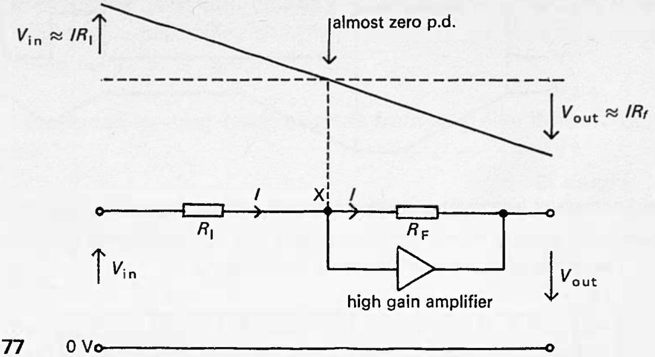



**Figure 77**
The see-saw circuit.

Figure 77 illustrates how a better see-saw circuit acts. If the amplifier has a high gain, point X never goes more than a fraction of a volt away from zero, so long as the output stays within bounds. The current $I$ flowing from the input to point X along the input resistor $R_I$, will be such that

$$V_{in} \approx IR_I$$

A properly designed amplifier draws next to no current, so almost all of the current $I$ flows in the feedback path, resistance $R_F$. The output terminal will be below point X in potential and, as X is nearly at 0 V, will be nearly equal in potential to $V_{out}$.

Thus

$$V_{out} \approx -IR_F$$

and

$$V_{out}/V_{in} \approx -R_F/R_I.$$

The values of $R_F$ and $R_I$ can be chosen to give any moderate gain, regardless of the gain of the amplifier itself, if that gain is very big. The gain of the transistor in the basic unit is too small to make a good amplifier for this purpose; point X is not at a nearly steady, near-zero voltage; and the amplifier only copes with positive inputs. So the basic unit only illustrates the idea.

## An integrating amplifier

More interesting things happen if the feedback is taken through a capacitor, as in figure 78.

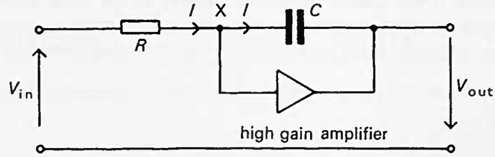



**Figure 78**
The integrating amplifier circuit.

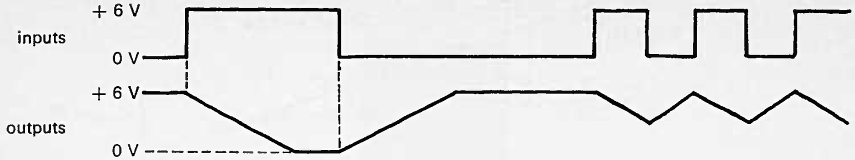



**Figure 79**
Inputs and outputs of integrating circuit using basic units.

*Two integrators in a row (constant acceleration)*

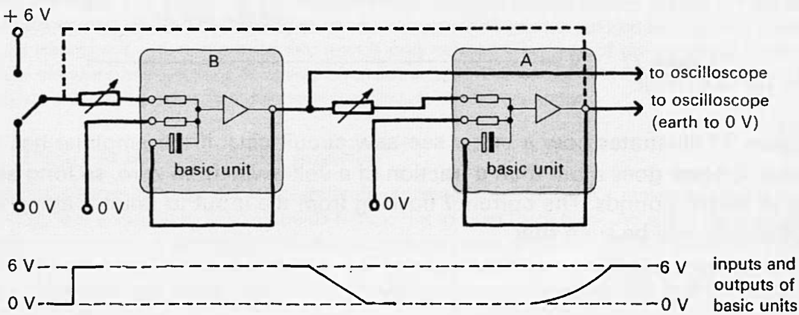



**Figure 80**
Two basic unit integrators.

Figure 80 shows two basic unit integrators connected together. If the input from the switch to the first one goes from 0 V to +6 V, a falling ramp should be seen on an oscilloscope connected to its output.

The output of the second integrator should give a rising parabola. A double-beam oscilloscope makes the display more effective.

The pair of basic units do *not* behave exactly like a pair of operational amplifiers. Their outputs lie between 0 and 6 V, not either side of 0 V. While B's input is at 0 V, its output is at 6 V, whereas that of an operational amplifier would be at 0 V too. When B's input has a sudden step applied to it, its output diminishes steadily, as is proper, but from 6 V towards 0 V, not – like an operational amplifier – from 0 V to negative values. In the initial state the 6 V output of B holds the output of A at 0 V. After the step applied to B, A's output ($y$) rises parabolically as its input from B falls steadily. The *changes* in the outputs of the units behave properly. The *values* they have are less easy to interpret: B's initial 6 V output still represents $dy/dt = 0$, for example.

If a return connection, shown as a broken line in figures 80 and 81, is taken from the output of the second unit to the input of the first, the system is bistable. It can be switched over by holding the input of one unit at 0 V or at +6 V for a while. If held there for a short while, the output starts to change over, but relaxes back when the input connection is broken.

An operational amplifier is not usually deliberately driven to the stage where it saturates, as in the instance above. But this example emphasizes the common features of electronic systems: bistables and astables are not in a world apart from amplifiers or analogue computers.

The circuit can be tried with a basic unit, taking the feedback from its output to the capacitative input. An input which steps sharply from 0 V to +6 V produces an output which is a slowly falling ramp, as in figure 79.

What earlier circuit produced sloping-ramp outputs from step-like inputs? (The integrating *RC* circuit.)

As before, point X in figure 78 cannot change potential, as it is the input to a high gain amplifier. $V_{out}$ is equal in magnitude to the potential difference across the capacitor.

$$V_{out} \approx -Q/C$$

Any charge $Q$ on the capacitor flowed through the resistance $R$. If $V_{in}$ rises and is then steady, the current $dQ/dt$ is steady, and the capacitor charges at a steady rate.

$$V_{in} \approx R dQ/dt.$$

In these circumstances, the output falls at a steady rate – being minus the integral of the input. In general,

$$V_{in} = -RC dV_{out}/dt$$

or

$$V_{out} = -\frac{1}{RC}\int V_{in} dt.$$

The circuit is in use in most laboratories, inside their oscilloscopes. It was invented long ago for producing a steadily changing voltage to drive time bases. It integrates, its input being proportional to minus the derivative of its output.

## Solving differential equations

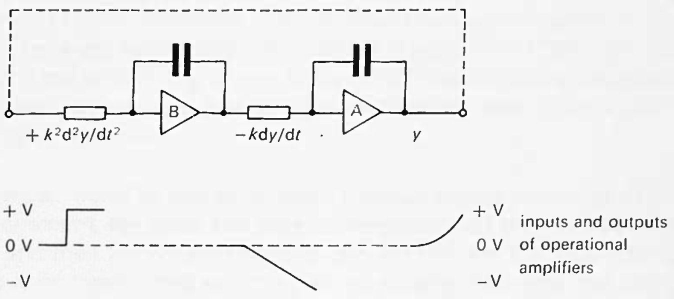



**Figure 81**
Two integrators in series.

Suppose one unit integrates the output of another. If the output of A, figure 81, is $y$, the input to it is $-kdy/dt$. This is B's output, so its input is $+k^2d^2y/dt^2$. If the output of A represents a displacement, the input to B is the acceleration (multiplied by a constant).

*Oscillations: solving $y = -k^2 d^2y/dt^2$*

Figure 82 shows a circuit which is suitable. The resistors, about 15 kΩ, in the inputs to the integrators can be omitted. The lead to 0 V from the capacitative input of the inverter seems to reduce damping. The resistor *R*, about 200 kΩ, needs to be carefully adjusted. Reducing it will decrease the amplitude, and improve the waveform, so *R* should be reduced if a large, sharp-cornered waveform is produced.

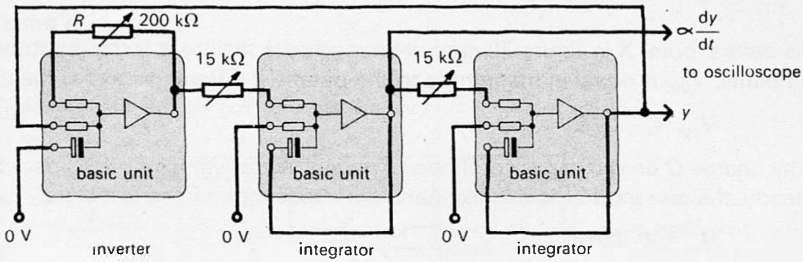



**Figure 82**
Three basic units which oscillate.

Reducing *R* further damps out the oscillations, so *R* should be increased as a first step if no waveform appears. A waveform will generally be started off if the lead from the output of the second integrator to the input of the inverter is broken momentarily.

An oscilloscope sensitivity of 0.5 V $cm^{-1}$ is suitable, with the time base at 100 ms $cm^{-1}$. The oscillations can be speeded up by taking the integrator feedback connections from their capacitative outputs.

The phase difference between $y$ and $dy/dt$ can be shown with a double-beam oscilloscope.

Let the acceleration be zero to start with, and also the velocity $dy/dt$. If a steady force were suddenly applied to a mass, how would the acceleration alter? (It would jump to a steady value.) What would the velocity do? (Increase steadily.) If this is tried, giving B's input a sudden step as in figure 81, its output decreases steadily, as it should, being $-dy/dt$.

Under constant acceleration, the displacement should increase as $t^2$. The output of A does so, as may be seen, along with the other changes, on an oscilloscope. If the initial conditions are different, the outcome is different.

Now suppose that a return connection, shown as a broken line in figure 81, is taken from the output of A to the input of B. With the same initial conditions, a rise in the input to B is fed back as a further rise, after the delay inherent in the slow build-up of $y$ after a change in $d^2y/dt^2$. The system drives itself away from zero output until it can amplify no more. Because that happens sooner or later, the system is bistable.

What if the output $y$ from A were turned into $-y$ (or $-cy$) before being returned to the input of B, as in figure 83, using a see-saw amplifier C of gain $-1$ ($-c$ in general)?

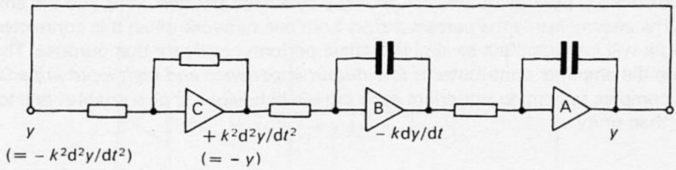



**Figure 83**
Operational amplifiers solving $y = -k^2 d^2y/dt^2$.

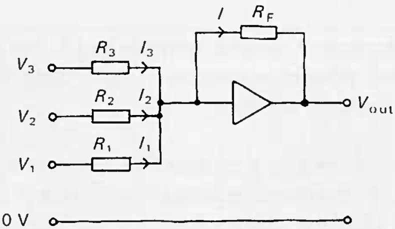
It is now possible for the system to stay 'at rest', with each term zero, since any slight rise in $y$ diminishes $d^2y/dt^2$, increases $-dy/dt$, which decreases $y$ again. In the same way, a mass held between two springs, for which $y$ is equal to $-k^2d^2y/dt^2$, is also stable at rest. But if the system is given an initial 'kick', say by raising the input of A ($dy/dt$) for a moment, it oscillates, just as the mass held between springs will oscillate if it is given an initial velocity.

The spring-held mass might be said to oscillate because an initial velocity *later* produces a displacement, the force and acceleration produced thereby *later* reducing first the velocity and then the displacement to zero. By the time the displacement is zero, the velocity is no longer zero, and the process repeats. Similarly, one might say that the amplifier system oscillates because a change in one input later causes changes in others, which later cause a change in the first once again, the time lags between these changes being such as to keep them all going. It is another case of feedback combined with delay (the delay being the sluggish response of an integrating circuit).

Alternatively, one might say that both can oscillate because they obey the equation $d^2y/dt^2 = -k^2y$, one of whose solutions is $y = y_0 \sin kt$.

## Note for teachers

Much has been left out of the brief treatment suggested. To build systems of any complexity, one must combine signals, and the inverting amplifier can be made into a summing amplifier by giving it some more input resistors in parallel with the first. See figure 84.




$$I \approx I_1 + I_2 + I_3$$

$$\text{Thus, } \frac{V_{out}}{R_F} \approx \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}$$

**Figure 84**
Summing amplifier.

What is in many ways the most important point of all has been omitted. *RC* circuits on their own can integrate approximately; potentiometers can multiply by a fixed fraction. Why add the amplifier to the circuit at all? The answer lies in the current drawn from one network when it is connected to another. One *RC* network will integrate, but several in a chain perform poorly for that purpose. The most important thing the amplifier contributes is *low output impedance and high input impedance,* so that elements in a complex system do not affect each other's behaviour. It also enables one to multiply by a factor greater than unity.

## Analogue computing

In the examples given, systems of amplifiers have imitated the behaviour of an accelerated mass and also an oscillating spring and mass, in the sense that voltages in the amplifier system change in the same way with time as do displacements, or speeds, or accelerations in the other systems. Such electronic analogues can quite easily be set up to represent fairly complicated things: a tall tower oscillating in a wind, for example. And the tower can be 'rebuilt' to a different specification if it 'collapses', with no harm done.

Figure 85, also in the *Students' book* as figure 27, shows a system of operational amplifiers set up to study the bending of a tower.

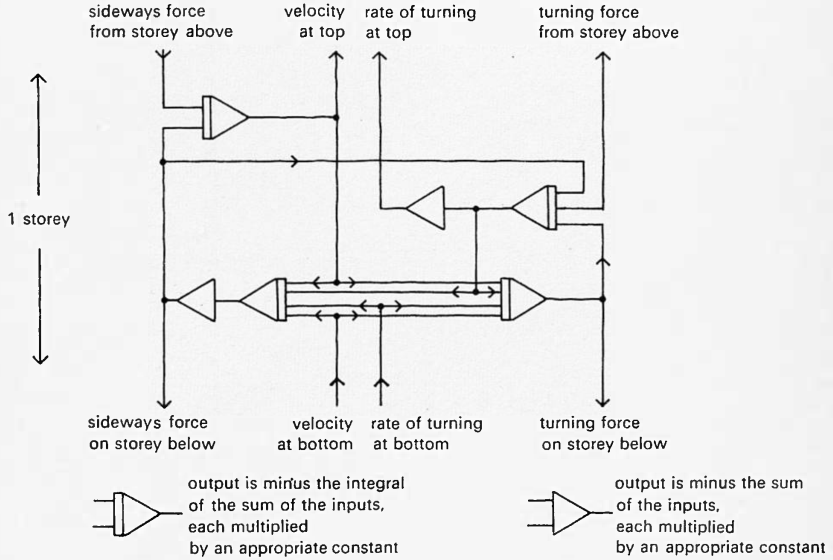



**Figure 85** (same as SB figure 27)
Operational amplifiers used to simulate the response of a building to an earthquake.
The system represents one storey of a tall tower. Each storey can move and rotate, and exert a moving or turning force on those above or below it. The whole tower would be represented by as many such systems as there are storeys, all connected together.
*After Hollingdale, S.H. and Tootill, G. C. (1970)* Electronic computers. *Penguin.*

## Part Three

# Circuits containing inductance

*Time:* about a week.

This Part could be transferred as a whole to Unit 7, *Magnetic fields*. It would fit in well there, and provide more practical work in the last half of the course as a whole, while still leaving the Unit on electronics a satisfactory sort of shape.

If Unit 6 is being transplanted into a different course, it may well be that this Part should be omitted, especially if time is short.

## Treating inductors as black boxes

In the spirit of this Unit as a whole, it is suggested that inductors be studied for what they do, not for how they do it, at this stage. To study them otherwise would involve a long digression, doing work that belongs in Unit 7. If this part is taken over to Unit 7, the 'black box' aspect can be played down.

Naturally, information the class wants should not be withheld. They may know enough about electromagnetic induction to appreciate that a voltage is required to change the flux within a coil, and *that the voltage is bigger the faster the flux changes. Such information can, however, be given by the* way, as it were, at this point with a promise of a later expansion in detail.

Demonstration

### 6.12 The behaviour of an inductor

1033 cell holder with two U2 cells

1017 resistance substitution box

1030 high inductance coil

92G double C-core and clip

1007 double-beam oscilloscope
*or*
64 oscilloscope

92R m.e.s. bulb (2.5V, 0.3A) *2*

92S neon lamp *1*

92T m.e.s. holder *3*

541/1 rheostat (10–15 Ω)

1000 leads

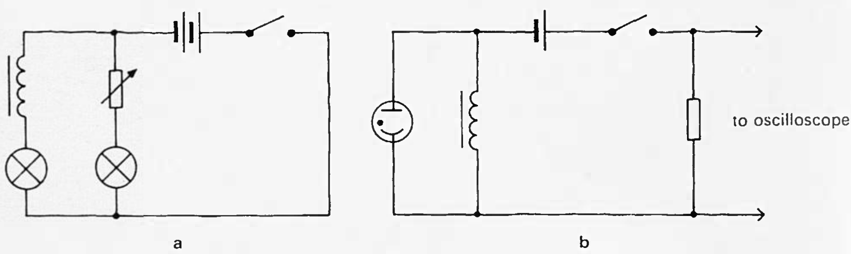



**Figure 86**
Simple demonstrations with an inductor.

Figure 86 shows two simple demonstrations with an inductor. In figure 86 *a* one 2.5 V lamp is lit in series with the inductor. Adjust the rheostat connected to a second lamp so that it is lit as brightly as the first. When the switch connecting both lamps to two cells is closed, the lamp in series with the inductor comes on after the lamp in series with the resistor.

Figure 86 *b* has an inductor in series with a resistance of about 5 Ω, across which leads go to an oscilloscope to indicate the changing current in the circuit. When the switch is closed, the current grows gradually, with a time constant of the order of a second. For simplicity, raise the gain of the oscilloscope to 0.1 V $cm^{-1}$ so that only the first, linear portion of the rise is seen, as in figure 87. The complete rise in current will ultimately flatten out at the maximum current, and may also show a sudden drop in time constant (a steepening kink in the curve) where the core saturates, following earlier departures from the ideal curve of the form $1 - \exp(-kt)$ due to non-linearities of the iron core. Using more than one cell will make these difficulties worse. It is best at this stage if the oscilloscope

## Inductors

A capacitor is, in some respects, like a spring, in that its charge is proportional to its voltage, as the change in length $x$ of a spring is (often) proportional to the tension in the spring.

A mass has the property that a force is needed to change its velocity. There is a circuit component with an analogous property; a voltage is needed simply to change the current in it. The analogy belongs to the same family as the capacitor–spring analogy, because if charge $Q$ corresponds to displacement $x$, current – equal to $dQ/dt$ – is analogous to velocity $dx/dt$. The analogy does not mean that a p.d. *is* a force, any more than it means that a charge *is* a displacement.

Such a component, an *inductor*, can be produced and some simple experiments can be done with it to suggest that the above description is a fair one. No real iron-cored inductor behaves quite as simply as has been suggested, because inductors rely on the properties of iron, which change as the current in the coil round the iron changes. But over limited ranges of current, the analogy works. It works well for air-cored inductors.

Demonstration
### 6.12 The behaviour of an inductor

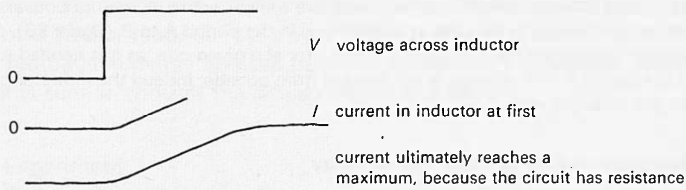



**Figure 87**
Growth of current in an inductor.

If a car had a signal lamp to indicate when it had reached the speed limit, the lamp would always light some time after the engine began to exert a force to move the car off from rest. If an inductor has a lamp in series with it, which lights when the current reaches a certain value, the lamp lights some time after a steady voltage has been switched across the inductor.

If the growth of current is watched on an oscilloscope, the effect of applying a steady voltage to an inductor is to produce a steadily rising current. Of course, if the circuit has resistance, and it always has, the current cannot grow indefinitely, and must ultimately flatten out, as indicated in figure 87.

For a mass:
force = mass × rate of change of velocity $F = m\mathrm{d}v/\mathrm{d}t$.
For an inductor:
voltage = inductance × rate of change of current $V = L\mathrm{d}I/\mathrm{d}t$.

spot rises linearly and goes off the screen. If desired the gain can then be reduced to show that there are complications, some of which will be explored later. When the switch is opened, the neon lamp flashes.

