Physics

Students' book **Unit 6**

Electronics and reactive circuits

Nuffield Advanced Science

Copy 1

Physics Students' book Unit 6

Electronics and reactive circuits

14 082713 7

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

Physics Students' book Unit 6

Electronics and reactive circuits

Nuffield Advanced Science
Published for the Nuffield Foundation by Penguin Books

Penguin Books Ltd, Harmondsworth, Middlesex, England
Penguin Books Inc., 7110 Ambassador Road,
Baltimore, Md 21207, U.S.A.
Penguin Books Ltd, Ringwood, Victoria, Australia

Design and art direction by Ivan and Robin Dodd
Illustrations designed and produced by Penguin Education

Filmset in 9 on 11pt 'Monophoto' Univers Medium
by Keyspools Limited, Golborne, Lancashire
and made and printed in Great Britain
by C. Tinling & Co. Limited, Prescot and London

Contents

Consultative Committee

Professor Sir Nevill Mott, F.R.S. (Chairman)
Professor Sir Ronald Nyholm, F.R.S. (Vice-Chairman)
Professor J. T. Allanson
Dr P. J. Black
N. Booth, H.M.I.
Professor C. C. Butler, F.R.S.
Professor E. H. Coulson
D. C. Firth
Dr J. R. Garrood
Dr A. D. C. Grassie
Professor H. F. Halliwell
Miss S. J. Hill
Miss D. M. Kett
Professor K. W. Keohane
Professor J. Lewis
J. L. Lewis
A. J. Mee
Professor D. J. Millen
J. M. Ogborn
E. Shire
Dr J. E. Spice
Dr P. Sykes
E. W. Tapper
C. L. Williams, H.M.I.

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

To the student

This book contains some of the things you need to help you to understand the work of this Unit, and some reading which we hope will help you to see how the work is relevant to the practical, everyday world. It does not contain all you need: you will have to consult textbooks and other more general books as well, working through theoretical arguments, reading about experiments, and finding out more about how the ideas can be put to practical use.

This book contains many questions; more than you will be able to do while working on this Unit. Later on, you may wish to use some of them for revision. You will find questions which take you step by step through the theoretical arguments in the course; students who took part in the trials have said that these questions are a good way to understand a piece of theory. You will have to pick and choose, according to your needs and tastes, amongst the other questions. A few give you simple practice in calculation. More invite you to argue about or discuss a problem, and some of these – usually marked '*For discussion*' – are not suited to formal written answers. They are meant to start off a discussion, which may then wander far from the question.

There are a few harder questions to challenge the clever, and you should not expect to be able to tackle every question easily. But most are meant for ordinary human beings, not for budding geniuses. If in doubt, try the obvious answer: usually there is no catch! Most questions have some kind of answer in the section headed 'Answers', though some of these suggest where you might find the necessary information, instead of giving it. We have tried hard not to give wrong answers, but, being fallible like yourselves, may not have succeeded.

Some questions ask you to guess, speculate, or give your private opinion: obviously they have no one right answer.

What you are being asked to learn to do

This course aims to help you to become more like a physicist. Most of you will not become physicists, but will use physics or learn more of it in one of a variety of scientific jobs or in further education. Physics, and the world with it, are changing so fast that no one can tell what bits of physics you will use in, say, ten years' time; however, one can be pretty sure that there are some basic ideas that will be relevant to the new problems of tomorrow. We have tried to build the course around what we believe to be these basic ideas.

So one thing the course aims at is helping you to become able to learn, in the future, the new ideas in physics you may meet, and helping you to become able to use the physics you have learned. It does that because these are the tasks that will face you.

In the future, you will need to be able to learn from books and articles; that is why the course contains a good deal of reading (in a list at the end, you will find details of books referred to in the text). To use the physics you have met, you need to understand it – that is, to be able to use it in new kinds of problems. That is why so many questions in this book ask you to make up arguments about new problems, using what you know.

What is 'understanding'? That is, how does one recognize that someone understands a piece of physics? We think it is something like this. Suppose a group of people are talking about a problem in physics. Very rarely, even among research workers, will anyone immediately see an answer. More often, they each have some ideas which they try out in discussion with colleagues. Those who 'understand' their physics are the ones who can offer sensible, relevant ideas that would help towards clearing up the problem. A reasonably competent physicist expects himself and others to be able to draw on their knowledge and use it to make sensible contributions to the discussion of problems.

So to test whether you understand a piece of physics, it is asking too much to expect you to solve a new problem completely and correctly; few – if any – experts can do that. The test should be that of physicists talking together: can you produce sensible ideas that are relevant and would help a bit towards clearing up a problem? This is the test that will be used in the examination, and is the way to decide how well you have managed a question or problem in the work of the course.

The course also aims to show you what doing physics is like, and this is another reason for encouraging plenty of discussion of problems, for that is the way physicists work. It tries to show what kinds of questions physicists ask themselves and what sorts of ways they use to tackle them. We think this is important because to use physics successfully and to judge its claims and achievements you need to understand what it can, and what it cannot do. That is why several questions ask you about such things as how theories, models, experiments, and facts fit together. Physicists also guess, estimate, and speculate, so other questions ask you to do these things too, to find out what doing them is like and to become better at doing them.

There are a lot of misunderstandings about what physics is like. Some say it is all facts; others that it is all theory, having little to do with what happens in practice. Many are puzzled; asking whether what physics says is true or not, or how physicists arrive at their ideas. We hope you will find chances in this course to think about such matters, and that you will form your own views.

Some of the questions ask about how physics can be used in engineering and technology, and the articles in this book are also about that, because we think that you will rightly want to know when what you learn is of practical value.

Finally, one of the main reasons we want to offer you some physics is that we like the subject and get excited about it. So we hope you enjoy it too.

Summary of Unit 6 Electronics and reactive circuits

Most of the earlier Units have contained the sort of physics a physicist recognizes at once. They were concerned with finding out how things happen, with trying to explain why they happen, and with trying to analyse problems or to take matter and atoms apart to see what they might be like inside.

Unit 6 involves the sort of work an engineer would recognize at once. It is about putting things together to do something useful, rather than taking them apart. If a physicist is to be compared with a child who takes his watch apart to see how it works, an engineer is to be compared with one who invents a new kind of watch which is twice as reliable, and half as expensive, as those we have now.

Much of the work of the Unit is practical work with electronic circuits contained in boxes. It would have been possible to include teaching in this Unit about how the boxes work, but we have not done so. What is in the boxes does not matter much: at the time of writing they contain transistors, but in a few years they may well contain integrated circuits. What matters is what the boxes will do, and what you can do with them to build up useful electronic systems such as counters, amplifiers, and so on.

It is very likely that you will use electronic devices after you finish this course, in later courses, in research, or in practical problems. If you do, you will usually take down from a shelf boxes which, properly combined, will do what you want. You might want an oscillator, a switch, and a counter, to time something, for example. The idea behind this Unit is to teach you what can be done with electronic boxes in combination, and to let you try some engineering of your own, putting electronic devices together to solve practical problems.

All electronic devices contain capacitors and resistors, and some contain inductors or transformers. So this Unit includes something about such circuits, too.

The work of this Unit (and the *Teachers' guide*) is divided into four Parts, as below. This book itself, and the questions in particular, are, however, *not* divided into these Parts, because the different aspects of the work are closely intermingled. This summary will, however, call attention to its essential features.

Part One

Electronic building bricks

Electronic systems

Looking at devices like scalers, oscilloscopes, radio sets, etc., not as complicated circuits but as sets of parts combining to do a job.

A many purpose unit

The 'basic unit' as a box capable of doing several things.

Making small systems

Combining basic units to make new systems which select, count, do logic, or produce pulses, as well as other things.

Part Two

Circuits containing capacitance

Signal modifying circuits

The effect on signals of circuits containing resistors and capacitors. Explaining the behaviour of these circuits.

Energy in alternating current circuits

The energy dissipated in a circuit when the current is continually changing.

Electronic mathematics

Operational amplifiers used to solve differential equations. *RC* circuits differentiating and integrating. Feedback.

Part Three

Circuits containing inductance

Signal modifying circuits

The effect on signals of circuits containing resistors and inductors.