### Voltage 'opposing' a change of current?

It is usual to write $V = -L\mathrm{d}I/\mathrm{d}t$, and to say that the voltage 'opposes' the change of current. But when one writes $IR + L\mathrm{d}I/\mathrm{d}t$ for the sum of voltages across $R$ and $L$ in series, as is also usual, the minus sign seems to have vanished. The difference is due to a shift of point of view; we suggest that for most purposes in the course, it is better to have one point of view, and to stick to it. We suggest using the view in which the sign is positive.

To see the difference, consider a resistor connected to a battery. It is usual to write $+IR$ for the p.d. across the resistor, and $+I^2R$ for the rate of energy transformation. In this convention, energy *deposited in the resistor from a source* is reckoned positive. If the battery e.m.f. is $E$, one writes $IR - E = 0$ and $I^2R - IE = 0$. The *source* $E$ has a negative sign; the *sink* has a positive sign. In words, one speaks of the voltage needed to drive current $I$ through resistance $R$.

Figure 88 shows current, voltage, and energy flow for an inductor, on the same convention. From A to B, the current is positive and rising. Energy is being *deposited in the inductor* (in its magnetic field). If, as for the resistor, $V = L\mathrm{d}I/\mathrm{d}t$ is reckoned positive, as in figure 88, the rate of supply of energy $IL\mathrm{d}I/\mathrm{d}t$ is positive. At B, the inductor has its greatest energy. From B to C, the inductor delivers back that energy: it now behaves as a source – a *negative sink*. The sign of $V$ correspondingly goes negative. One is never led to the crazy view that there is no p.d. across a pure inductor on the grounds that $L\mathrm{d}I/\mathrm{d}t$ somehow 'cancels' the applied e.m.f.

Any confusion arises out of this dual role of inductors, as sources and sinks. The two views are equivalent, and neither is more correct than the other. We think it better to keep to one, and not make hidden shifts of point of view. On the *sink-positive* view, in the period A to B (figure 88), a p.d. $V$ (positive) is needed to increase the current in the inductor at a given rate, as it is needed to drive current in a resistor. In the period B to C, energy is not needed from outside; indeed the inductor gives back energy, and the p.d. changes sign.

### Inductance and mass – another analogy

The analogy between $L$ and $m$ is introduced here partly to make the action of an inductor seem less peculiar, by drawing a familiar parallel, and partly to help later on, when we shall want to discuss the oscillations of an $LC$ circuit as being like a mass and spring system.

Experiment
## 6.13 Pulses into *LR* circuits

1075 electronics kit

1033 cell holder with four U2 cells

1017 resistance substitution box

1030 high inductance coil

92G double C-core and clip

1009 signal generator (not essential, see below)

104 low voltage power unit
*or*
27 transformer

1000 leads

In the first case, the equation is useful as it stands only if the mass is constant, which it may not be. In the second, the equation is useful as it stands if the inductance $L$ is constant, which it very often is not. But sometimes $L$ is approximately constant (it *is* constant for air-cored coils, but not for iron-cored ones).

In this experiment, the p.d. across the inductor is of the order of 1 V. Initially, the current rises by about 0.1 A in about 1 s, as may be noted from the movement of the oscilloscope spot. (If the resistor is 5 Ω, the spot may rise at about 0.5 V per second.)

The current rises at about 0.1 A $s^{-1}$, so the inductance $L$ is of the order 10 $\frac{V}{A\,s^{-1}}$. The unit is called the henry, symbol H.

Why is there a pulse of voltage large enough to flash a neon lamp when the current is switched off? The current must drop rapidly, say at the rate 10 A $s^{-1}$ (0.1 A in 0.01 s) to produce a voltage of the order of 100 V. The oscilloscope shows that the current does drop very rapidly.

What is the mechanical analogue of such a large pulse of voltage? (A car hitting a brick wall, or a tennis ball whose velocity is suddenly changed by a short, sharp hit.)

To say that an inductor is analogous to a mass is only to say that the equations describing the two things have a similar form. The analogy is said to be a 'formal' analogy. No one claims that masses and inductors are alike in any concrete way; there are just some similar features in the way they behave. The comparison is like that between radioactive decay and the decay of charge on a capacitor: some of the behaviour is similar, though the situations are different.

Experiment
## 6.13 Pulses into *LR* circuits

This experiment is very like experiment 6.7, in which square pulses were fed to circuits containing capacitors, to see how these circuits changed the pulses. As then, two circuits suggest themselves. Figure 89 shows them.

In circuit *a* the output is proportional to the current in the inductor, and is very much like the circuit just used (figure 86 *b*). Students ought to be willing to guess what will happen if the circuit is fed with on–off square pulses.

Circuit *b* is different, but some students may be willing to guess how the output, which is the voltage across the inductor, will vary if the circuit is fed a current that goes rapidly up and down.

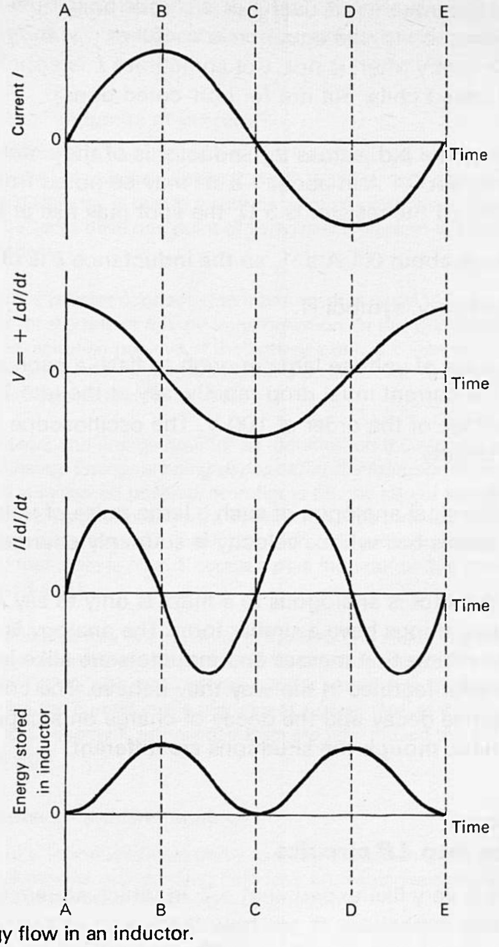



**Figure 88**
Current, voltage, and energy flow in an inductor.

Figure 57, page 57, gives a number of ways of making square pulses. It is best to avoid slow motion, single pulses this time, as the time constant of the circuit cannot be made very big. The inductor is a 1080-turn coil on a double C-core, held with a clip. The C-core faces must be clean and in good contact. Its inductance is about 15 H, and its resistance about 6 Ω. Two frequencies are worth trying; 50 Hz square pulses derived from the mains supply using a basic unit to square the sinusoidal supply, and 1 kHz or more from an astable multivibrator, whose output is squared in the same way. (A signal generator with a square wave output can also be used.)

Figure 90 shows these two sources, one driving each sort of *LR* circuit.

In figure 89 *a*, the resistance may be 1 kΩ at 1 kHz, and about 4.7 kΩ at 50 Hz. The resistance should be *reduced* to make the circuit 'integrate' better.

For circuit *b*, the resistance may be 220 kΩ at 1 kHz, and 15 kΩ at 50 Hz. The resistance should be *increased* to make the circuit 'differentiate' better.

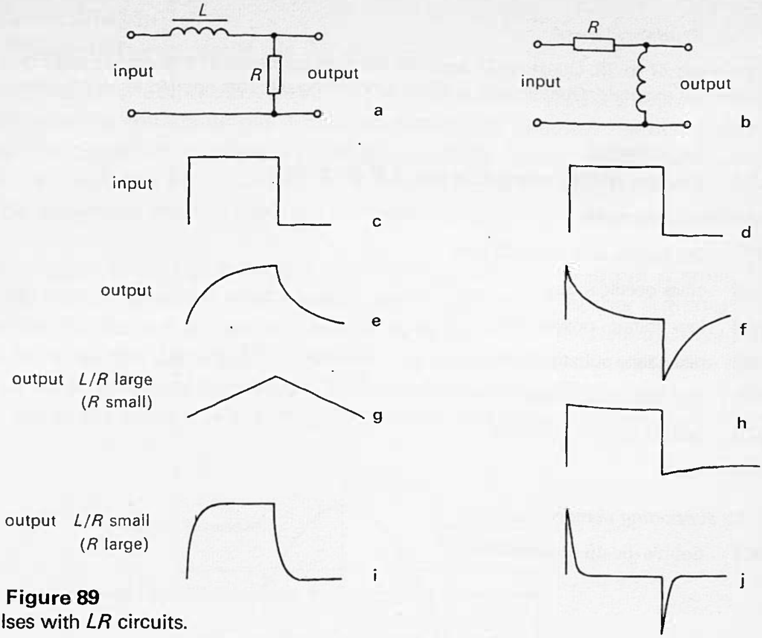



**Figure 89**
Square pulses with *LR* circuits.

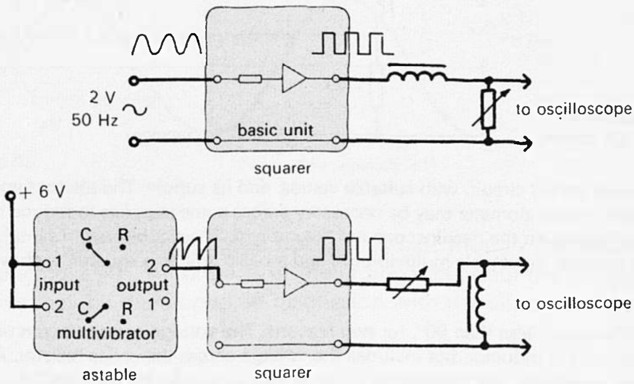



**Figure 90**
Two ways of feeding square pulses to two *LR* circuits.

Figure 89 shows what happens. When *R* is small, the current in *R* in circuit *a* grows slowly and falls slowly, and the circuit integrates (see *g*). When *R* is small in circuit *b*, little voltage across *L* is needed to raise or reduce the slowly changing current, and the output almost follows the input.

When *R* is large, the current changes quickly, so that circuit *a* is able to follow the input, but circuit *b* produces short, sharp pulses of voltage across *L* as the sudden current changes occur. This circuit differentiates (see *j*).

### *Students' book*

See questions 37 to 39. Question 37 explores the analogy between inductance and mass. Question 38 is a numerical example. Question 39 is about alternating currents applied to an *LR* circuit.

## Experiment
## 6.14 Phase differences in an *LR* circuit

| | |
|---|---|
| 1075 | electronics kit |
| 1033 | cell holder with four U2 cells |
| 158 | class oscilloscope |
| 104 | low voltage power unit |
| 1017 | resistance substitution box |
| 1030 | high inductance coil |
| 92G | double C-core with clip |
| 1000 | leads |

*For extra supporting demonstration:*

| | |
|---|---|
| 1007 | double-beam oscilloscope |

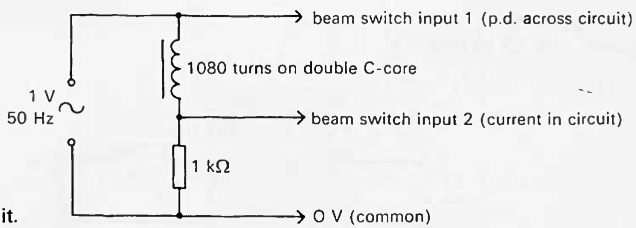



**Figure 91**
Phases in an *LR* circuit.

Figure 91 shows the *LR* circuit, with suitable values, and its supply. The alternating supply should not exceed 1 V, and a potentiometer may be necessary across some supplies to reduce the input to a point at which the waveforms on the oscilloscope are not clipped. The double-beam switch, made from the beam splitter module, an astable multivibrator, and a basic unit as a squarer, is shown in figure 66, experiment 6.9.

The phase difference is less than 90°, for two reasons. The voltage across the circuit, on beam 1, is not the voltage across the inductor, but includes the voltage across the series resistor. Also, the inductor has itself some resistance. The impedance of the inductance at 50 Hz exceeds 3 kΩ, while its resistance is less than 10 Ω, so the former error is the more important, if the resistance in series is 1 kΩ.

### Extra demonstration

It will probably help to show the same experiment in a corner of the laboratory, using the demonstration double-beam oscilloscope. The resistor can be decreased to perhaps 100 Ω, using a larger gain on the 'current' trace than on the 'voltage' trace, so that the phase difference is more nearly 90°.

### Treatment using phasors

If the phasor treatment, Appendix C, was used for capacitors it can be used again for inductors, and then for *LC* circuits in the work that follows. We repeat that this treatment is not part of the Advanced Physics course, but is intended to help those who will be happier with a more incisive, mathematical treatment.

Demonstration

## 6.14 Phase differences in an *LR* circuit

In experiment 6.9, the current in a capacitor was found to rise to a maximum before a sinusoidally varying voltage across it reached maximum, because the charging current is big when the capacitor is empty but filling up rapidly. Students may be invited to anticipate the result of a similar experiment with an inductor. A complete answer is hardly to be expected, but the exercise in reasoning has value even if it is incomplete.

It might be argued at least that the p.d. will be large when the current is small, for it is then that the current changes most rapidly, and $V = L\mathrm{d}I/\mathrm{d}t$. A further argument might say that when the current is near zero but rising to a positive value, a positive p.d. is needed to increase the current. (By 'positive' we mean that + to − is in the same sense as for a conventional current going through a resistor.) If the voltage is at a maximum when the current is growing, the current will reach its maximum *after* the voltage.

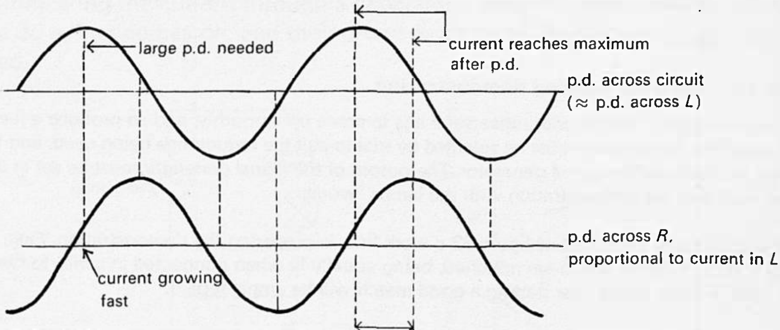



**Figure 92**
Oscilloscope traces from an *LR* circuit.

Figure 92 shows what the oscilloscope traces look like, though the phase difference has been made almost 90°. All or parts of the arguments about the phase difference suggested above may be developed, in discussion with the class, after they have seen the result of the experiment.

### Optional: the impedance of an inductor

Some students will like to have their knowledge made more complete by seeing how to find the reactance offered by an inductor to alternating current at any frequency. This course does not require the result, but it is the sort of result which it may be convenient for some students to have heard about.

If an alternating current $I$ flows in an inductor, and

$$I = I_{\max} \sin 2\pi ft$$

the voltage across the inductor is $L\mathrm{d}I/\mathrm{d}t$, that is,

$$V = 2\pi fLI_{\max} \cos 2\pi ft.$$

Demonstration

## 6.15 Changes of current with frequency in circuits containing capacitance and inductance

1009 signal generator

181 general purpose amplifier (see below)

1081 decade capacitance unit (1–10 μF)

1037 set of solenoids
*or*

147D coil with 300 turns (demountable transformer kit)
*or*

1058 coil with 120+120 turns

52 Worcester circuit board kit

1057 alternating current ammeter *3*
*or*

1005 multi-range meter

1007 double-beam oscilloscope

1000 leads

### 16.5a The lamp lighting demonstration

The demonstration needs prior rehearsal if it is to come off smoothly, and so produce a feeling of surprise. The capacitance must be selected by trial to suit the inductance being used, and the frequency range available on the signal generator. The output of the signal generator must be set in advance to a level such that the demonstration with the lamps 'works'.

It is best to make the circuit of figure 93 *c* work first, in preparing the demonstration. First, select three 1.25 V, 0.25 A lamps which are matched, being equally lit when connected in series to two or three dry cells. Trouble taken over getting a good match will be amply repaid.

Connect up the circuit of figure 93 *c*, using these lamps, the *low impedance* output of the signal generator, the decade capacitance unit set to 1 μF, and an *air-cored* inductor. The most convenient inductor is one of the set of solenoids, item 1037. Try one or other of the solenoids with many turns. Other coils, mentioned in the apparatus list, will also serve. The advantage of the solenoids is that a somewhat different inductance can be tried simply by using another solenoid from the set.

Using the three-lamp circuit, vary the frequency of the signal generator over the range 1 kHz to 10 kHz, or 300 Hz to 3 kHz, according to the range provided. Set the output level of the signal generator so that the lamp connected to both circuits (lamp 3 in figure 93 *c*) is on at the low end of the range, on at the top end, but off for a narrow range of frequencies. If the output is too high. the lamp never goes off; if it is too low, the lamp is off at most frequencies.

If the resonant frequency just discovered is near the high end of the range, increase the capacitance. A value from 2 to 6 μF is generally suitable. If lamp 2 cannot be made to go off in the frequency range available, start again with a fatter coil having more turns. Use a capacitance such that the resonant frequency is in the middle of the available range, say 2 kHz or 1 kHz for the two ranges given above, respectively.

Make a fine adjustment to the output level such that lamp 1 does go out at the low end of the range, lamp 2 does go out at the high end of the range, and lamp 3 goes out, but not over a wide spread of frequencies, at the resonant frequency.

Do not alter the output of the signal generator at all from now on. Removing the inductor and two lamps brings one to the circuit of figure 93 *a*. Set the frequency low, and raise it, so that the lamp lights.

The ratio of the largest voltage $2\pi fLI_{max}$ to the largest current $I_{max}$ is

maximum voltage/maximum current $= 2\pi fL$.

It must be noted that the maximum voltage does *not* occur at the same time as the maximum current. The term *reactance* is reserved for such ratios of voltages and currents with a phase difference of $\pi/2$. But the reactance is in ohms, nevertheless. A 10 H inductance has a reactance of about 3000 Ω at 50 Hz.

Demonstration

## 6.15 Changes of current with frequency in circuits containing capacitance and inductance

### 6.15a A lamp-lighting demonstration

This demonstration presents a pretty puzzle; a commonsense prediction which unexpectedly fails to come true.

A lamp indicating the current through a capacitor supplied from a signal generator, as in figure 93 *a*, first comes on, and then grows brighter as the frequency is increased.

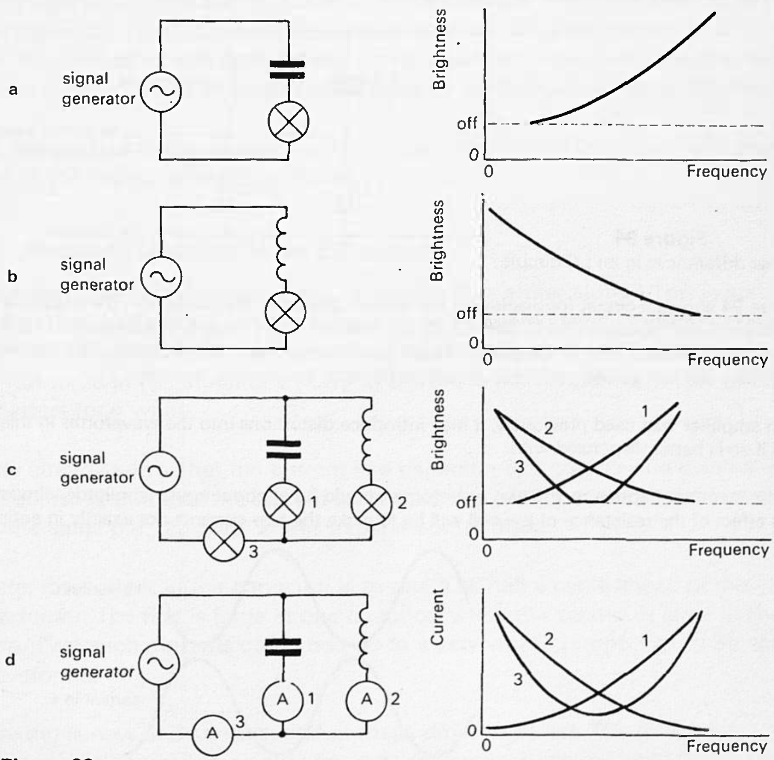



**Figure 93**
Currents in an *LC* circuit.

Remove the capacitor, and substitute the inductor. Reduce the frequency so that the lamp lights.

Bring the frequency up to the previously determined resonant frequency, saying that you want the lamp 'half on'. Add the capacitor and its lamp in parallel with the inductor and its lamp, and note that the capacitor-lamp is 'half on' too.

Argue that if lamp 3 is inserted, it ought to be full on, and then insert it. If the demonstration has been carefully managed, it will be off.