Using analogies

Inductance and mass. Comparison of an oscillating *LC* circuit with a mass and a spring.

Part Four

Building electronic systems

Putting electronics to work

Doing electronic engineering: putting together systems to do interesting and potentially useful jobs.

Systems and feedback

Electronic systems

Figure 1 shows the circuit of an electronic device. The purpose of the device is to provide a flashing warning light whenever the temperature falls below a certain value. It could be used in a car to give warning of icy conditions, or in the home to indicate a need to turn on the heating in a baby's bedroom. The first thing one notices about the circuit in figure 1 is that it is complicated. It contains eight transistors, fifteen resistors, five capacitors, and a lamp, and, as you may guess, to explain how each part works would take a long time.

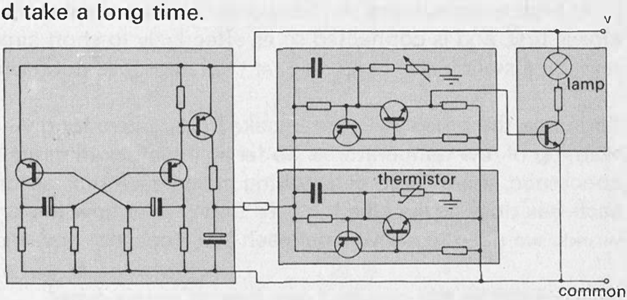


Figure 1
Low temperature warning device.
Adapted from RCA (1970) Solid-state hobby circuits manual HM-91, *RCA Solid-State Division.*

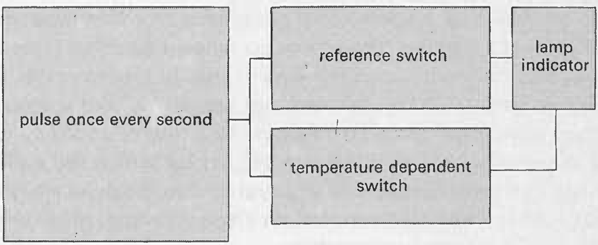


Figure 2
Block diagram of a low temperature warning device.

Figure 2, the block diagram, shows a simpler way of looking at the device. Parts of the circuit in figure 1 have been put into four boxes. Each box has one definite job to do; together, they add up to a temperature warning device. The large box on the left in figure 2 emits an electrical pulse once a second, and the pulses go to two switches. The upper (reference) switch passes the pulse on to a lamp, when the pulse reaches a high enough voltage. The lower (temperature-dependent) switch passes the pulse on when the pulse reaches a voltage which depends on how warm a resistor (a thermistor) in the switch is. At low temperatures, the reference switch closes before the temperature-dependent switch, and the lamp flashes once a second as the pulses reach it. At high temperatures, the temperature-dependent switch closes first, and is connected so as effectively to short circuit the reference switch and lamp, so that the lamp does not flash.

Together, the boxes in figure 2 make up a *system* for giving warning of low temperatures. So far as the block diagram is concerned, there could be anything inside each box, as long as each box does its specified job. To understand how the system works, we need to know what each box does, not how it does it.

Figure 3 shows the circuit of one form of scaler–timer manufactured for school use. The circuit is even more complicated than the previous one, though both use some of the same components: transistors, resistors, and capacitors.

The temperature alarm system contains a box that produces a pulse once a second. The scaler contains a box that produces a thousand pulses a second: the same job, but done faster. This box can be seen in figure 4, a block diagram of the scaler–timer. Pulses from it go, through a switch, to a row of counters, so that the number of thousandths of a second for which the switch is closed can be counted, and the system functions as a high speed stop watch. The counters contain electrodes that glow when a voltage is switched across them.