Finally, having shown what happens to all three lamps if the frequency is varied, replace them by alternating current ammeters. If the available current covers too little of the most sensitive, 0–1 A range, or if the meters are too small to be seen easily, a multi-range meter placed in the three positions in turn may be an improvement.

Sceptical students may attribute changes in the brightness of the lamps to variations in the generator output with frequency. To meet the objection, an oscilloscope should be to hand to be connected across the output, to show that the output changes little. It may be that the signal generator does not deliver enough power to light the lamps. It certainly will not if it only has a high impedance output. The remedy is to take the output from a general purpose amplifier (item 181) driving it from the oscillator. Take the output from the low impedance output of the amplifier which usually drives a loudspeaker, having switched any loudspeaker provided in the amplifier out of circuit.

### 6.15b Phase difference demonstration

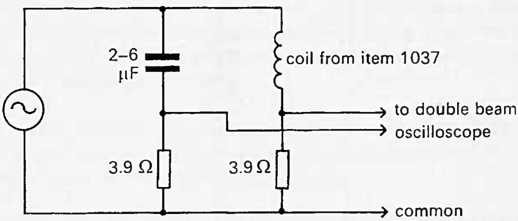



**Figure 94**
Phase differences in an *LC* circuit.

Figure 94 shows a circuit for displaying the relative phases of the currents in the capacitor and the inductor. Small resistors (3.9 Ω, item 52 H) are inserted in the leads to the capacitor and the inductor, taking the common lead to the double-beam oscilloscope from their junction. The two beams are used to display the p.d. across each resistor, proportional to the currents in each.

If an amplifier was used previously, it may introduce distortions into the waveforms in this experiment, and if so is better dispensed with.

At the resonant frequency, the two waveforms should be of about equal amplitude, almost in antiphase. The effect of the resistance of the coil will be to make the two currents not exactly in antiphase.

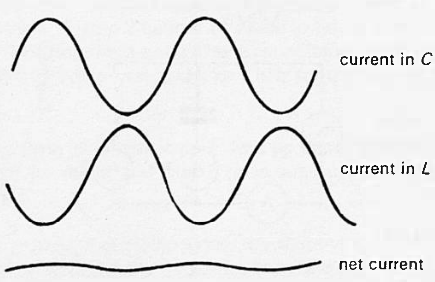



**Figure 95**
Currents in a parallel *LC* circuit.

Then show an identical lamp, indicating the current through an inductor supplied from the signal generator, as in figure 93 *b*, which is bright at low frequencies, but dims and goes out as the frequency is increased.

Now argue that the coil and capacitor in parallel, with the frequency such that each on its own lights the lamp dimly, will together pass enough current into a third lamp carrying current from both, as in figure 93 *c*, to light that lamp brightly. Two good things should make a still better thing.

Then try it. The two lamps, one in series with the capacitor and one in series with the inductor, are both alight. The lamp carrying current from both is *not*.

Here is a genuine case of two and two not making four, but students will probably find that at once too simple and too sophisticated a remark.

Show that if the frequency is set at a low value, the lamp connected to the inductor and the lamp connected to both circuits are both on. As the frequency is raised, both lamps get dimmer, the lamp connected to both circuits getting dimmer faster. The lamp connected to the capacitor comes on, and there is a stage where both inductor-lamp and capacitor-lamp are on, but the third lamp is off. Then the inductor-lamp goes out, the capacitor-lamp gets brighter, and so does the lamp connected to both circuits. The current in one branch falls, and the current in the other branch rises as the frequency is raised, but the current conducted by both together has a minimum.

Finally, the truth of these statements about the currents can be tested with ammeters in place of the lamps, as in figure 93 *d*.

### 6.15b Phase differences in an *LC* circuit

How can two alternating currents add up to less than either alone? This is just the sort of problem that, while new and puzzling, can be answered from students' previous experience, though to answer it quickly will be difficult for them. Perhaps it would be as well not to be in too much of a hurry to show the next experiment, but to pass to other matters for a while.

Students already know that the current in a capacitor is a quarter of a cycle ahead of the p.d. across it, and that the current in an inductor is about a quarter of a cycle behind the same p.d., applied, in this experiment, to both.

Therefore, the current in the capacitor is as much as half a cycle ahead of the current in the inductor. The first is large in one direction when the second is large in the other direction. Two such currents could add up to a very small current. Figure 95 shows the two waveforms.

The thinking is new and strange, and perhaps rather abstract. The two-beam oscilloscope can be used to display potential differences proportional to the two currents, taken across small resistors in series with each reactive component. The two

Experiment

## 6.16 Oscillations in a parallel *LC* circuit

| | |
|---|---|
| 1051 | capacitors, 500 μF, 250 μF, 100 μF, 50 μF |
| 1030 | high inductance coil |
| 92G | double C-core and clip |
| 1033 | cell holder with four U2 cells |
| 158 | class oscilloscope |
| 1000 | leads |

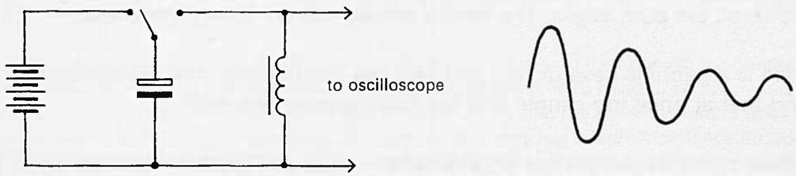



**Figure 96**
Slow oscillations in an *LC* circuit.

Figure 96 shows the circuit. The 1080-turn high inductance coil is used, with a double C-core clipped through it. For the highest inductance, the faces of the C-cores should be clean and well pressed together.

The oscilloscope timebase speed should be at its slowest, being increased later if necessary. A switch is not needed, the connection being made by a flying lead attached to the capacitor. As usual, the capacitor's polarity must be correct. The switchover is best made just after the slowly moving oscilloscope spot has appeared on the left of the screen.

At least four or five decaying oscillations should be observed.

The capacitance is easily altered by using other capacitors. The inductance can be changed by removing the clip and separating the C-cores. As the frequency rises, the time base will need to be speeded up.

It is worth trying to note the change in the period of oscillation when $C$ is reduced from 500 μF to 100 μF. A shade more than twice as many oscillations may now occupy the same time as previously, since $C$ has changed by a factor of rather more than four, and the frequency is inversely proportional to the square root of $C$. The tolerances on electrolytic capacitors make a more precise test hardly worth while.

### *Students' book*

See questions 40 and 41.

are out of step. This can be fitted in with the previous facts discovered about phase differences in *RC* and in *LR* circuits, as indicated above.

What is going on in the circuit? When current goes *down* the capacitor branch, figure 97, it is going *up* the inductor branch. Half a cycle later, what is happening? (Current *down* through *L* and *up* through *C*.)

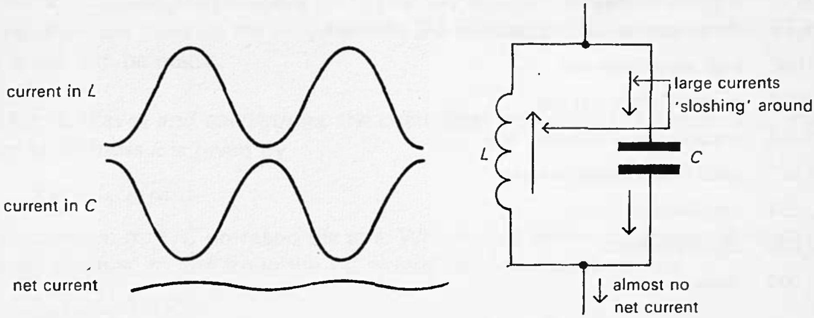



**Figure 97**
Currents 'sloshing' round in an *LC* circuit.

A picture of large currents 'sloshing' backwards and forwards between the inductor and the capacitor begins to emerge. The net current fed in can be small, while the 'sloshing' currents are large. This is the reality behind the abstraction of adding out-of-step alternating currents to obtain a smaller alternating current.

Experiment
### 6.16 Oscillations in a parallel *LC* circuit

The class can now be invited to see whether they can make currents 'slosh' round slowly inside an *LC* combination.

Figure 96 shows such a combination. The capacitor is charged, and then switched over to the inductor, while the p.d. across the circuit is watched on an oscilloscope. Slow, decaying oscillations are observed.

A capacitor is like a spring; an inductor is like a mass. If these are joined, as in figure 98, and the spring is pulled (capacitor charged), what happens? (The system oscillates.)

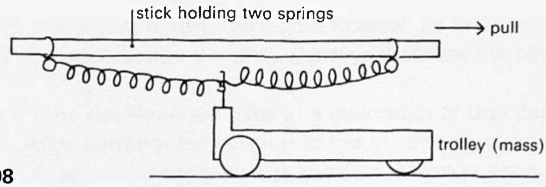



**Figure 98**
Mechanical analogue of an *LC* circuit.

### Oscillation frequency from a differential equation

The simple argument by analogy will be best for most students, as it can be done quickly. Those who would enjoy it could be shown how the circuit is described by the equation $d^2Q/dt^2 = -(1/LC)Q$, whose solutions include sinusoidal oscillations of frequency $(1/2\pi)\sqrt{1/LC}$. To do this is, of course, simply to use a mathematical model in place of a mechanical one.

Demonstration

## 6.17 Resonance in a parallel *LC* circuit

1030 high inductance coil
92G double C-core and clip
1018 capacitance substitution box
1017 resistance substitution box
64 oscilloscope
1009 signal generator
1000 leads

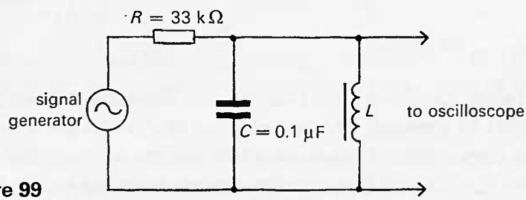



**Figure 99**
*LC* resonance.

In figure 99, $L$ is the 1080-turn high inductance coil, with or without both its C-cores. $R$, 33 k$\Omega$, is taken from a resistance substitution box, and $C$, which may be 0.1 $\mu$F, is taken from a capacitance substitution box. The signal generator is set to give a sinusoidal output, and its high impedance output may be used. With the above values, the resonant frequency is about 300 Hz with both C-cores in place, about 2 kHz with one in place, and about 3.5 kHz when the coil is air-cored.

If a stiffer spring is used, what happens to the oscillation frequency? (It rises.) A smaller capacitance corresponds to a stiffer spring ($1/C$ corresponds to stiffness $k$). The class can try other capacitors and see that the frequency changes in the expected direction.

Taking the iron out of the coil will reduce its inductance, as a trial of the previous inductance-estimating experiment (6.12) would in principle show. What effect will reducing the mass have on the frequency of the mechanical analogue? (Increase it.) Again, a test can be made.

From Unit 4, *Waves and oscillations,* the oscillation frequency $f$ of a mass $m$ joined to a spring of stiffness $k$ is given by

$$2\pi f = \sqrt{k/m}.$$

$L$ corresponds to $m$; $1/C$ corresponds to $k$. What might be the frequency at which electricity 'sloshes' to and fro in the $LC$ circuit? It seems worth trying

$$2\pi f = \sqrt{1/LC}.$$

The inductance of the coil in use was estimated very roughly at 10 H in experiment 6.12. If $C = 500\ \mu\text{F}$, the above suggestion leads to the rough prediction

$$f \approx \frac{1}{2\pi}\sqrt{\frac{1}{10\times 500\times 10^{-6}}} = \frac{1}{2\pi}\sqrt{200} \approx 2\ \text{Hz}.$$

It should be clear from the experiment that the predicted frequency has the proper order of magnitude, though a stringent test is scarcely possible.

Demonstration

### 6.17 Resonance in a parallel *LC* circuit

If the stick holding the two springs in figure 98 is shaken slowly, more quickly, and then very fast, how much does the trolley move? (A little, a lot, a little.) The effect was investigated in Unit 4, and is called resonance.

The next demonstration shows that an $LC$ circuit will resonate. The fact that $LC$ circuits do this is important in radio sets where such circuits are used to resonate to just the radio frequency of the station one wants to hear, without responding to others.

A signal of varying frequency is sent through a resistor, as in figure 99, to a parallel $LC$ combination, and an oscilloscope watches the signal across the combination.

The voltage seen on the oscilloscope rises to a maximum at one definite frequency. At that frequency, large currents are surging in the $LC$ circuit, but little net current passes in the resistor, as earlier experiments showed. There is, then, a large alternating voltage across $LC$. At other frequencies, the voltage across the resistor is bigger, as the current through the combination is bigger, and the currents in $L$ and in $C$ are not equal, though still nearly opposite, and do not cancel.

Optional demonstration

## 6.18 Radio, and 'slow radio'

| | |
|---|---|
| 1051 | tuning capacitor, 365 pF or 500 pF maximum |
| 1037 | set of solenoids<br>*or*<br>improvised tuning coil (see experiment 6.1) |
| 1051 | diode, OA 81 or 1 GP 5 |
| 181 | general purpose amplifier<br>*and* |
| 183 | loudspeaker (if not in 181) |
| 1059 | earpiece |
| 1009 | signal generator |
| 170 | low frequency a.c. generator |
| 30 | slotted base |
| 9 A | motor from Malvern energy conversion kit |
| 9 M | driving belt from Malvern energy conversion kit |
| 59 | l.t. variable voltage supply |
| 541/2 | rheostat (330 Ω) |
| 1081 | decade capacitance unit (1–10 μF) |
| 1017 | resistance substitution box |
| 1018 | capacitance substitution box |
| 44/2 | G-clamp (small) *2* |
| 92 X | reel of 26 s.w.g. PVC covered wire (for aerial) |
| 64 | oscilloscope<br>*or* |
| 1007 | double-beam oscilloscope |
| 1000 | leads |

Figure 100 shows the 'slow radio' circuit in two parts. The 1 kHz signal from a signal generator goes across the slow a.c. device, as shown, and a 330 Ω rheostat which can be used to vary the depth of modulation. The slow a.c. device is rotated at about five or ten revolutions a second, using the l.t. variable voltage supply, an electric motor, and a drive belt. The motor and slow a.c. device need to be G-clamped to the bench. Use the oscilloscope to show the 'amplitude modulated carrier wave' across terminals E and A.

Then add the second part of the circuit, figure 100 *b,* which shows the output signal across the 1 kΩ resistor representing an earpiece before the 8 μF capacitor is added across the diode. Adding the capacitor leaves only the slow oscillations visible on an oscilloscope connected across the 'earpiece'.

Optional demonstration

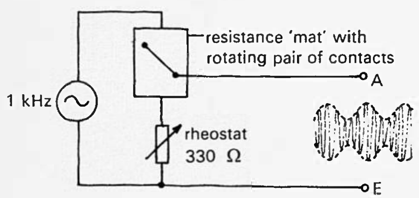
## 6.18 Radio, and 'slow radio'

Demonstration 6.1, with which Unit 6 started off, may be recalled, and perhaps repeated, to show an important practical use of combinations of inductors and capacitors in electronic circuits. Similar combinations can be used in oscillators, such as those which generate the radio signal itself. How could an amplifier and a frequency selecting circuit be made into an oscillator? (Perhaps by feeding back the amplifier output to its input, with the circuit selecting a frequency to be fed back strongly.) Such practical tasks will occupy the whole of the last part of this Unit, when students return to building electronic systems, with the resources of circuits containing capacitors, resistors, and inductors at their disposal.

Before moving to the last Part, some students may like to take a further look at the working of a radio set, passed over rather cursorily in demonstration 6.1. Having seen the 'real' radio working again, it may help to show them 'radio in slow motion.'

The high frequency radio wave oscillations, at 1 MHz for medium wave radio and about 100 MHz for television, are imitated by a 1 kHz oscillation from a signal generator. Instead of having the radio signal's amplitude made larger and smaller at the frequency of the speech or music being transmitted, the generator's signal is made larger and smaller by putting it across a rotating slow a.c. generator. Figure 100 *a* shows the circuit and the 'amplitude modulated' version of the 1 kHz signal that emerges.

This amplitude modulated signal goes to a diode and a resistor to represent the earpiece used in the 'real' radio. The signal across this 'earpiece' resistor is shown in figure 100 *b*. Its average value rises and falls at the frequency of rotation of the slow motion a.c. generator. If a capacitor is placed across the resistor, the rapid 1 kHz fluctuations are filtered out, leaving only the slow 'wanted' signal, which does not pass as easily through the capacitor.



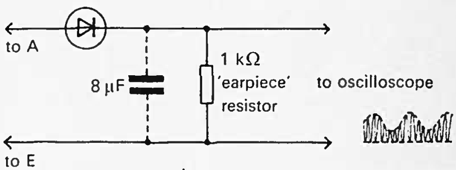




**Figure 100**
'Slow radio'.

Part Four

# Building electronic systems

*Time:* up to a week.

This Part departs from the form of the rest of the book, which has text material on the righthand pages and commentary or practical information on the facing lefthand pages. It consists almost wholly of a list of possible jobs to do, with diagrams showing possible solutions.

## Putting electronics to work: building systems

This last Part of the Unit is, in a way, the most important of all. Time should be saved for it, even at the price of cutting out earlier work in the Unit. Although it should prove to be enjoyable, it is more than an amusement, best fitted into out-of-class activities. It has a serious purpose, and deserves to be taken seriously.

The work of this Part consists essentially of individual engineering jobs to be done by students. They are offered, or they choose, a problem, and they try to build a system which solves the problem or answers the need expressed in it.

The purpose is not instruction in the answers to the problems. The idea is that each student should *feel* what it is like to have to try to solve a practical electronic problem, and should experience the interplay of guessing, of trying things out, of finding half understood *ad hoc* solutions, of needing to remember and use basic physical principles, of having flashes of inspiration, and the tedium of long periods of slow progress or no progress, all of which go to make up the working life of an engineer.

We suggest that each student should try about two tasks in class teaching time. We think that the value to a student will be greater if he or she is left alone with one or two tasks, than if he or she is led by instructions through half a dozen in the same time. Naturally, questions expressed by students should be answered, though unsolicited interference is to be avoided. This may lead to many students spending a good deal of time sitting in front of apparatus thinking and 'not getting anywhere'. We think the apparent short-term waste of leaving them to it is outweighed by the long-term advantage of their having been asked to think for themselves.

The tasks that follow are meant only as suggestions, and we hope the school will soon acquire a long list of its own. Many have solutions other than those given.

## Symbols used in diagrams in Part Four

For greater simplicity, the symbols used in the electronic systems in this Part are abbreviated versions of those used previously. Figure 101 shows how they have been abbreviated. The inputs and outputs to each module are shown in the places they occupy on that module, but no indication of the circuit within the module is given, as it has been up to now in some cases. Instead, the name of the module is printed in each symbol, together with its function in the system. Groups of modules which together perform a function, such as two basic units connected as a slow astable, have that function printed below the combination.

Many of these systems could have been drawn using the accepted symbols for electronic logic and other circuits. We have not done this; partly because there is no reason to expect a teacher to be familiar with the symbols; partly because some of our modules each serve more than one function, not all of which have an appropriate symbol; partly because teachers need to see at a glance which modules to choose. The accepted symbol will often denote two or more of our modules, whilst we think there ought to be a one-to-one correspondence in the diagrams, between symbols shown and modules required, so that teachers or laboratory assistants can count the numbers of each module involved in a system.