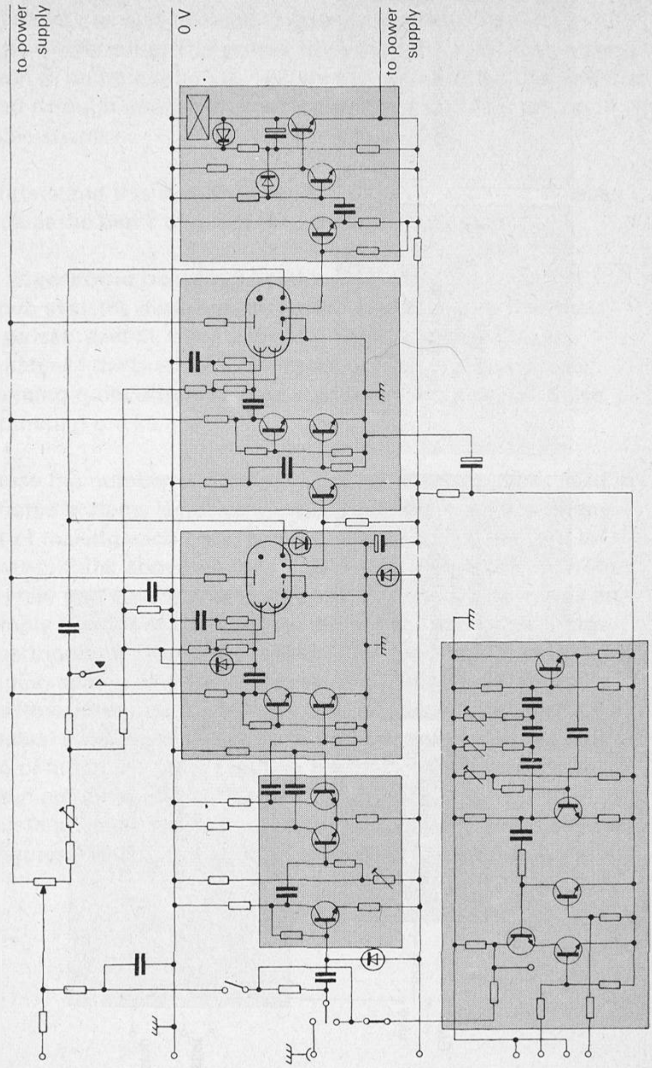


Figure 3
Scaler–timer circuit diagram (omitting power supply circuits).
Courtesy, Edwards Scientific International Ltd.

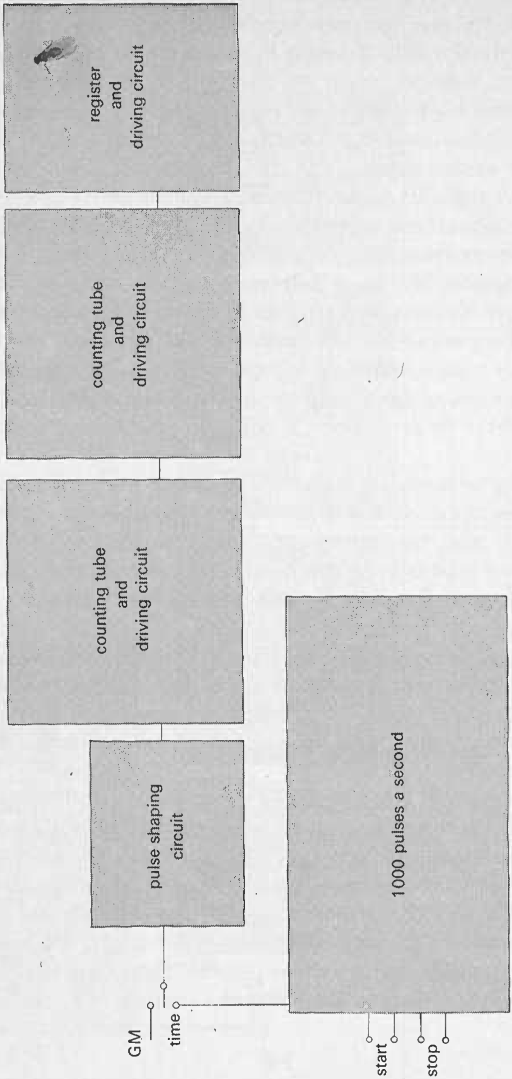


Figure 4
Block diagram of the scaler-timer shown in figure 3.

The system can also be used to count the pulses from a Geiger–Müller tube. The pulses from the tube may not be large enough or sharp enough to operate the counters, so they are first passed through another box which makes the pulses into a suitable shape.