The abbreviated symbols assume that it is understood that the multivibrator module can be used where the bistable module is shown, that for this use its switches will be

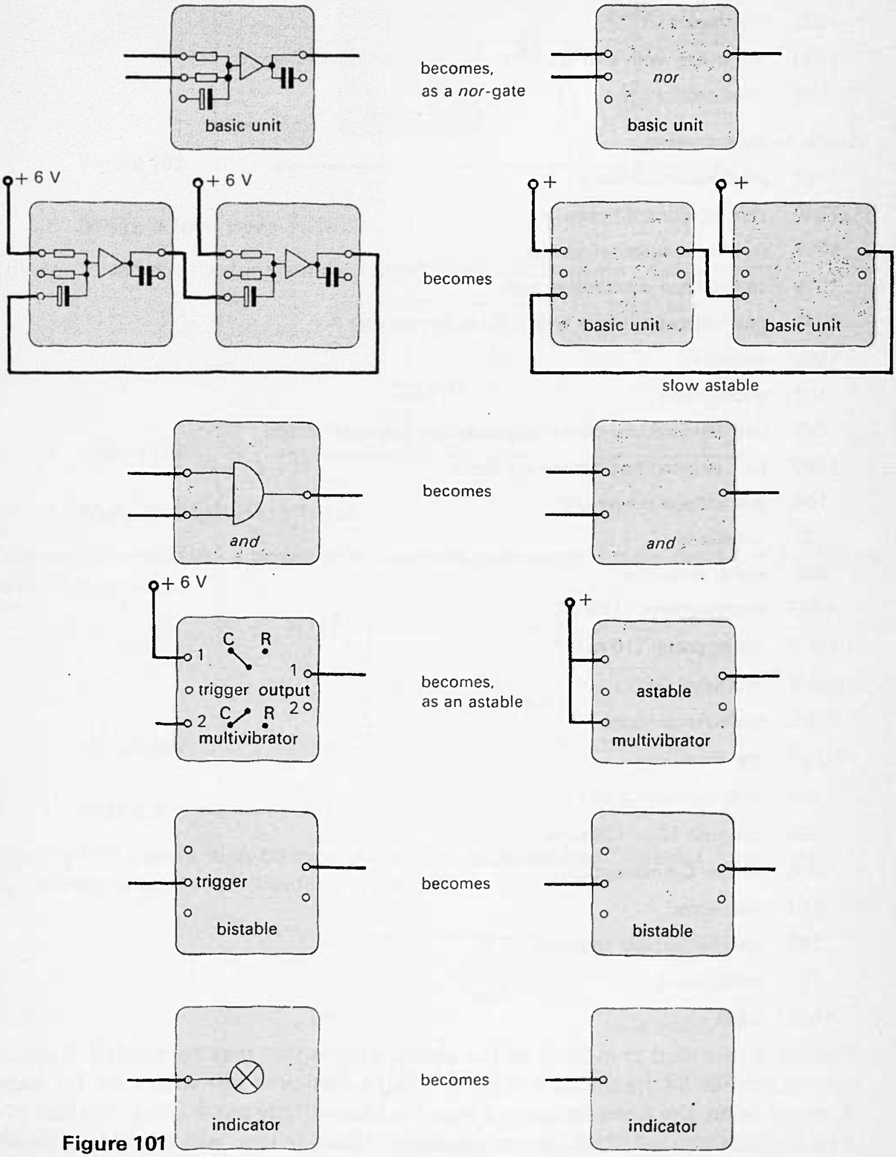



**Figure 101**
Abbreviated symbols.

set to 'R', and that for use as an astable, its switches are set to 'C'. On those occasions when a monostable multivibrator is suggested, the switch alongside the input connected to +6 V is at 'C', the other switch being at 'R'.

Individual tasks

### 6.19 Putting electronics to work

| | |
|---|---|
| 1075 | electronics kit |
| 1033 | cell holder with four U2 cells |
| 158 | class oscilloscope |

*Access to the following:*

| | |
|---|---|
| 1051 | small electrical items |
| 1040 | clip component holder |
| 1017 | resistance substitution box |
| 1018 | capacitance substitution box |
| 1041 | potentiometer holder with 5 kΩ potentiometer |
| 1059 | earpiece |
| 157 | microphone |
| 1047 | two-terminal box containing cadmium sulphide resistor |
| 1047 | two-terminal box containing diode |
| 104 | low voltage power unit |
| 27 | transformer |
| 1009 | signal generator |
| 1002 | microammeter (100 μA) |
| 1003/2 | milliammeter (10 mA) |
| 1004/2 | voltmeter (10 V) |
| 1005 | multi-range meter |
| 1035 | pre-amplifier |
| 1030 | high inductance coil |
| 1058 | coil with 120+120 turns |
| 92G | double C-core and clip |
| 92N | thermistor |
| 181 | general purpose amplifier |
| 183 | loudspeaker |
| 1000 | leads |

This list is intended to include all the obvious items that may be needed. It obviously cannot include all the things a student doing a particular task might ask for, especially if, as we hope, the tasks suggested here are treated only as samples. The rest of this Part consists of a list of suggested problems, tasks, or jobs which can be offered to students. They are deliberately varied in difficulty.

Tasks from experiment 6.4 which were not used at that stage can be added to the list below. Many other tasks will no doubt occur to teachers, as well as to students.

1 **Use an *RC* circuit to turn 2 V a.c. into short, sharp, negative going spikes**

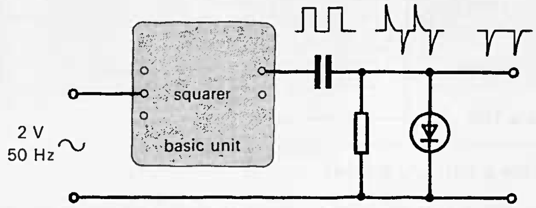



**Figure 102**

2 **Make a low pass filter**

A device to reduce the high pitched scratching sounds from a worn record is wanted.

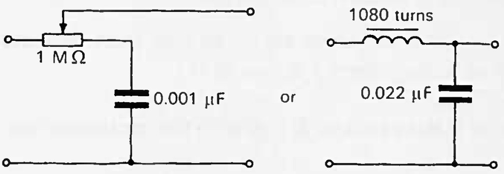



**Figure 103**

3 **Make a high pass filter**

A device to reduce the amount of mains hum and motor rumble produced by a record player is wanted.

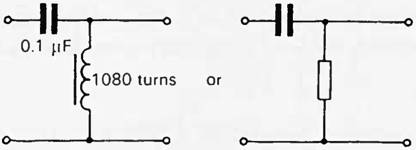



**Figure 104**

4 **Make a crossover filter**

A device that passes high frequencies to one loudspeaker ('tweeter') and low frequencies to another ('woofer') is wanted.

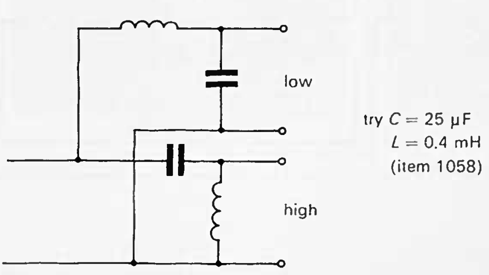



**Figure 105**

## 5 Make a bleeper that emits an audible pulse of sound when a button is pushed and released

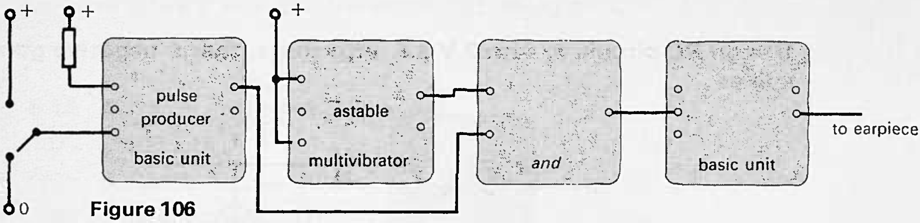



Figure 106

## 6 Make a binary adder

Use three bistables and three indicators to make a binary counter, to count from 0 to 7 pulses. (Figure 108.)

## 7 Make a binary subtracter

Modify 6 so that if all lamps are on to start with, incoming pulses will turn them off in the binary sequence from 7 down to 0.

The solution is the same as 6, but with the indicators connected to the other bistable outputs.

## 8 Make a lamp give six flashes in a row

The device should emit six short flashes after a button is pressed.

In the system shown in figure 107, a pulse is adjusted until it is long enough to let six shorter pulses through the *and*-gate. Not every basic unit will give a long enough pulse.

In an alternative solution, figure 109, a binary counter counts the flashes. After six flashes, both inputs to the *or*-gate are low, its output is low and this closes the *and*-gate, and no more signals come through. The switch resets the binary counter.

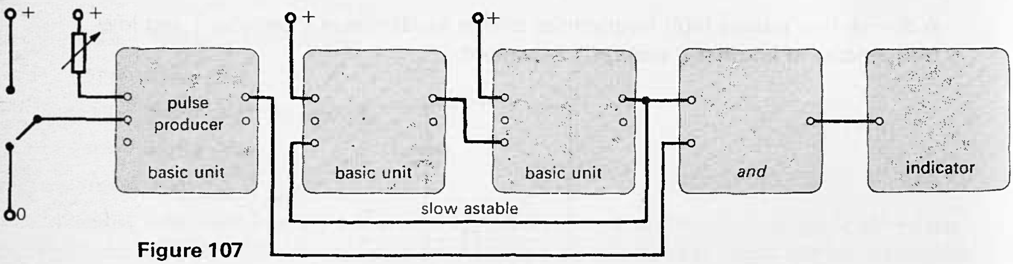
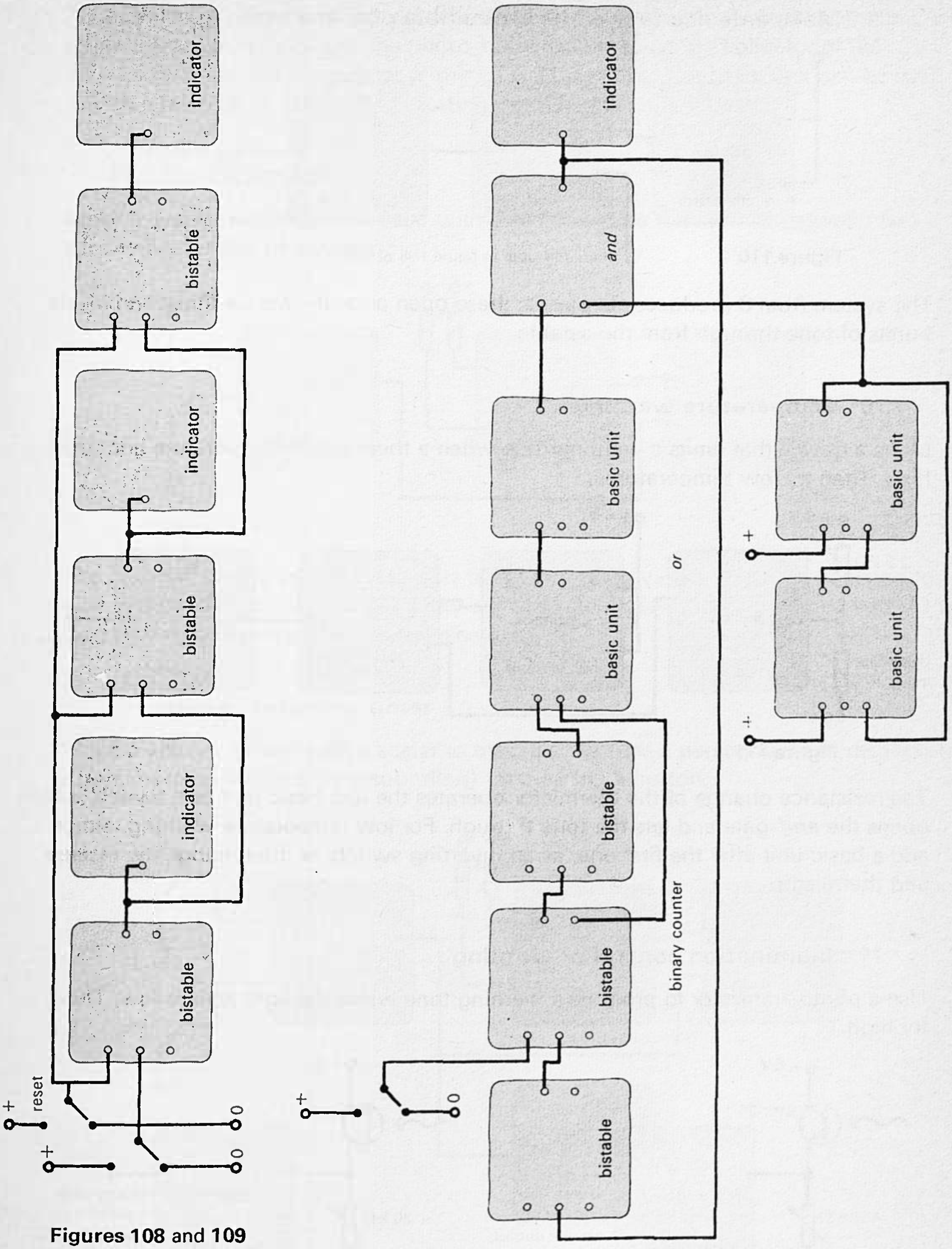



Figure 107




**Figures 108 and 109**

## 9 Make a device that emits six audible pips in a row

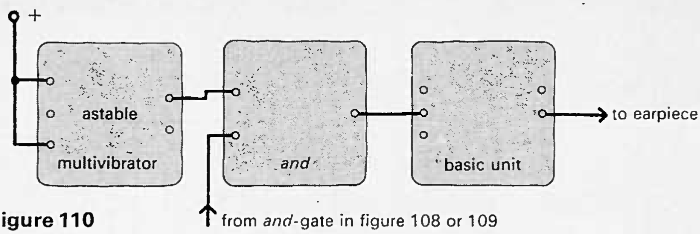



**Figure 110**

The system from 8 produces six pulses; these open an *and*-gate six times and let six bursts of tone through from the astable.

## 10 Temperature warning

Make a device that emits a warning tone when a thermistor's temperature becomes high. Then try low temperatures.

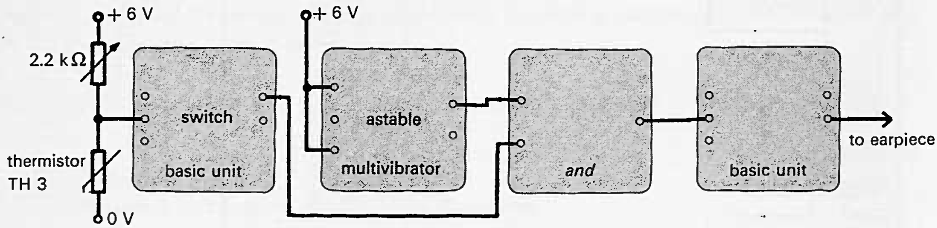



**Figure 111**

The resistance change of the thermistor operates the first basic unit as a switch, which opens the *and*-gate and lets the tone through. For low temperature warning, either add a basic unit after the first one, as an inverting switch, or interchange the resistor and thermistor.

## 11 Illumination control or warning

Use a photo-transistor to produce a warning tone when the light level is low. Then try high.

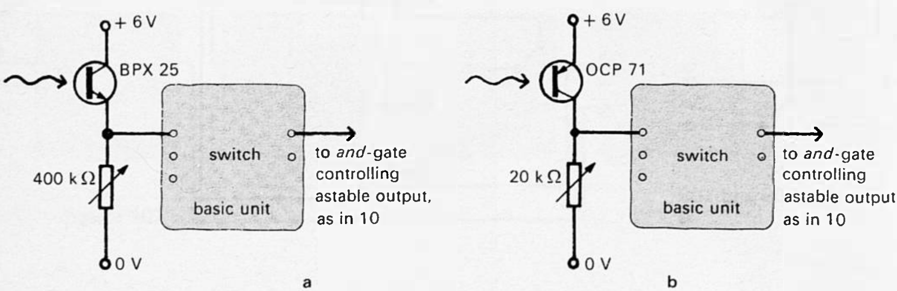



**Figure 112**

For high illumination warning, add another basic unit as an inverter after the first, or interchange the resistor and the photo-transistor, keeping the collector of the BPX 25 positive and the emitter of the OCP 71 positive. The basic unit can be used to switch a lamp on or off, with interesting possibilities for feedback.

### 12 Timing device

Make a system which can be used with a scaler to time the interval between two successive pushes of a button.

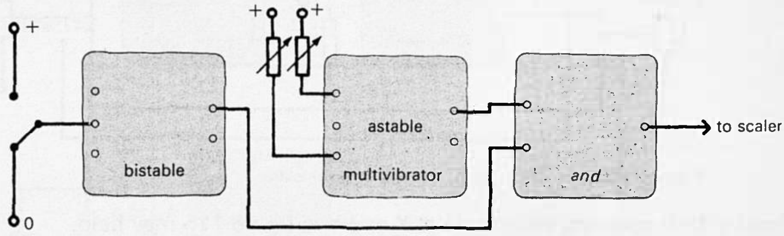



**Figure 113**

The resistors on the astable enable its frequency to be varied. It can be adjusted to give pulses every millisecond or every centisecond. This can be combined with 11 to time flashes or intervals between flashes.

### 13 Human response timer

Make a system for use with a scaler to measure the time a person takes to respond to a lamp coming on (or a tone sounding) by pressing a button.

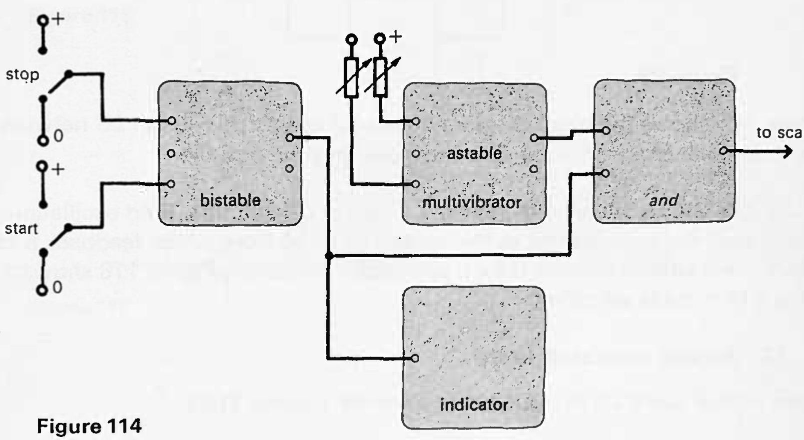



**Figure 114**

The circuit is very similar to that for 12. Many similar timing systems can be devised: timing the fall of a ball or the time of flight of a bullet, for example.

## 14 Intercom

Make a room-to-room intercom, using two earpieces, with a *send* and *receive* switch for each.

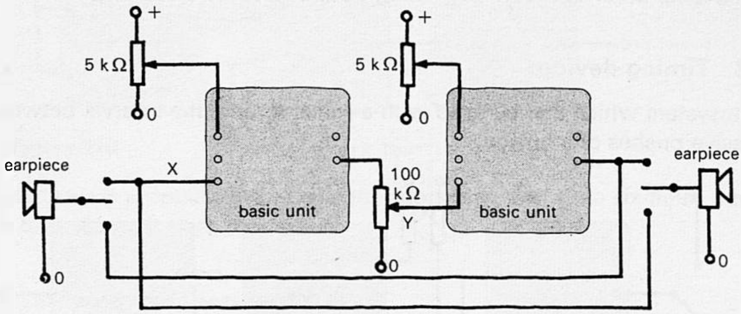



**Figure 115**

Small 0.1 μF coupling capacitors at X and Y in figure 115 may help.

## 15 *LC* oscillator

Make an oscillator in which an *LC* circuit determines the oscillation frequency. Try to produce good sinusoidal oscillations.

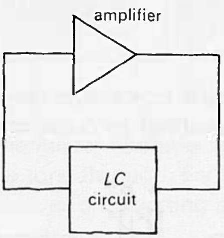



**Figure 116**

Figure 116 shows the block diagram of any *LC* oscillator, with an *LC* network in the feedback path of an amplifier. The feedback must be positive.

Figure 117 shows one simple, not very professional solution. If no oscillations occur, interchange the connections to the secondary of *M*, from which feedback is taken. Adjust the feedback resistor *R* for a sinusoidal waveform. Figure 118 shows a solution using a two-stage amplifier.

## 16 Sound operated lamp

Make a lamp come on in response to a sound. (Figure 119.)

*R* should be adjusted so that the indicator just fails to light in the absence of a sound signal.

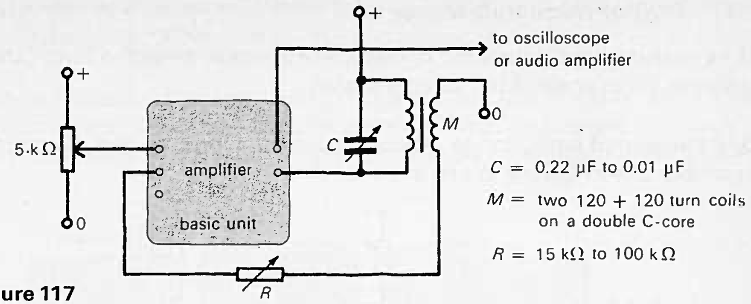



**Figure 117**

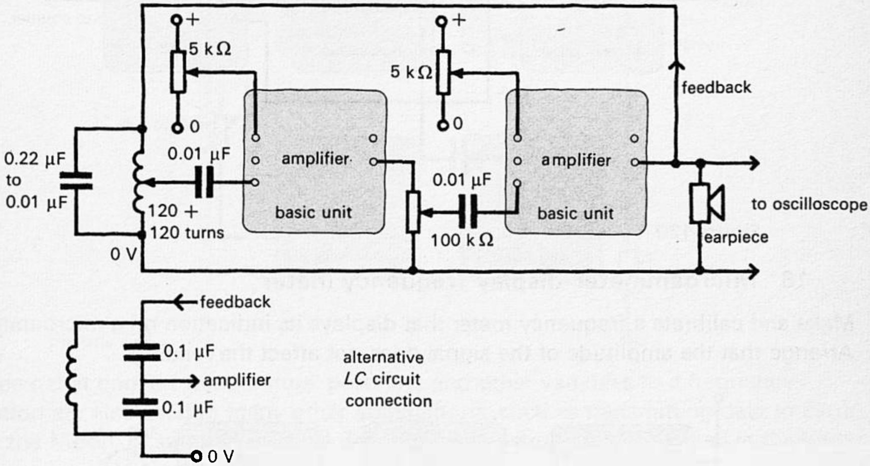



**Figure 118**

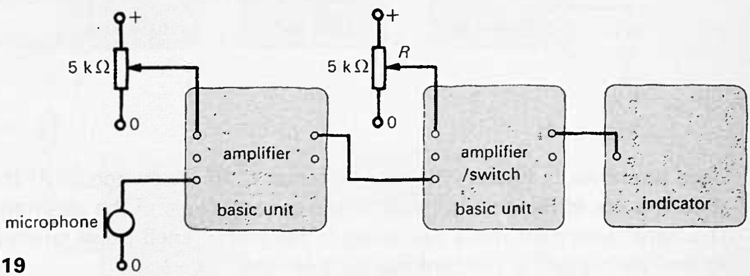



**Figure 119**

## 17 Digital frequency meter

Make a system that displays the frequency of a supply in digital form (binary using the electronics kit, in scale of ten using a scaler).