To understand this system, as with the previous one, it is easier to look at the block diagram than the circuit diagram.

Electronic building bricks

The two systems discussed so far have contained boxes that emit pulses, switch, count, shape pulses, and give a visual indication of the presence of a voltage. Many other systems, performing quite different tasks, can be built out of just these few building bricks.

Because the number of different kinds of building bricks used in electronic systems is not very large, while there are very many ways of making each brick from individual components, it is simpler to think about electronic devices as systems built from these few parts, rather than to try to think of each device as an assembly of transistors, resistors, capacitors, and other things. Furthermore, the best available design of each building brick changes rapidly, as new components, such as field effect transistors, integrated circuits, and so on, become available. In ten years' time, we may expect to find electronic systems still made of much the same building bricks, but with each brick containing quite different components. So a good way to understand electronic systems is not to look at circuit diagrams, like figures 1 and 3, but at block diagrams, like figures 2 and 4.

RC circuits as building bricks

Figures 1 and 3 contain plenty of resistors and capacitors. So does figure 5, showing the part of a record player amplifier which magnifies and corrects the signal from a gramophone pickup and passes it on to another amplifier to drive the loudspeaker.

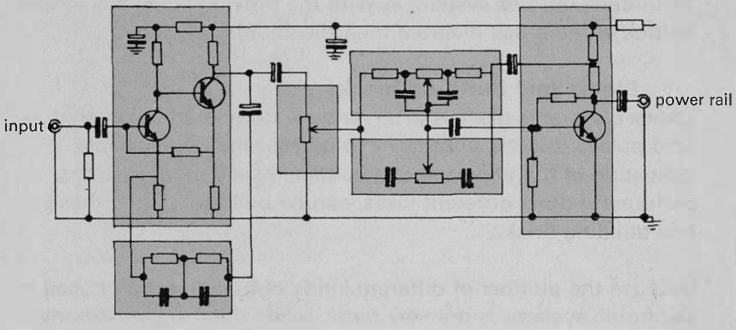


Figure 5
Circuit of record player pre-amplifier.
After Transistor audio and radio circuits *(1969) Mullard.*

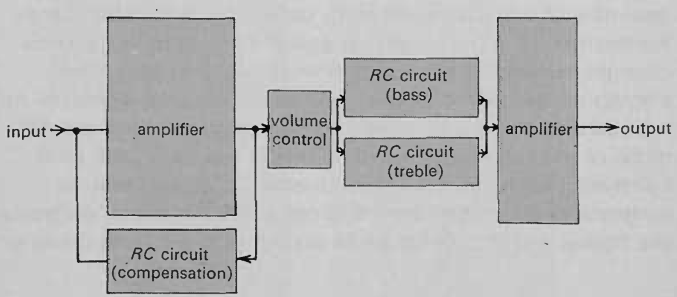


Figure 6
Block diagram of a record player pre-amplifier.

The system consists mainly of two amplifiers in a row, as the block diagram, figure 6, shows. The system also uses resistors and capacitors in a new way, as signal-modifying building bricks in their own right. The box labelled *volume control* in figure 6, the block diagram, contains a potentiometer, which passes on the signal from the first amplifier to the second, having reduced it by whatever amount is needed to achieve a comfortable volume of sound. In front of the second amplifier in figure 6 are shown two circuits containing resistors and capacitors. These also reduce the signal passing through them, but by an amount which depends on its frequency. The circuit labelled *RC circuit (bass)* is used to modify the strength of low frequency signals passed from the first amplifier to the second, so that the sound from the loudspeaker may be made richer or poorer in low frequency, bass, sounds. The circuit labelled *RC circuit (treble)* does a similar job for high frequency sounds. Together, they enable the system to be adjusted to produce a pleasing overall sound quality.

The third *RC* circuit, labelled *RC circuit (compensation)* in figure 6, corrects the imbalance between low and high frequency signals which is always produced by any record pickup. The interesting thing about this circuit is that it is connected so as to feed some of the output of the first amplifier back to that amplifier's own input. Such an arrangement is called *feedback* (there is also some feedback used in the bass and treble control circuits, but for clarity, this has been left out of the block diagram).