Adjust the second basic unit to produce a pulse 1 s long, so that the counter displays the number of oscillations in one second.

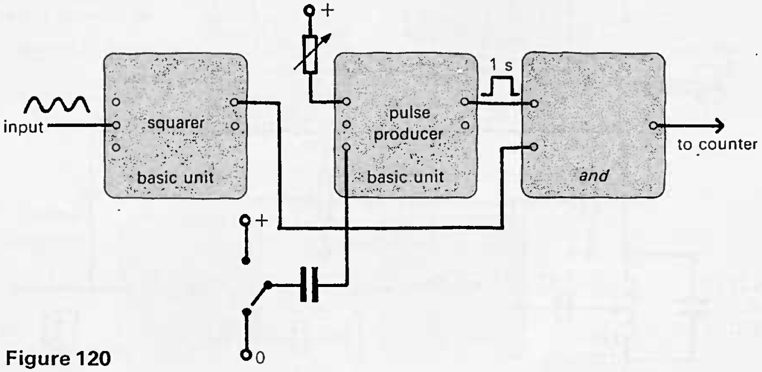



**Figure 120**

## 18 Microammeter-display frequency meter

Make and calibrate a frequency meter that displays its indication on a microammeter. Arrange that the amplitude of the signal does not affect the reading.

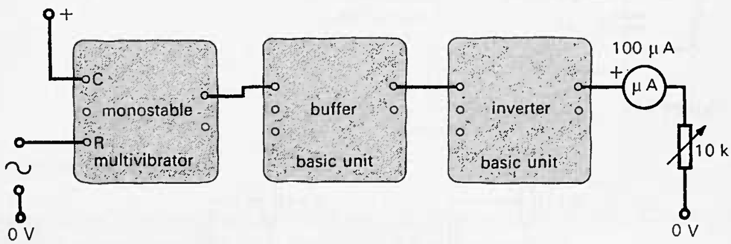



**Figure 121**

Used as shown in figure 121 (top switch to C, lower switch to R) the monostable emits a pulse of fixed height and length at each cycle of the alternating input. The basic units pass these pulses on to the meter. Each pulse conveys a fixed charge, so that the current is proportional to their rate.

## 19 Blind student's thermometer

Make a device that emits a tone whose pitch varies with temperature. Provide a second tone whose pitch can be matched to the first by turning a dial, the dial to be calibrated with Braille markings as a thermometer.

The thermistor should have a low thermal capacity (bead type, for example, TH B15) and a high resistance (10 kΩ to 100 kΩ at room temperature).

This solution is suggested because the matching of two pitches can be done with considerable accuracy. Other solutions are possible. Such devices are genuinely needed in the education of the blind, and all too few are commercially available.

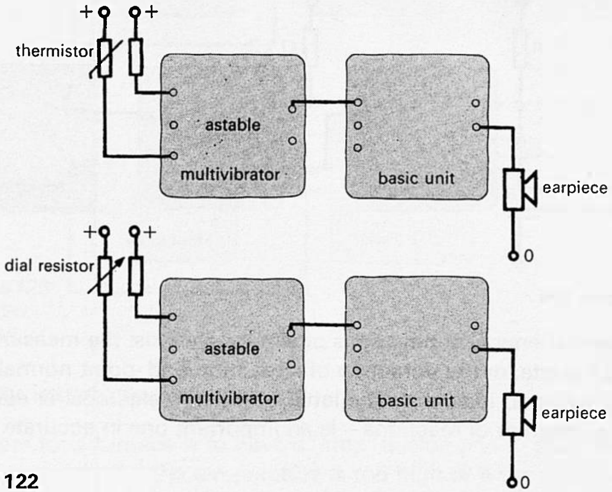



Figure 122

Systems that convert temperature, pressure, and other variables to a frequency variation are also used in many other applications, such as transmitting data to Earth from the Moon, or sending medical data out from instruments implanted in the body.

## 20 Blind student's illumination meter

This system is similar to the one for 19.

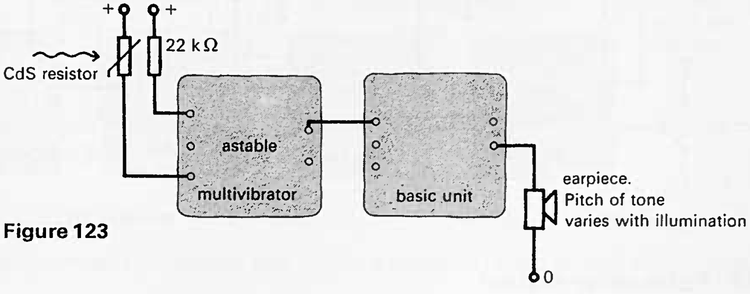



Figure 123

## 21 Blind student's pipette

Make a system which gives an audible warning when liquid in a pipette reaches a fixed level. Most liquids measured in pipettes in school chemistry conduct electricity a little, at least. Adjust $R$ in figure 124 for reliable operation. Using water, this may be 100–200 kΩ.

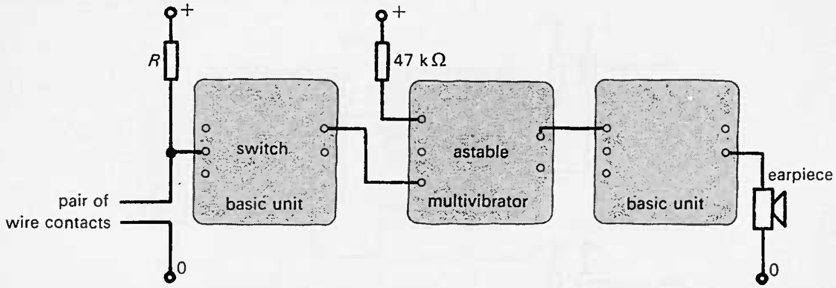



**Figure 124**

There are many chemical applications of similar systems: the measuring of the height of liquid in a burette, or the detection of a reaction end-point normally signalled visually by a coloured indicator. The latter problem – electrical or electronic means of following the progress of reactions – is an important one in accurate chemical work.

## 22 Detecting two associated pulses

In an experiment in nuclear physics, pairs of counts from decays of particles may occur close together if they have a common origin. Devise a system to indicate if two pulses fall within a fixed time of each other.

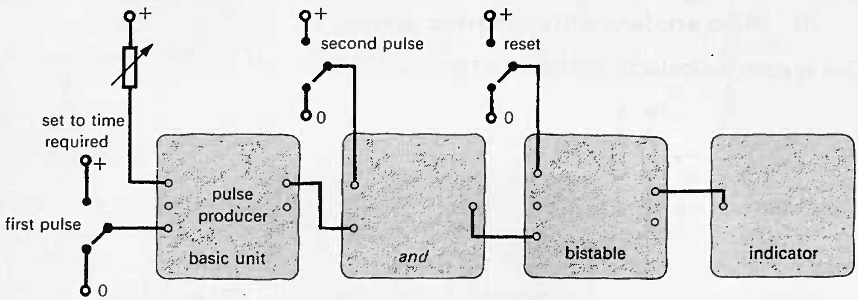



**Figure 125**

## 23 Pulse delay system

Make a system that extends a square pulse by a fixed time. Then add to the system to remove the front part of the extended pulse, and so produce a pulse like the original one, but delayed by a fixed time.

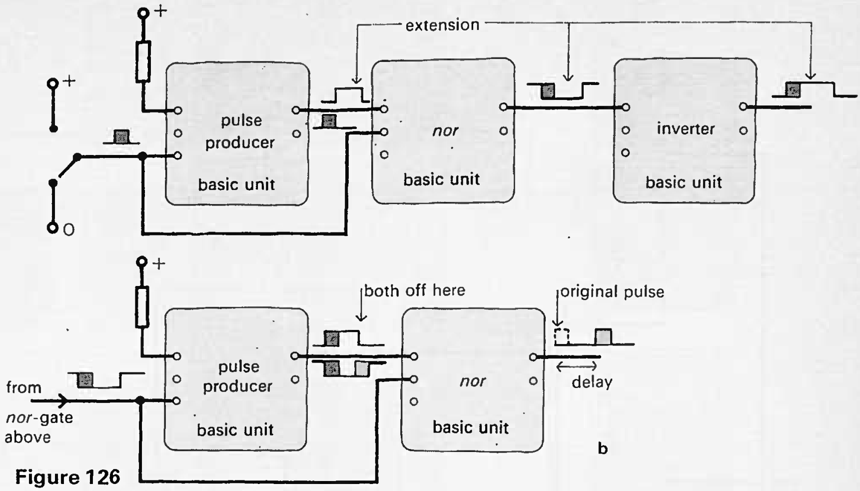



**Figure 126**
**a** Extending a pulse.
**b** Delaying a pulse.

## 24 Safety interlock system

A heating system for a furnace is to have a 'stop' button and a 'start' button, but the heating is to be turned off if the temperature is too high or if the safety door is open, and must not come on if the 'start' button is pressed under these circumstances. A lamp indicator can be used to show when the system is on.

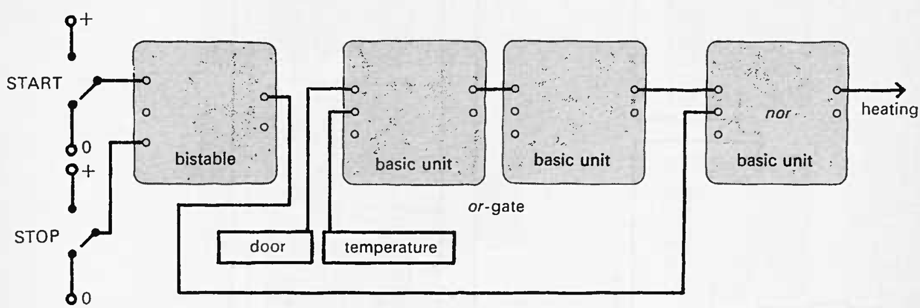



**Figure 127**

## 25 Traffic lights

Make three lamps (red, amber, and green, if possible) flash in traffic light sequence.

Figure 128 shows a simple solution, in which 'stop', 'go', and 'caution' time intervals are equal. Figure 130 shows a more complex system which lights two sets of lamps and makes the 'stop' and 'go' periods seven times longer than the 'caution' period. In both systems, the green lamp is lit when the red and amber are both off. This is done by lighting it from a *nor*-gate connected to these two lamps.

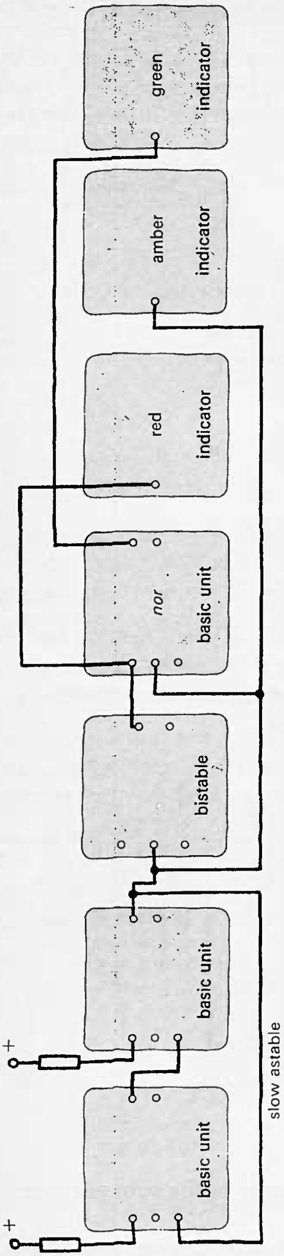
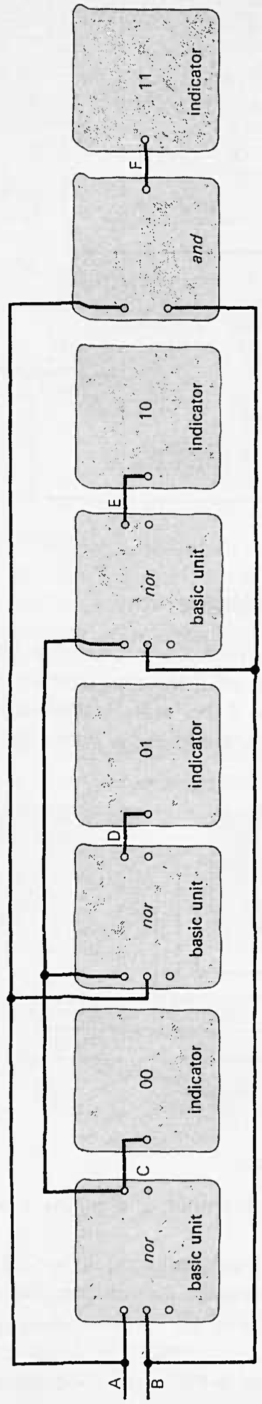



**Figure 128**
Traffic lights.




| A | B | C | D | E | F |
|---|---|---|---|---|---|
| 0 | 0 | 1 | 0 | 0 | 0 |
| 0 | 1 | 0 | 1 | 0 | 0 |
| 1 | 0 | 0 | 0 | 1 | 0 |
| 1 | 1 | 0 | 0 | 0 | 1 |

**Figure 129**
Binary decoder.

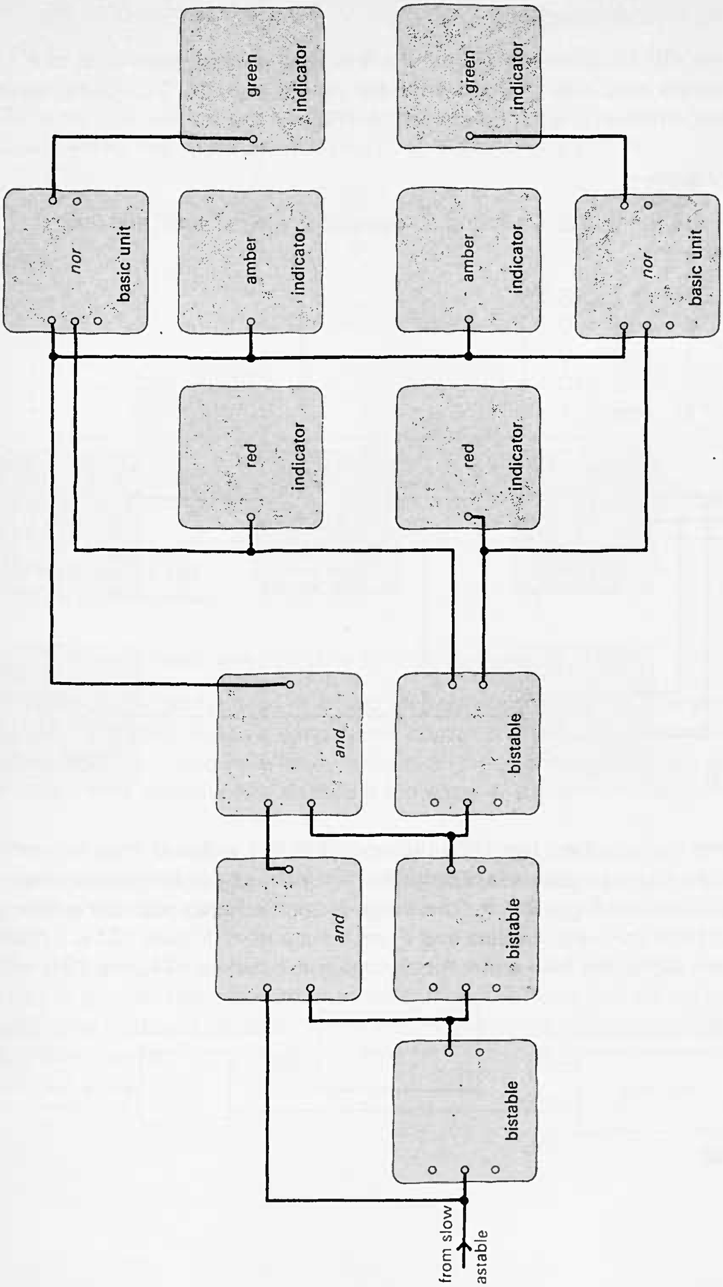



**Figure 130**
Traffic lights (alternative).

## 26 Decoding binary numbers

A binary counter (see 6) produces an output 0 or 1 on one wire for each digit of a binary number. Make a system that decodes the binary numbers 00, 01, 10, 11, so that just one of four lamps lights for each combination. (Figure 129.)

## 27 A binary adder

Make a system to add the two digits A and B together to give a 'sum' and 'carry' digit, in binary arithmetic.

| A+B = | SUM | and | CARRY |
|---|---|---|---|
| 0+0 = | 0 | and | 0 |
| 0+1 = | 1 | and | 0 |
| 1+0 = | 1 | and | 0 |
| 1+1 = | 1 | and | 1 |

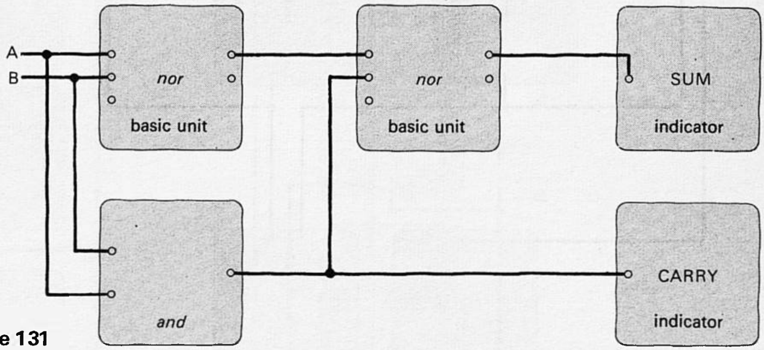



**Figure 131**
Half adder.

A computer adding two numbers like 1001110 and 1101101 will add them in pairs of digits, starting at the right, as usual. Except for the first pair, any of the others may also have to include a carry digit. Devise one stage of such a binary number adder, using two of the above two-digit adders and a small extra item. Figure 132 is a block diagram of such an adder, the half-adder blocks being the system of figure 131.

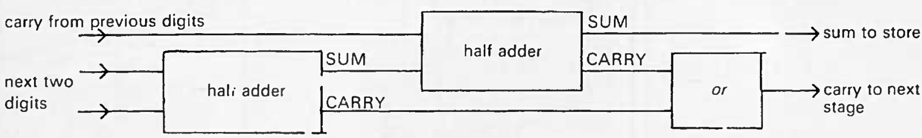



**Figure 132**
Full adder.

## 28 Counters

A way of counting pulses is to make them light lamps in rotation. If there are ten lamps numbered 0 to 9, the system is a decade counter. Light three lamps in rotation. Then try four, which can be done with only two bistables, since two bistables will count up to four in binary arithmetic. (Figures 133 and 134.)

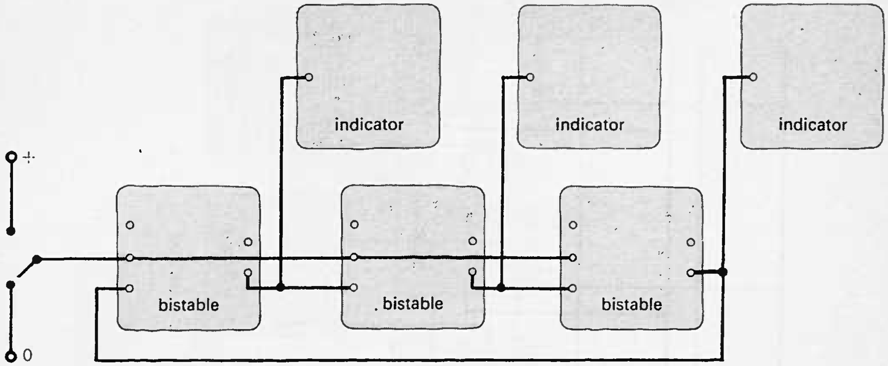



**Figure 133**
Counter (scale of three).

## 29 Compare the lengths of two pulses

This system could be used in an experiment about learning. The person being tested is to press a button, when a lamp A will come on. After a predetermined period, the lamp will go off, and he is to try to learn to release his button as it does so. An indication of whether he released it too soon or too late is to be provided.