The output from the pickup may be lacking in low frequencies compared with high ones, so the first amplifier must amplify low frequencies more than high ones. By itself, the amplifier magnifies signals of all audible frequencies about equally. The feedback circuit of resistors and capacitors is then arranged to send more of the high frequency signals than of the low frequency ones back to the amplifier input, but to send them to the input not in phase with the incoming signals from the pickup. The combination of the difference in phase and the different amounts of each frequency that are fed back has the net effect of making the amplifier produce an output signal with a greater proportion of low frequencies than there was in the input signal.

Feedback in systems

The amplifier system of figure 6 uses feedback in a rather complicated way, but the idea of feedback is a simple and important one. This idea is used by engineers to help them understand how systems work, or how they can be made to work

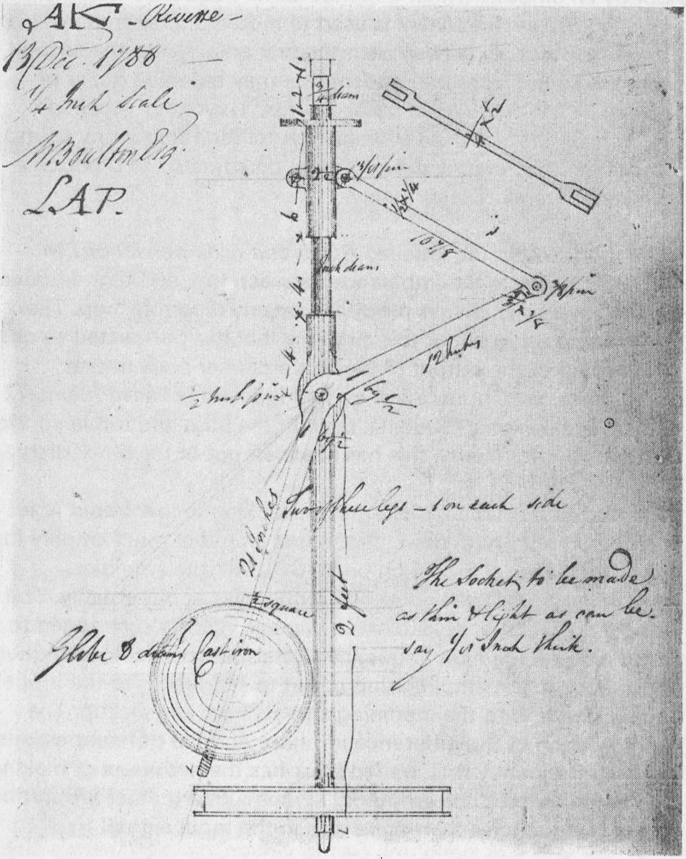


Figure 7

A drawing made in 1788 of Watt's steam engine governor. No earlier drawing of the device is known. Only one ball is shown, but the sketch says, 'Two of these legs – 1 on each side' in the centre of the figure.
From the Boulton and Watt Collection, Birmingham Reference Library.

better. It is not limited to electronic systems. The examples that follow may help to illustrate what feedback is, how it works, and how systems that use it are much more familiar to us than appears at first sight. They will show that the engineer's way of looking at a system as a whole can both simplify the problem, and give new insight into how the system works. Its behaviour, especially if there is feedback in it, is as surprising as it is interesting.

Watt's governor: an early example of feedback

Figure 7 shows the earliest known drawing of James Watt's steam engine governor. A shaft is turned by the output shaft of the steam engine which, but for the governor, would tend to race at high speed when not driving a load. The shaft carries a pair of balls around with it (only one is shown). If the shaft's speed increases, the balls turn in a larger circle and rise upwards, pulling down a collar attached to a cranked arm. The collar is part of a valve which then reduces the supply of steam to the engine. Any rise in the speed of the engine reduces the speed again, because a signal indicating the rising output speed is fed back to the input (steam flow) so as to reduce it. The system is shown as a block diagram in figure 8. This sort of feedback is called *negative feedback;* if the output rises, the feedback from output to input tends to reduce the input, and so also the output.