The *and*-gate in figure 135 whose lamp indicates 'too soon' receives the pre-timed pulse. Its other input, because of the inverter connected to it, is high, and the gate is open, unless the switched pulse is on for all of the pre-timed pulse length.

The *nor*-gate, whose lamp indicates 'too late', is held off by the pre-timed pulse as long as it lasts. The other input to the *nor*-gate is high, and so the gate is off, except while the button is pressed, so the lamp lights if the switched pulse over-runs the pre-timed pulse.

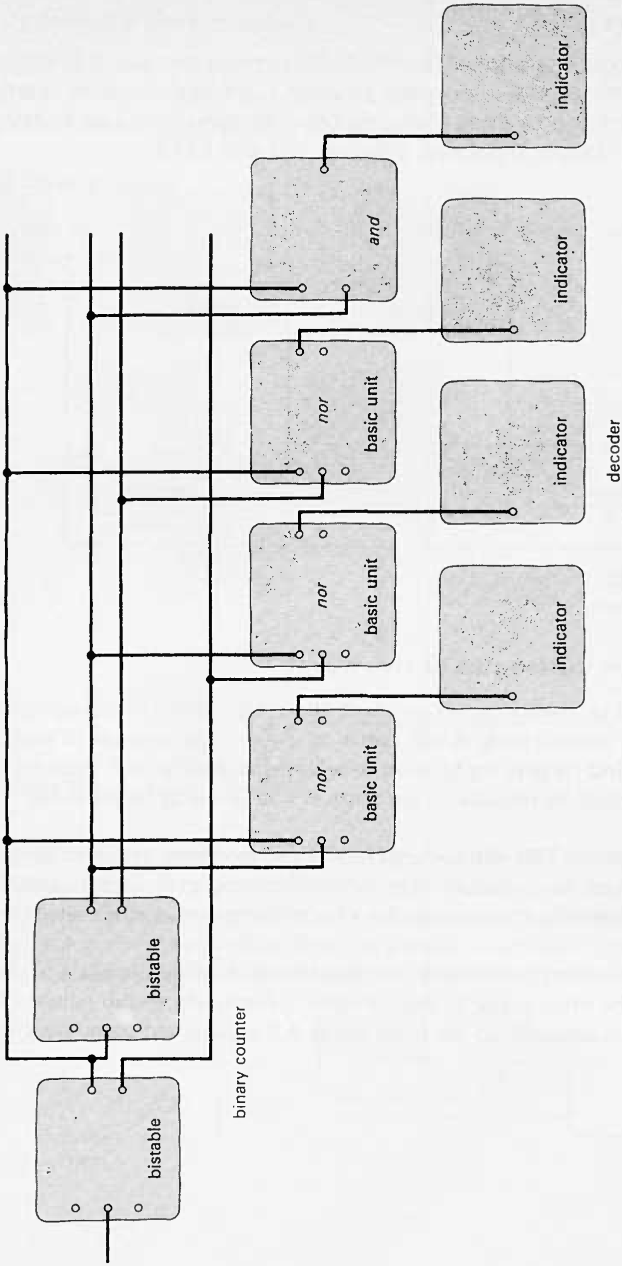



**Figure 134**
Counter (scale of four).

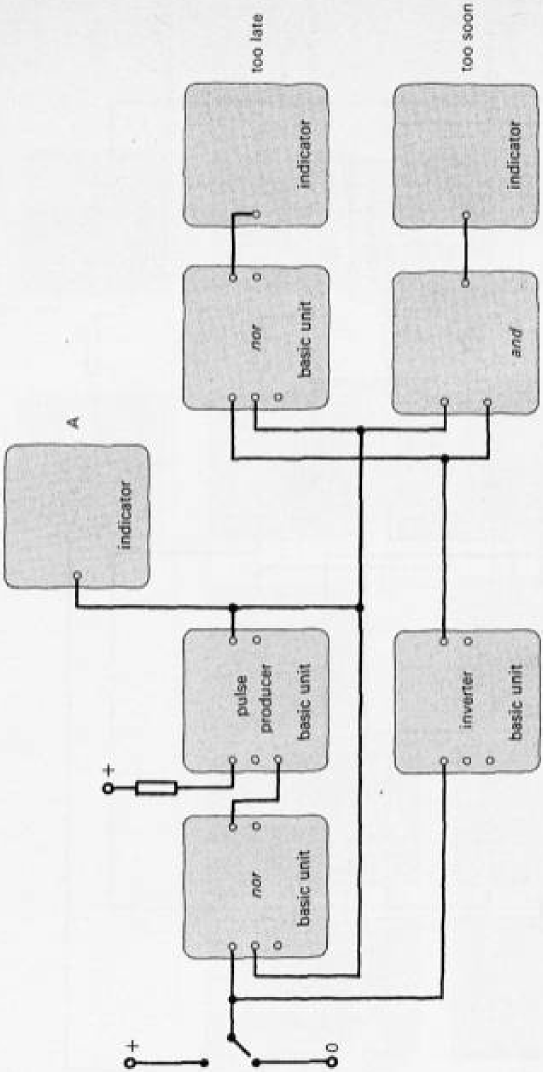



**Figure 135**
Comparison of pulse lengths.

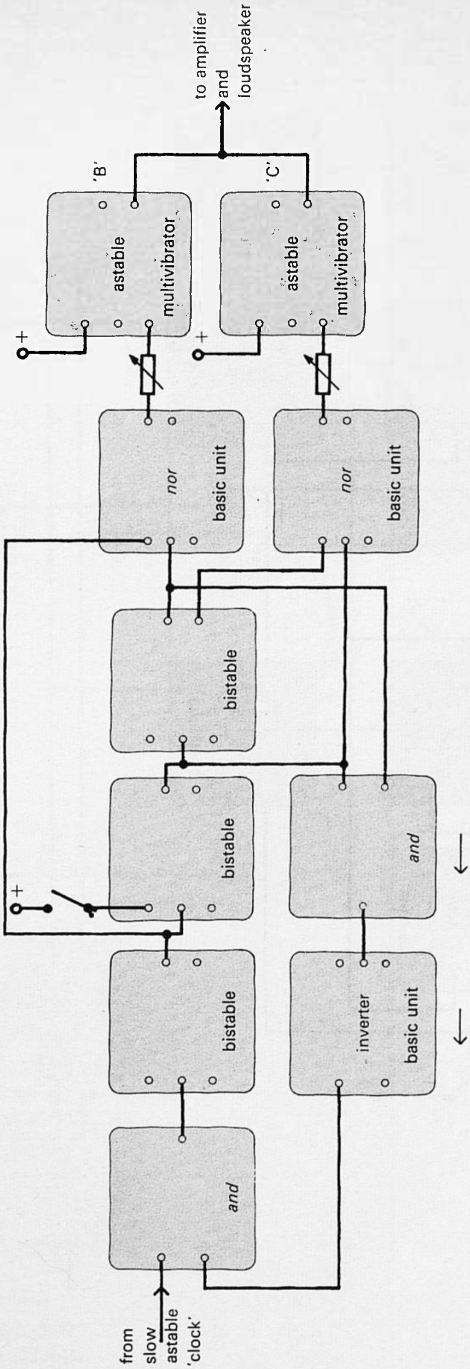



**Figure 136**
System to play B–B–C.

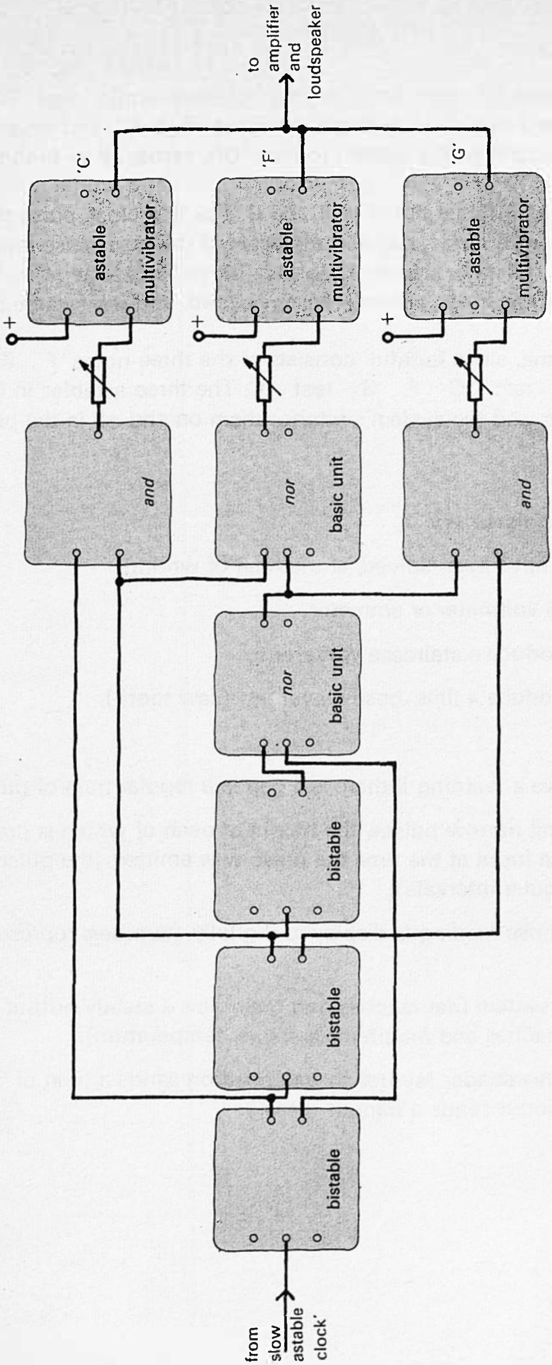



**Figure 137**
System to play 'Oh, come, all ye faithful'.

## 30 Playing tunes

Students in the trials made the electronics kit play 'Colonel Bogey' and 'Three blind mice'. Figure 136 shows a system to produce the tones 'B-B-C', and figure 137 adds to the kit's musical repertoire with a system to play 'Oh, come, all ye faithful'.

The two astables in figure 136 are tuned to B and C. The first clock pulse through the *and*-gate goes to B, which sounds, and sounds again at the next pulse after a one-note silence. After one more silence, C sounds for two notes-worth of time. Then the *and*-gate through which clock pulses enter is opened, and the system stops.

The first line of 'Oh, come, all ye faithful' consists of the three notes 'F', 'C', and 'G' in the sequence, F F rest C F G rest C. The three astables in figure 137 produce the three tones, and the system switches them on and off in the proper sequence.

### Further systems to try

Not all of the following have been solved, at the time of writing:

Blind student's voltmeter or ammeter.

A system to produce a staircase waveform.

A system to produce a time-base waveform (saw tooth).

Metal locator.

A system to give a warning if there is a gap in a regular train of pulses.

A system to emit narrow pulses, the height of each of which is proportional to the size of an input at the time the pulse was emitted (the pulses sample the input at regular intervals).

A voltmeter whose reading is displayed digitally (numbers represented by lit lamps).

A 'voltstat' (a system that reaches and maintains a steady output voltage, as a thermostat reaches and maintains a steady temperature).

Automatic Morse sender (switch in one position sends a train of 'dashes'; in the other position it sends a train of 'dots').

# Appendices

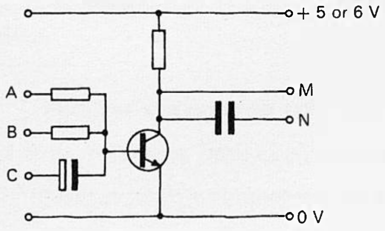
## Appendix A
## Details of modules in the electronics kit

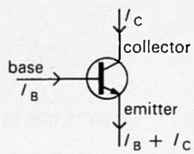
This Appendix is provided for teachers who want to know what is in the modules, and how they work. It is not necessary to understand it all to teach the Unit.

### The basic unit

*Circuit of the basic unit*

Figure 138 *a* shows the circuit of the basic unit, which contains an *npn* silicon transistor. Figure 138 *b* indicates the names of the three terminals of the transistor: the *base*, the *emitter*, and the *collector*. Figure 138 *c* shows the connections of terminals on a baseboard or on a module to points in the circuit.



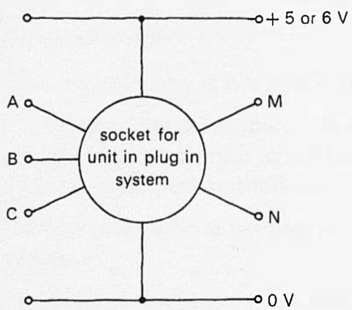




**Figure 138**
**a** Circuit of basic unit.
**b** Connections to a transistor.
**c** Connections to a basic unit.

An *npn* transistor is used with its collector positive with respect to its emitter. If the base current, $I_B$, is zero, the collector current, $I_C$, is very small, less than 1 μA.

If the base is made positive with respect to the emitter, it is found that current only flows into the base when the p.d. between base and emitter, $V_{BE}$, exceeds 0.5 V, and that $V_{BE}$ only increases to about 0.7 V under normal circumstances for a large range of base currents.

The collector current, $I_C$, which flows when there is a base current, is controlled mainly by that base current. This is particularly so for the conditions under which the basic unit is used. The collector–emitter p.d., $V_{CE}$, has very little effect on $I_C$ compared with the effect of a change in $I_B$, provided $V_{CE}$ is greater than about 0.2 V. If $V_{CE}$ is reduced below 0.2 V, then $I_C$ falls and becomes zero when $V_{CE}$ is zero. Provided $V_{CE} > 0.2$ V, $I_C = \beta \times I_B$, where $\beta$ is a factor, the current gain, which remains fairly constant over a fairly wide range of values of $I_B$ for a given transistor, though its magnitude may vary widely (50 to 300) from one transistor to another of the same type. The orders of magnitude of currents for transistors of the kind used in the electronics kit, are up to 1 mA for $I_B$ and up to 100 mA for $I_C$, but they are used much below these levels except in the case of the lamp indicator module. Figure 139 indicates the characteristics described above.

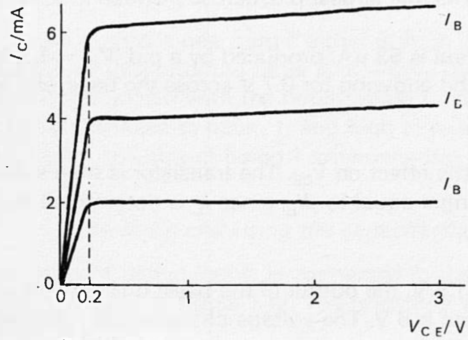



**Figure 139**
Transistor characteristics.

*Basic unit using a resistive input*

The basic unit, figure 138, has resistors connected to the collector and to the base. Figure 140 shows the symbols which will be used in describing the operation of the circuit. Note that the output p.d. is the same as $V_{CE}$.

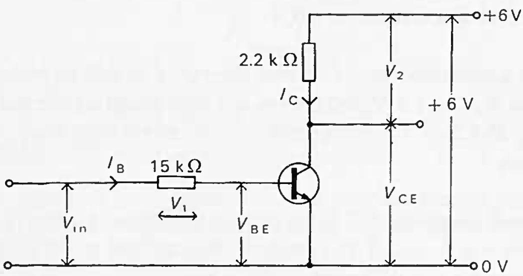



**Figure 140**

Suppose that $V_{in} = 0$. Then $I_B = 0$ and hence $I_C = 0$ and $V_2 = 0$. As there is no p.d. across the 2.2 kΩ resistor, $V_{CE} = 6$ V. Thus, when the input is connected to the 0 V rail, the output voltage is 6 V.

Now suppose that $V_{in}$ is slowly increased. $I_B$ remains zero until $V_{BE}$ (and hence $V_{in}$) exceeds 0.5 V. Up to this point, $I_C$ is almost zero and $V_{CE}$ remains at 6 V. However, when base current flows, a collector current $I_C = \beta \times I_B$ will flow, and there will then be a p.d. $V_2$ across the 2.2 kΩ resistor, and $V_{CE}$ will be less than 6 V. To illustrate this, suppose $V_{in} = 0.85$ V. Since $V_{BE} = 0.7$ V when base current flows, $V_1 = 0.15$ V, $I_B = 10$ μA (0.15 V across 15 kΩ). If $\beta = 50$, then $I_C = 0.5$ mA. This current produces a p.d. $V_2 = 1.1$ V across the 2.2 kΩ load resistor so that $V_{CE} = 4.9$ V. By similar calculation, when $V_{in} = 1.15$ V, $I_C = 1.5$ mA, $V_{CE} = 2.7$ V; and when $V_{in} = 1.45$ V, $I_C = 2.5$ mA, and $V_{CE} = 0.5$ V.

Clearly, $I_C$ can never exceed 2.73 mA, the current in a 2.2 kΩ resistor under a p.d. of 6 V. In fact, the maximum value of $I_C$ is less than this, about 2.65 mA, since there is a p.d. of some 0.2 V across the transistor, so that the largest p.d. across the load is some 5.8 V.

If $\beta = 50$, the corresponding base current is 53 μA, produced by a p.d. $V_{in} = 1.5$ V at the input, giving 0.8 V across 15 kΩ, and allowing for 0.7 V across the base-emitter junction.

Increase of $V_{in}$ above 1.5 V has very little effect on $V_{CE}$. The transistor is then said to be saturated, or bottomed, and $I_C$ is no longer equal to $\beta I_B$, since $I_C$ is determined by the supply voltage and the load resistance.

Thus, for all values of $V_{in}$ greater than 1.5 V, the output of the basic unit is 0.2 V or less, and for all $V_{in}$ less than 0.5 V, the output is 6 V. The voltage characteristic obtained in experiment 6.2 shows these changes.

### *The basic unit with two resistive inputs*

If two resistances, each 15 kΩ, joined to the base, are both connected to either the 0 V rail or the +6 V rail, the effect is as if the base input resistance were 7.5 kΩ. If both are connected to +6 V, the transistor is even more heavily saturated than when one input is connected to +6 V, and the output is less than 0.2 V. If both are connected to 0 V, the base current is zero and the output is +6 V.

If one 15 kΩ input resistor is connected to +6 V and the other to 0 V as in figure 141, it is tempting to suppose that $V_{BE} = +3$ V, regarding the two resistors across the supply as a potential divider. But this would require $I_B = 0$, and if $V_{BE}$ were +3 V, $I_B$ would certainly not be zero.

If there is base current, $V_{BE}$ will be about 0.7 V, as previously. Thus $I_1$, figure 141, will be the current in 15 kΩ under a p.d. of 0.7 V; $I_2$ will be the current in 15 kΩ under a p.d. of (6.0−0.7) V, and $I_B$ will be the difference, 306 μA.

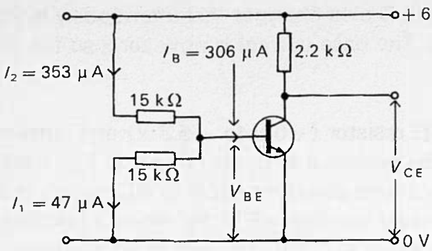



**Figure 141**

Any base current $I_B$ in excess of 53 μA saturates the transistor, from previous arguments. So $I_C$ has its maximum value, 2.65 mA, and the output $V_{CE}$ is near zero.

Thus the output is near zero if either or both inputs are at +6 V, and is only +6 V if neither one input nor the other is at +6 V. The unit functions as a *nor*-gate, if a high input is associated with the binary value 1 and a low input with the value 0. (If low input is taken to mean 1, and high to mean 0, the unit functions as a *not-and* or *nand*-gate, the output being 1 whenever input one and input two are not both 1.)

*The basic unit using the capacitative input to produce a pulse*

One of the resistive inputs is connected to the 6 V rail and the capacitative input to the push switch, as in figure 142. The operation will be described by considering a cycle of changes.

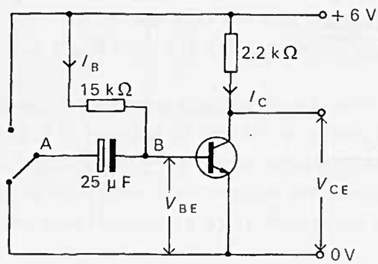



**Figure 142**

**a** When point A, figure 142, is at 0 V, current $I_B$ flows to the base, the transistor is saturated, and the output is low. $V_{BE}$ is about 0.7 V.