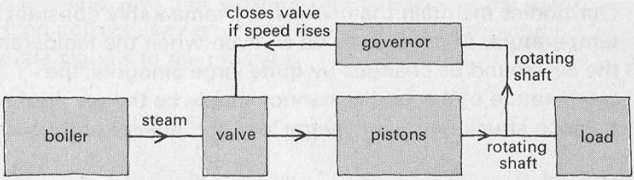


Figure 8
Block diagram of a governed steam engine with negative feedback.

Feedback in temperature control

The water in a washing machine needs to be heated to the right temperature, and then to be kept at that temperature. This is done by a simple form of feedback, using a temperature-sensitive switch. The switch could be electronic, as in the temperature alarm of figure 1, but it is usually mechanical, made of a metal strip that bends when it is hot, and thus opens or closes a contact.

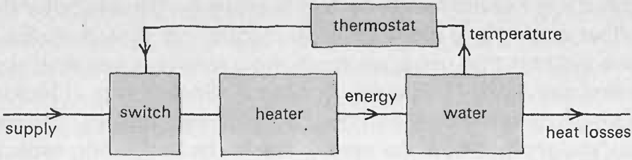


Figure 9
A simple thermostatic system.

Figure 9 shows such a system. The heater supplies energy to the water. When the water reaches the desired temperature, a switch in the thermostat cuts off the supply of energy to the heater. As the water cools below the proper temperature, the thermostat switches the supply on again. Notice that this system is less subtle than Watt's governor. The governor can gradually reduce the supply of steam as the speed increases, while the thermostat simply turns the energy supply on and off. As a result, the water temperature is not kept quite steady, but rises and falls between temperatures above and below those at which the thermostat switches on and off. The steam engine governor can, by contast, achieve a steady speed of rotation by regulating the steam flow smoothly.

Feedback in the human body

Our bodies maintain themselves at a remarkably constant temperature. Because they do so even when the temperature of the air around us changes by quite large amounts, the temperature of our bodies cannot simply be the result of a balance struck between energy loss and energy production.

Overall, the system works as shown in figure 10, though many details need to be filled in. The skin contains nerves which sense its temperature, and these send signals to the brain. A part of the brain (in the hypothalamus) then sends out signals which regulate the rate of energy production and of energy loss from the skin, varying them if the body temperature rises or falls. The full details of the control system, in so far as they are known, are, however, more complex than this.

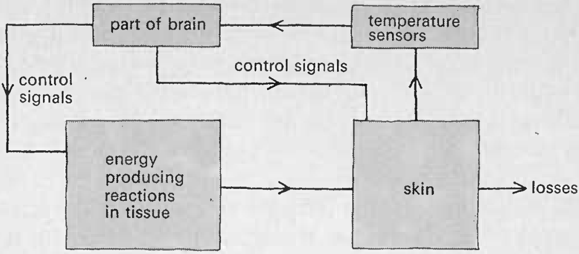


Figure 10
Temperature regulation in the body.

Our rate of breathing is controlled in a similar way. If the level of carbon dioxide in the blood rises, this is detected in the brain, and signals go to the chest muscles and diaphragm which increase the rate of breathing, until the carbon dioxide level falls again as a result.

Another use of feedback in our bodies helps to achieve our remarkable ability to use and control delicate tools.

We are able to manipulate things between fingers and thumb because signals about the motion of the fingers, the pressure they are exerting, and their position, are fed back to the brain which then corrects any error in the desired result by sending appropriate signals to the muscles.

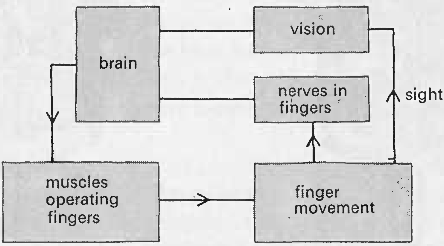


Figure 11
A system for controlling finger movements.

The senses of sight and touch are both involved in the feedback to the brain. You have only to recall what it is like fumbling with your coat buttons when your fingers are numb with cold to realize the importance, in controlling manipulation, of the signals back to the brain from nerves in the fingers, especially those indicating the pressure exerted by the fingers.