**b** When A is switched to +6 V, at that instant point B rises by +6 V since the p.d. across the capacitor cannot change instantaneously, and $V_{BE}$ momentarily becomes 6.7 V. Charge flows from the capacitor into the base and the capacitor quickly charges up until there is 5.3 V across it and $V_{BE}$ is back to 0.7 V. $V_{CE}$ stays at a low value throughout.

**c** When A is switched to 0 V, point B also changes instantaneously in potential by −6 V, going to −5.3 V from +0.7 V. The base current is now zero, so the output jumps to +6 V.

There is a p.d. of 11.3 V across the 15 kΩ resistor (+6 V to −5.3 V) and current flows through it to discharge the capacitor. The potential at B, also equal to $V_{BE}$, rises slowly from −5.3 V towards +6 V with a time constant equal to $RC$, which is about 0.4 s if $C = 25\ \mu F$ and $R = 15\ k\Omega$. $V_{BE}$ never reaches +6 V, for when it reaches +0.5 V base current flows, and it stops rising at 0.7 V. As soon as base current flows, the output voltage rapidly falls back to zero, having been high for a time equal to that for $V_{BE}$ to rise from −5.3 V to between 0.5 V and 0.7 V. The output pulse lasts for about 0.7 $RC$, or about 0.25 s.

The pulse duration may be increased by inserting additional resistance in series with the 15 kΩ resistor, but this additional resistance cannot be increased indefinitely because the transistor must be saturated when A is at 0 V. The maximum additional resistance is therefore that which gives a base current of 53 μA for a current gain of 50. Since the p.d. across the total resistance is 5.3 V, the additional resistance is limited to a maximum value of about 100 kΩ. The pulse duration is then several seconds. Figure 143 shows how the potential at A, at B, and at the output changes with time.

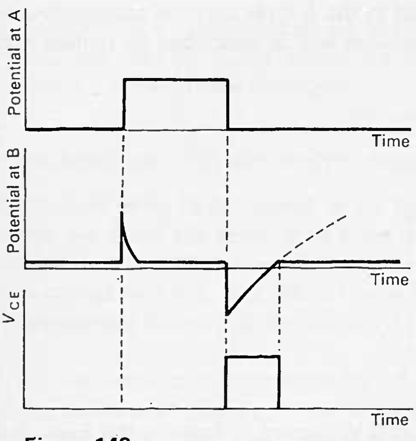



**Figure 143**

### The lamp indicator module

The module is designed for use with lamps rated at 6 V, 0.06 A. If a single transistor had been used, then a base current of about 1 mA (60 mA/50) would possibly have been required to light the lamp, and this would have been drawn from the output of the other unit. Such a current forms an appreciable drain when the maximum current flow through the load resistor of a basic unit is only 2.65 mA. The second transistor shown in figure 144 is added to reduce this current drain.

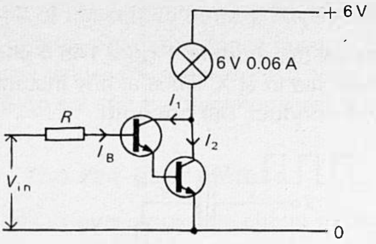



**Figure 144**
The lamp indicator module.

Suppose the current gain of each transistor is $\beta$, and that currents $I_B$, $I_1$, and $I_2$ flow as shown in figure 144. If the transistors are not saturated,

$$I_1 = \beta I_B.$$

Currents $I_B$ and $\beta I_B$ flow into the first transistor, so that the current out of the emitter is $(\beta+1)I_B$. This is the base current for the second transistor, so that $I_2 = \beta(\beta+1)I_B$.

The lamp current $= (I_1+I_2) = \beta(\beta+2)I_B$ and thus, to a good approximation, the lamp current $= \beta^2 I_B$.

A 6 V, 0.06 A lamp will light when the current through it is 50 mA. The highest $I_B$ to give this current, for transistors for which $\beta = 50$, will be about 20 μA. If $\beta = 100$, then $I_B$ will be only 5 μA.

The input resistor, about 100 kΩ, has been chosen so that the lamp lights when the input voltage $V_{in}$ is about 3 V if $\beta = 50$, and 2 V if $\beta = 100$.

There is merit in having a second input, with a lower resistor, so that if $\beta = 40$, the lamp is lit at 3 V, instead of the 4.6 V which would be required if $R$ were 100 kΩ. This input also enables lamps of larger power to be used, such as 4 V, 0.15 A, which light at an input of less than 4 V through the low resistance input. 47 kΩ is a suitable value for the low resistance input. For such lamps, use a 4.5 V power supply.

## Beam splitter module

Figure 145 *a* shows the circuit of the beam splitter module. Figure 145 *b* shows the circuit as seen by the source of square pulses fed in at X, since at any instant either the diode joined to A or that joined to B will conduct, but not both.

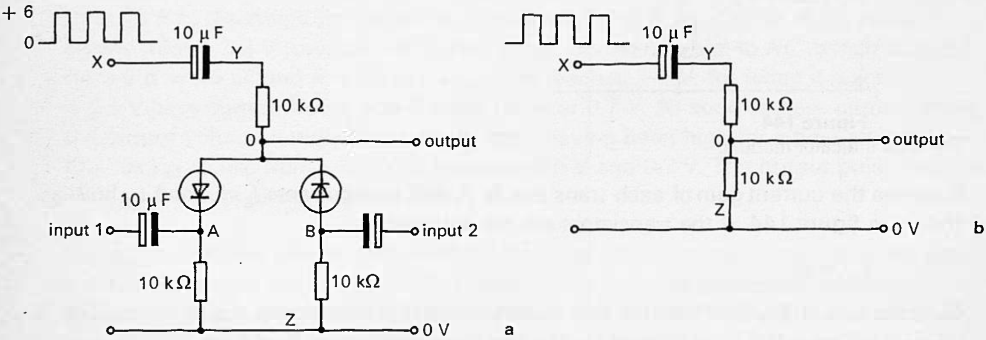



**Figure 145**
**a** Beam splitter module.
**b** Circuit as seen by the square wave source.

The time constant, $RC$, of this circuit ($R = 20\ \text{k}\Omega$, $C = 10\ \mu\text{F}$) is about 0.2 s, much longer than the repetition time, about 0.4 ms, of the 2.5 kHz square pulses fed to X. Thus the p.d. across YZ is almost identical with the input, a 6 V square waveform. But the mean value of the p.d. across YZ must be zero after a time of the order $RC$ has elapsed, so it settles down, as shown in figure 146, to a square waveform varying between +3 V and −3 V.

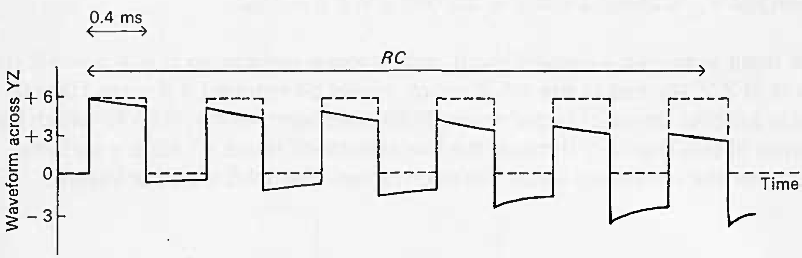



**Figure 146**

Across the output OZ there is therefore half as large a square waveform, of peak value ±1.5 V.

While the diode at A conducts, input 1 is connected directly to the oscilloscope via a 10 μF capacitor, and a waveform fed to input 1 is superposed on the corresponding part of the square output at O. Similarly, voltages fed to input 2 are superposed on the other half of the square output. For these voltages to be unmodified by the beam splitter, their source impedance must be much less than 10 kΩ and 10 μF in series. Their peak values must not exceed 1.5 V or a diode that should be conducting will cease to do so, and the waveform will be clipped.

### The *and*-gate module

Figure 147 shows a possible circuit for the *and*-gate module, consisting of three transistors connected as a pair of inverters followed by a *nor*-gate. The circuit is essentially that used in the system shown in figure 49 (page 47).

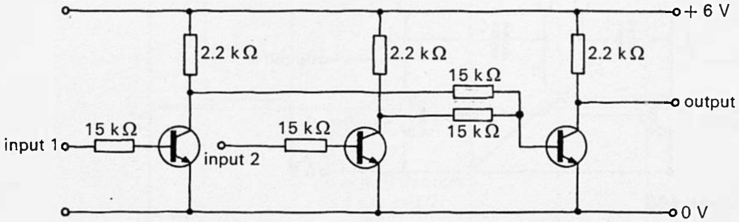



**Figure 147**
The *and*-gate module.

### The multivibrator module

Figure 148 shows the circuit of the multivibrator module. To use the module as a bistable, both switches are set to connect the transistor base to the output of the other transistor via the 15 kΩ resistors. To use the module as an astable, both switches should make a similar connection via the 0.047 μF capacitors, inputs 1 and 2 also being connected to +6 V.

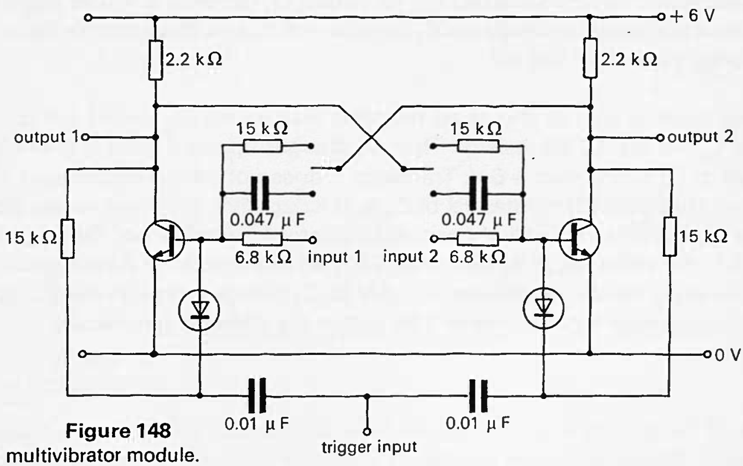



**Figure 148**
The multivibrator module.

If one switch connects via the resistor, and the other via the capacitor, with the corresponding input joined to +6 V, the module is monostable.

The switches can be replaced by connecting links, if desired.

### *The astable circuit*

Figure 149 shows the circuit when the module is connected as an astable.

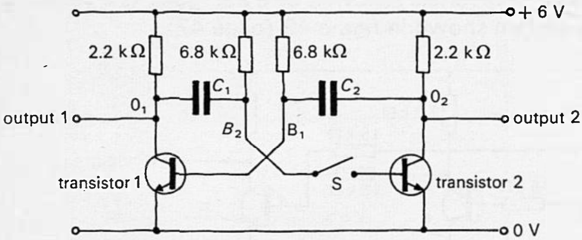



**Figure 149**
Astable circuit.

Suppose switch S is at first open. Then transistor 1 conducts, and its output $O_1$ is near 0 V. Transistor 2 does not conduct, and its output $O_2$ is high. $B_1$ is at about 0.7 V, say 1 V, so there is about 5 V across capacitor $C_2$. Currents flow into $B_1$ and $O_1$, but not into $B_2$ and $O_2$.

Now suppose switch S is closed. The base of transistor 2 goes to +6 V, and this transistor goes on. $B_2$ falls quickly to about 1 V. The p.d. across $C_1$ cannot change sharply, and so $O_1$ drops by 5 V from 0 V to −5 V. Transistor 1 goes off. It is held off because, transistor 2 having switched on, its output $O_2$ drops to 0 V. The p.d. of 5 V across $C_2$ cannot change instantly, so $B_1$ goes to −5 V, and this negative base potential keeps transistor 1 cut off.

Both $C_1$ and $C_2$ now start to charge up the other way round, $C_2$ via the 6.8 kΩ resistor and $C_1$ via the 2.2 kΩ resistor. Thus $C_1$ charges up more quickly than $C_2$ and the potential at $O_1$ soon nears +6 V. Transistor 1 does not switch on because $C_2$ charges more slowly and the potential of $B_1$ is still negative. However, when the potential of $B_1$ becomes about 1 V positive, transistor 1 switches on. The potential at $O_1$ falls to 0 V, the potential at $B_2$ becomes −5 V so that transistor 2 now switches off. The potential at $O_2$ rapidly rises towards +6 V as $C_2$ charges through the 2.2 kΩ resistor. The cycle now repeats. Figure 150 shows the changes graphically.

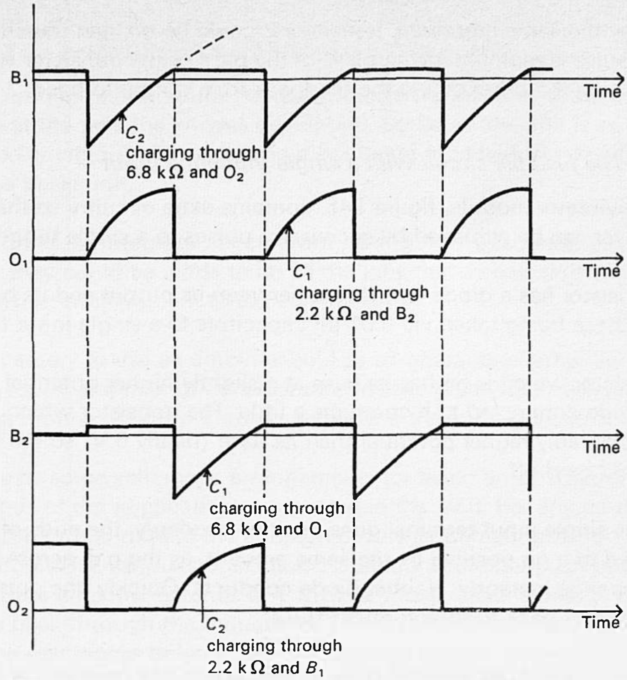



**Figure 150**
Voltage variations in the astable circuit.

### *The bistable circuit*

Figure 151 shows the bistable circuit without the added diodes used to trigger it from one input.

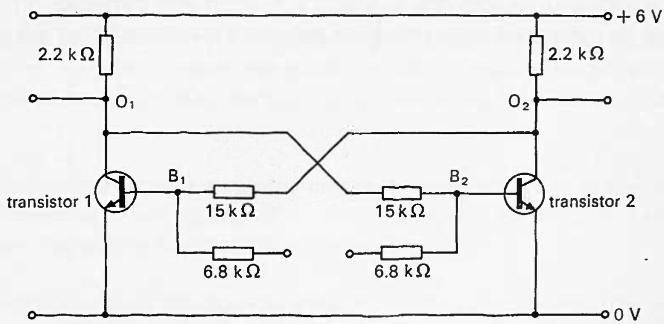



**Figure 151**
Simple bistable circuit.

Transistors 1 and 2 cannot both be on at the same time. If transistor 1 is on, its output $O_1$ is low, so the base $B_2$ of transistor 2 is low and transistor 2 is off. This puts the other output $O_2$ high, which makes $B_1$ take base current, keeping transistor 1 on, as was first assumed.

Clearly, by the same argument, transistor 2 could be on, and transistor 1 off. If a positive pulse is momentarily applied to the base of the transistor which is off, it goes on, switching the other off via the feedback from output to base.

### *The bistable circuit with a single triggering input*

The multivibrator module, figure 148, contains extra circuitry so that the bistable changeover can be achieved by successive pulses to a single trigger input.

Each transistor has a diode connected between its output and its base via a 15 kΩ resistor, these being taken via 0.01 μF capacitors to a single input terminal.

The transistor which is on has its base at a slightly higher potential than its output, so the diode connected to it conducts a little. The transistor which is off has its output at a considerably higher potential than its base (nearly 6 V) so the diode connected to it is held hard off.

When the single input terminal goes positive suddenly, the ends of the diodes connected to it go positive by the same amount, as the p.d. across the capacitors cannot change instantly. Neither diode conducts. Quickly, the potentials at the diode terminals relax back to their former values.

When the single input terminal goes to zero again, the ends of the diodes connected to it go negative instantaneously. The diode connected to the transistor which is on, now conducts, since the p.d. across it in the conducting direction is now positive. The other diode, previously with −6 V or so across it, and held hard off, now has about 0 V across it, and may conduct, but only a little.

Because the diode connected to the transistor which is on conducts heavily, the base of that transistor rapidly falls below 0 V, turning that transistor off. The swing of its output thus induced turns the other transistor on, completing the switching process.

## Appendix B
## Possible use of an operational amplifier as a basic unit

The basic unit, and the other modules, contain transistors because these offered the cheapest system at the time the kit was developed. So far as the Unit is concerned, the contents might be anything, with experiment 6.3 being modified to suit whatever there is inside the basic unit.

Operational amplifiers, in integrated circuit form, are rapidly becoming cheaper, and it seems likely that they could be made to do all the jobs that a basic unit will do, besides making a worthwhile improvement to experiment 6.11.

It may not be necessary to use an amplifier sold as an operational amplifier; the essential need is for an amplifier of considerable voltage gain which will amplify d.c. as well as varying inputs, the output going negative if the input goes positive.

Figure 152 suggests some schematic arrangements for using an operational amplifier for various of the applications suggested in the Unit. For any particular amplifier used, each would require the addition of further components. Suppliers of amplifiers give circuits for various applications. Stability is often a great problem, since if the response of the amplifier extends to 1 MHz or more, sharp transient voltages can occur and be fed back through the inductance or capacitance of leads connecting units together, the reactances of leads being important at such frequencies.

Such amplifiers also give outputs above and below 0 V, and in logic circuit applications one would have to bias the amplifier appropriately if $+V$ and $-V$ were to represent 1 and 0 respectively, $V$ being the limiting voltage to which the amplifier can be driven.

All these bias and stability arrangements are omitted in figure 152, as they would have to be designed for the chosen amplifier.

Many such amplifiers have two inputs. One, marked $-$, sends the output down as the input rises; the other, marked $+$, sends the output up as the input rises. Figure 152 *d* to *f* shows how one such amplifier can replace two inverting amplifiers in some applications.

We have not, at the time of writing, explored any of these possibilities in practice. This Appendix is included to encourage others to do so. There is no reason to think that developing simple, stable, foolproof devices will be easy.

The use of an integrated circuit operational amplifier for the work on operational amplifiers (6.11) is, however, an easy matter, and is greatly to be preferred to the use of basic units as suggested in this *Guide.* Figure 153 gives circuits for a see-saw amplifier and an integrator, using the cheap 741 amplifier available (at the time of writing) from Radiospares Ltd.

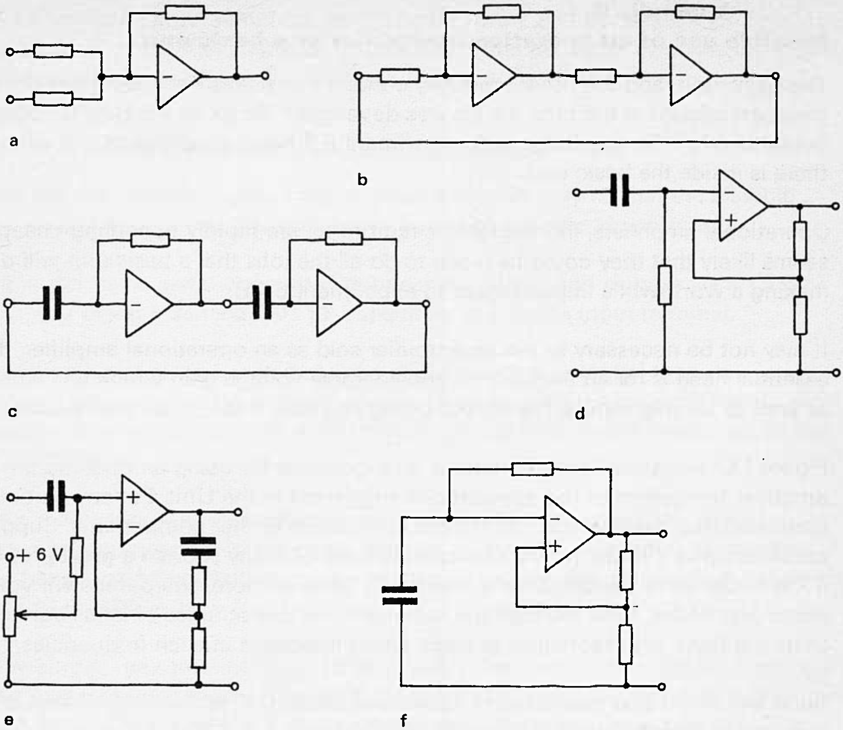



**Figure 152**

a *Nor.* **b** Bistable. **c** Astable (as shown, could suffer much trouble from transients). **d** Single input, bistable. **e** Monostable. **f** Astable.

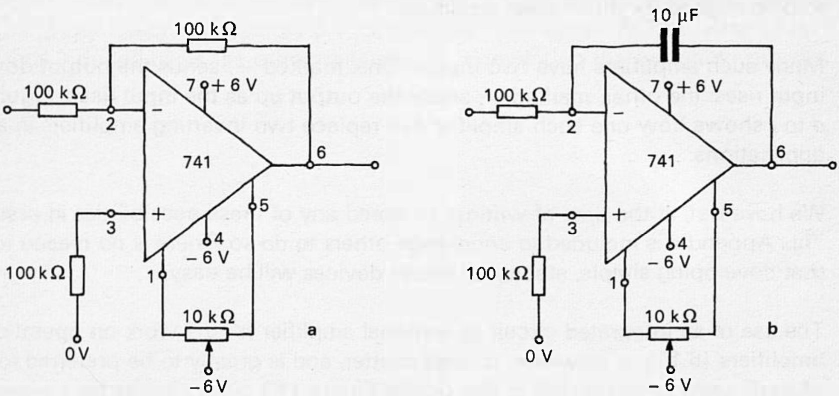



**Figure 153**

a See-saw amplifier. **b** Integrating amplifier.

## Appendix C
## Phasor treatment of reactive circuits

This Appendix concerns the addition of alternating currents or voltages by the phasor technique, in which the alternating quantity is represented by the projection onto a fixed axis of a rotating line of constant length. If the length of the line is $r$, the projection is $r \sin\omega t$, where $\omega$ is the angular velocity of rotation of the line.

Such rotating lines have several of the properties of vectors, and in particular they add by the usual vector rule. They are often called *phasors*, the name indicating that the relative phase angle between the added quantities is all-important and, for the purist, distinguishing the rotating lines from vectors which have properties they do not share. (No obvious meaning attaches to the translation of a phasor, for example.)

The phasor technique is well known, and is developed in detail in several books. See in particular, Bennet, *Electricity and modern physics.* For this reason, this Appendix is limited to pointing out where the phasor technique could be used, and the depth to which it might be taken.

The phasor treatment is not part of the Nuffield Advanced Physics course, and nothing in the examination ought to require its use. Nor is it best to consider the treatment as an alternative to that suggested in this *Guide*. It should be regarded as additional material which may interest and help that proportion of students who can grasp it with little difficulty. It would certainly help those who are going on to read physics or electrical engineering at university, especially if they intend to take a special entrance or scholarship examination.

As with other examples of extra mathematics, we think there is advantage in offering it to those who can appreciate it, without forcing it on those who cannot.

### Introduction of phasors

Experiment 6.9 is about phase differences in an $RC$ circuit, and provides an occasion to introduce the idea of adding phasors to represent the alternating potential differences across the series components of the circuit.

Having discussed the difficulty of adding sinusoidal variations with arbitrary phase differences if they are drawn out as graphs, the idea of adding instead the projection of a line rotating at the angular frequency of the alternating supply can be proposed, recalling work in Unit 4, *Waves and oscillations,* in which the notion was introduced in passing. All the rotating phasors go round at the same speed, so the sum of their projections is always equal to the projection of their (vector) sums, the angles between them staying fixed.

In the $RC$ series circuit, the current in the circuit and the p.d. across $R$ are in phase, as indicated by the zero angle between them in figure 154. The rotating current phasor has been 'frozen' at an arbitrary angle.

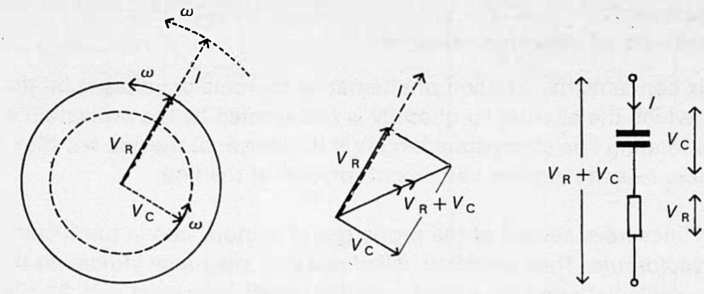



**Figure 154**
Current and voltage phasors in an *RC* circuit. The resultant vector sum has the magnitude $\sqrt{V_R^2+V_C^2}$.

The experiment, and the arguments suggested to go with it in this *Guide*, indicate that the p.d. across the capacitor trails one quarter of a cycle behind the current. Figure 154 shows $V_C$ an angle of 90° behind *I*, and so behind $V_R$, the phasors being supposed to rotate counter-clockwise.

Adding the phasors representing $V_R$ and $V_C$ (these symbols are used in figure 154 to label the phasors, though the length of a phasor is the maximum value *V* attains in a cycle, not *V* itself, which varies all the time), the phase angle between the p.d. across the whole circuit lags behind the current by an angle which is less than 90°. The angle can be calculated from the magnitudes of the voltages and the vector addition rule. The maximum voltages can be expressed in terms of the maximum current using $V_R = IR$ and $(V_C)_{max} = I_{max}/2\pi fC$.

The impedance can now be calculated. Perhaps it is more important to relate the phasor sum back to the sinusoidal voltage it represents, showing how it looks when drawn as a graph on top of the current variation, and why it will be nearly in phase with the current if *R* is large but nearly 90° out of phase with the current if $1/2\pi fC$ is large (each compared to the other).

## Series *LR* circuit

Phase differences in a series *LR* circuit, experiment 6.14, are the next occasion when phasors can be employed. The argument is similar, the phasors representing $V_R$ and $V_L$ being added, and both assigned phases relative to the current *I*.

As argued in this *Guide*, $V_L$ is the voltage needed across the inductance because the current is *changing*. When the current is growing quickly from near zero towards a positive value, $V_L$ is large and in the direction a p.d. across a resistor carrying positive current would be, since energy is being delivered *to* both components in these circumstances. (Later, energy is taken from the inductor, but not from the resistor.)

$V_L$ is thus a maximum before *I*, which is then growing towards a maximum, and $V_L$ leads *I* by 90°, as in figure 155.

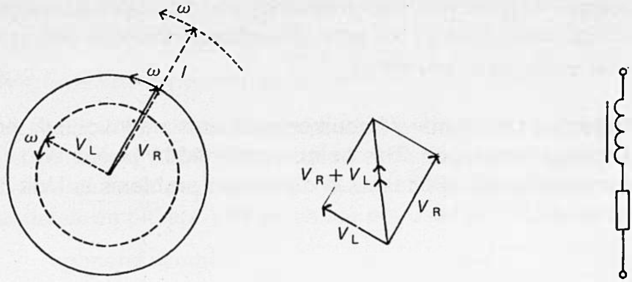



**Figure 155**
Current and voltage phasors in an *LR* circuit. The resultant vector sum has the magnitude $\sqrt{V_R^2+V_L^2}$.

As before, the impedance can be calculated, using $V_R = IR$ and $(V_L)_{max} = 2\pi f L I_{max}$. The effect of resistance inherent in the inductor can be allowed for by adding to $R$, and the reasons for the various phase lags observed in actual circuits can be explored.

## Parallel *LC* circuit

Experiment 6.15 includes a demonstration of the phase difference between the current in a capacitor and the current in an inductor if both are in parallel across the same alternating supply.

The main difference is that it is the currents, not the voltages, which have to be added by the phasor technique. The phases of the currents are settled with reference to the common voltage across the two components, the current in $C$ being ahead of $V$ (figure 154) and that in $L$ being behind $V$ (figure 155).

Figure 156 shows what the phasor diagram may look like. $I_C$ and $I_L$ are in antiphase, and if they are equal in magnitude, will add up to zero. At the frequency $f$ at which $2\pi fL = 1/2\pi fC$, the circuit has a particularly high impedance. The net current is small, but the currents in the two arms can be large, with a large voltage across the combination.

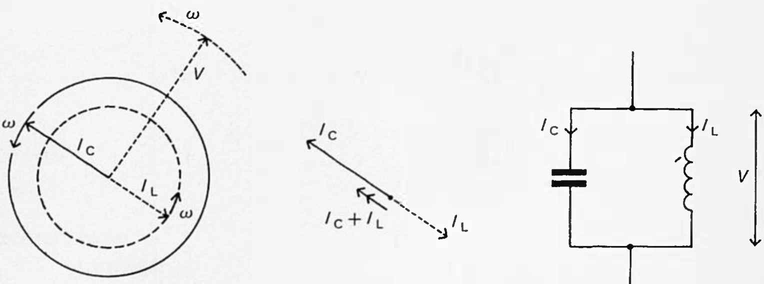



**Figure 156**
Voltage and current phasors in an *LC* circuit. The resultant vector sum has the magnitude $I_C - I_L$.

As suggested (page 103), the resonant frequency can be obtained without writing out a result for the impedance, though the latter is wanted if the effect of resistance on resonance is to be explored in any detail.

If may be worth adding that, if many circuit components are involved, the vector parallelogram becomes a polygon. This point, supported by one or two examples, is useful preparation for the use of phasors in diffraction problems in Unit 8, *Electromagnetic waves.*

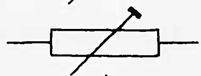
## Appendix D
## Circuit symbols and resistor codes

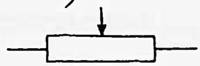
### Symbols for circuit diagrams

Some of the symbols for circuit diagrams used in this book are shown below. They follow British Standard 3939, *Graphical symbols for electrical power, telecommunications and electronics diagrams* (1966–70). However, the special symbols for gates, amplifiers, and so on are not used in this *Guide*.

*Resistor* general symbol 

variable resistor 

resistor with preset adjustment 

resistor with moving contact 

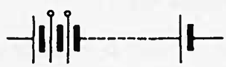
*Capacitor* general symbol 

polarized electrolytic capacitor 

*Inductor* general symbol 

inductor with core 

*Battery* primary or secondary cell 

battery with tappings 

*pn diode* 

*Transistor (npn)* 

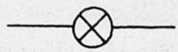
*Measuring instruments*

voltmeter 

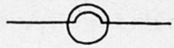

ammeter 


galvanometer 

*Signal lamp*

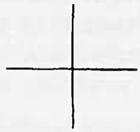


*Lamp for illumination*



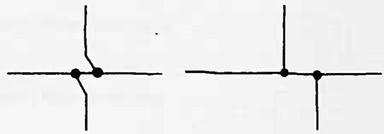
*Wires, junctions, terminals*

crossing of wires, no electrical contact

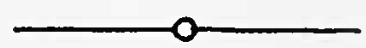


junction

double junction



terminal



## Colour code for resistors

A colour code has been in wide use for marking resistors with their values. It is proposed to replace it by a number–letter code (see below).

In the colour code, a resistor is marked with three or four bands of colour, A, B, C or A, B, C, D, as in figure 157.

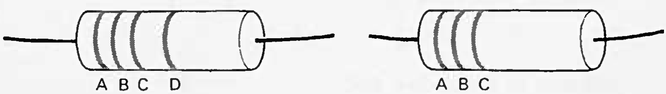



**Figure 157**

The colour of band A, nearest one end of the resistor, is a code for the first digit in the resistance value.

The colour of band B is a code for the second digit in the resistance value.

The colour of band C is the number of zeroes to follow these digits.

The code is: 0 Black 1 Brown 2 Red 3 Orange 4 Yellow 5 Green 6 Blue 7 Violet 8 Grey 9 White.

The colours from red to violet are in the order of the visible spectrum.
Thus, A Yellow B Violet C Orange means 47 000 Ω, or 47 kΩ.

Band D indicates the tolerance, according to the code:
Absent 20 per cent Silver 10 per cent Gold 5 per cent Red 2 per cent.

10 per cent resistors are sold in certain preferred values, which are 10, 12, 15, 18, 22, 27, 33, 39, 43, 47, 56, 68, 82, 100 ohms and their powers of ten. The practical reason is that *any* resistance falls within 10 per cent of one of these values, so *any* resistor can be sold as one of the preferred values, plus or minus 10 per cent.

### International number–letter code

*The value of the resistor* is given by a code which abbreviates the usual power of ten notation.

Instead of 1.5 Ω the code is 1R5, with R, for 'ohms', marking the decimal point. Thus 15 Ω is coded 15R, and 0.15 Ω is coded R15.

Larger resistances are coded using K for kΩ, or M for MΩ, in place of R for Ω.

Thus 1.5 kΩ is coded 1K5, while 15 kΩ is coded 15K. Similarly 1.5 MΩ is coded 1M5.

150 kΩ could be coded 150K, but the code is shorter if it is regarded as 0.15 MΩ, and coded M15.

The rule is that the code contains two figures, giving the resistance value to two significant figures. Where a decimal point would appear in this value expressed in Ω, kΩ, or MΩ, the appropriate letter R, K, or M is inserted.

*The tolerance of the resistor* is given by a second letter following the above code symbol. The tolerance code letters are:
1 per cent F    2 per cent G    5 per cent J    10 per cent K    20 per cent M.

Thus the code 6K8K indicates a 6.8 kΩ resistor, tolerance ±10 per cent.

# Lists of books and apparatus

## Books

None of the following books is essential for this Unit, though they may be helpful for those who want to find out more for themselves.

### For teachers

Amos, S. W. (1969) *Principles of transistor circuits*. Iliffe.

Delaney, C. F. G. (1971) *Electronics for the physicist*. Penguin.

Scroggie, M. G. (1961) *Principles of semiconductors*. Iliffe.

Scroggie, M. G. (1971) *Radio and electronic laboratory handbook*. Iliffe.

### For students

Bennet, G. A. G. (1968) *Electricity and modern physics*. (MKS version.) Arnold.

Benrey, R. M. (1965) *Understanding digital computers*. Iliffe.

Brand, M. and Brand, T. (1970) *Analogue computers*. Edward Arnold.

Brophy, J. J. (1966) *Semiconductor devices*. Allen & Unwin.

Hollingdale, S. H. and Tootill, G. C. (1970) *Electronic computers*. Penguin.

Marston, R. M. (1971) *110 integrated circuit projects for the home constructor*. Iliffe.

Marston, R. M. (1969) *110 semiconductor projects for the home constructor*. Iliffe.

Marston, R. M. (1969) *20 solid state projects for the home constructor*. Iliffe.

R.C.A. (1970) *Solid-state hobby circuits manual* HM-91. R.C.A. Solid-State Division.

Sjobbema, D. J. W. (1961) *Using transistors*. Macmillan.

Tustin, A. (1952) 'Feedback.' *Scientific American* Offprint No. 327.

## Apparatus

| | | |
|---|---|---|
| 9A | motor (from Malvern energy conversion kit) | 6.18 |
| 9M | driving belt (from Malvern energy conversion kit) | 6.18 |
| 27 | transformer | 6.2, 6.4, 6.7, 6.10, 6.13, 6.19 |
| 30 | slotted base | 6.8, 6.18 |
| 44/2 | G-clamp (small) | 6.18 |
| 52 | Worcester circuit board kit | 6.15 |
| 52L | mounted bell push | 6.10 |
| 59 | l.t. variable voltage supply | 6.18 |
| 64 | oscilloscope | 6.1, 6.6, 6.8, 6.10, 6.11, 6.12, 6.17, 6.18 |
| 70 | demonstration meter | 6.8 |
| 71/3 | 5 V d.c. dial | 6.8 |
| 71/4 | 2.5–0–2.5 mA dial | 6.8 |
| 92G | double C-core and clip | 6.12, 6.13, 6.14, 6.16, 6.17, 6.19 |
| 92R | m.e.s. bulb (2.5 V, 0.3 A) | 6.10, 6.12 |
| 92S | neon lamp | 6.12 |
| 92T | m.e.s. holder | 6.10, 6.12 |
| 92X | reel of 26 s.w.g. PVC covered wire | 6.1, 6.18 |
| 104 | low voltage power unit | 6.2, 6.4, 6.5, 6.7, 6.9, 6.10, 6.13, 6.14, 6.19 |
| 132N | thermistor | 6.4 |
| 147D | coil with 300 turns | 6.15 |
| 157 | microphone | 6.4, 6.6, 6.19 |
| 158 | class oscilloscope | 6.2, 6.4, 6.7, 6.9, 6.11, 6.14, 6.16, 6.19 |
| 170 | low frequency a.c. generator | 6.8, 6.18 |
| 181 | general purpose amplifier | 6.1, 6.5, 6.15, 6.18 6.19 |
| 183 | loudspeaker | 6.1, 6.5, 6.6, 6.18, 6.19 |
| 541/1 | rheostat (10–15 Ω) | 6.10, 6.12 |
| 541/2 | rheostat (330 Ω) | 6.10, 6.18 |
| 1000 | leads | all experiments |
| 1002 | microammeter | 6.3, 6.19 |
| 1003/2 | milliammeter (10 mA d.c.) | 6.3, 6.19 |
| 1004/2 | voltmeter (10 V d.c.) | 6.2, 6.19 |
| 1005 | multi-range meter | 6.10, 6.15, 6.19 |
| 1007 | double-beam oscilloscope | 6.5, 6.9, 6.11, 6.12, 6.14, 6.15, 6.18 |

| | | |
|---|---|---|
| 1009 | signal generator | 6.4, 6.6, 6.7, 6.13, 6.15, 6.17, 6.18, 6.19 |
| 1017 | resistance substitution box | 6.2, 6.4, 6.5, 6.7, 6.8, 6.9, 6.11, 6.12, 6.13, 6.14, 6.17, 6.18, 6.19 |
| 1018 | capacitance substitution box | 6.4, 6.6, 6.7, 6.9, 6.17, 6.18, 6.19 |
| 1021 | aerosol freezer | 6.4 |
| 1030 | high inductance coil | 6.12, 6.13, 6.14, 6.16, 6.17, 6.19 |
| 1033 | cell holder | 6.2, 6.3, 6.4, 6.5, 6.6, 6.7, 6.8, 6.9, 6.10, 6.11, 6.12, 6.13, 6.14, 6.16, 6.19 |
| 1035 | pre-amplifier | 6.19 |
| 1037 | set of solenoids | 6.1, 6.15, 6.18 |
| 1040 | clip component holder | 6.4, 6.7, 6.8, 6.19 |
| 1041 | potentiometer holder | 6.2, 6.3, 6.4, 6.6, 6.19 |
| 1047 | kit of two-terminal boxes | 6.4, 6.19 |
| 1051 | *small electrical items* | 6.4, 6.19 |
| | tuning capacitor, 365 pF or 500 pF maximum | 6.1, 6.18 |
| | diode, OA 81 or 1 GP 5 | 6.1, 6.18 |
| | preset potentiometer, 5 kΩ | 6.2, 6.3, 6.4, 6.6 |
| | preset potentiometer, 100 kΩ | 6.6 |
| | capacitor, 500 μF | 6.8, 6.16 |
| | capacitor, 250 μF | 6.16 |
| | capacitor, 100 μF | 6.16 |
| | capacitor, 50 μF | 6.16 |
| 1057 | alternating current ammeter | 6.15 |
| 1058 | coil with 120+120 turns | 6.15, 6.19 |
| 1059 | earpiece | 6.1, 6.4, 6.6, 6.18, 6.19 |
| 1075 | electronics kit | 6.2, 6.3, 6.4, 6.5, 6.6, 6.7, 6.9, 6.11, 6.13, 6.14, 6.19 |
| 1081 | decade capacitance unit (1–10 μF) | 6.2, 6.9, 6.10, 6.15, 6.18 |
| | joulemeter (optional) | 6.10 |

*Note:* Radiospares Ltd are now called RS Components Ltd.

# Index

Where significant information is given in an illustration or diagram, the page reference is italicized. In general, odd-numbered page references are to the main text, and even-numbered references are to commentary material.

Editor **Jon Ogborn**

Contributors
**P.J.Black Jon Ogborn** *Joint organizers, Advanced Physics*
**W.Bolton R.W.Fairbrother G.E.Foxcroft Martin Harrap John Harris A.L.Mansell A.W.Trotter**

**There are ten Units in the Advanced Physics course. This is the *Teachers' guide* for Unit 6, *Electronics and reactive circuits.* It is intended to provide whatever information and ideas are required for the day-to-day teaching of the Unit. The book begins with an Introduction setting out the purpose of the Unit, a summary of the Unit, and a list of suggested experiments. Following this, the main text consists of four Parts, 'Electronic building bricks', 'Circuits containing capacitance', 'Circuits containing inductance', and 'Building electronic systems'. It contains teaching suggestions, details of experiments, and a commentary giving background information and other guidance. There are also Appendices on 'Details of modules in the electronics kit', 'Possible use of an operational amplifier as a basic unit', 'Phasor treatment of reactive circuits', and 'Circuit symbols and resistor codes', and lists of relevant books and apparatus.**

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