Vision is also important. If you shut your eyes and try to pick up a small object someone has afterwards put in front of you, it is quite difficult to do, and even more difficult when you are wearing gloves which block the feedback from the sense of touch. It is not so hard if you take a look first, or if you look and try, and then shut your eyes and try again. These results suggest that the brain can store the necessary information, and use it on later occasions to supplement meagre feedback information.

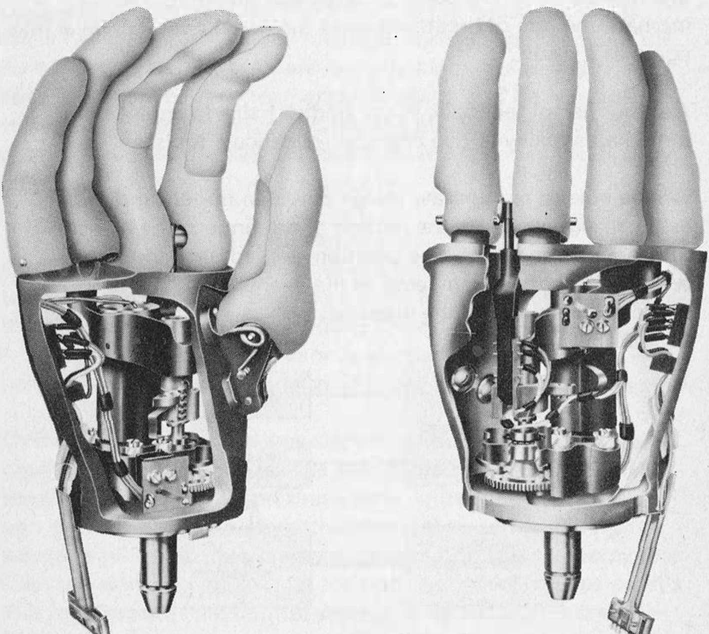


Figure 12
A prototype of an artificial hand developed at A.W.R.E., Aldermaston.
Photograph, UKAEA, by courtesy of the Director, A. W. R. E. Aldermaston.

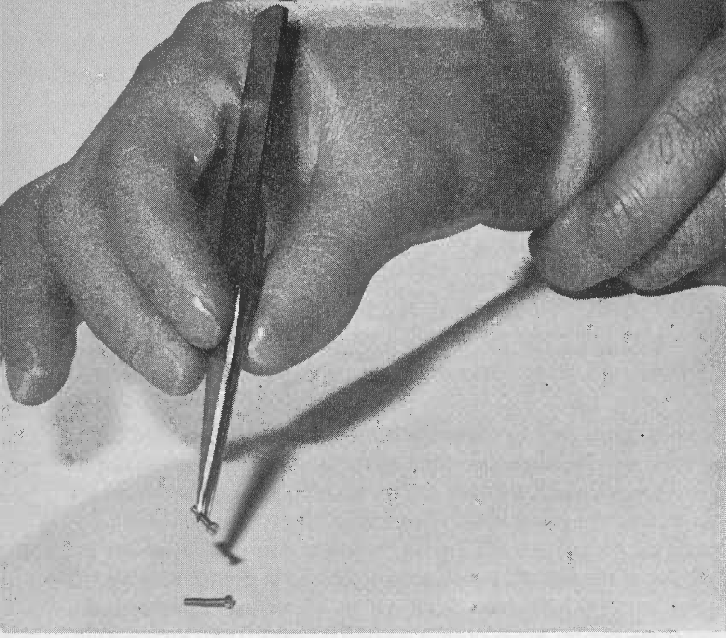


Figure 13
This photograph illustrates the delicacy of manipulation possible in a feedback controlled system.
Photograph, UKAEA.

Artificial limbs using feedback

Figures 12 and 13 show an artificial hand, powered by a small electric motor. If the hand is to be used effectively, it is necessary to control not only the force it exerts, but the speed with which it closes, and this is done by feeding back to the motor signals which measure both speed of motion and force exerted.

Figure 14 shows some of the system involved in the working of the artificial hand. The motion of the motor which drives the hand is controlled by an amplifier to which information about the force the hand is exerting and the velocity of its finger motion is fed back. These two feedback loops help the hand to work smoothly, but they cannot make it do what its owner

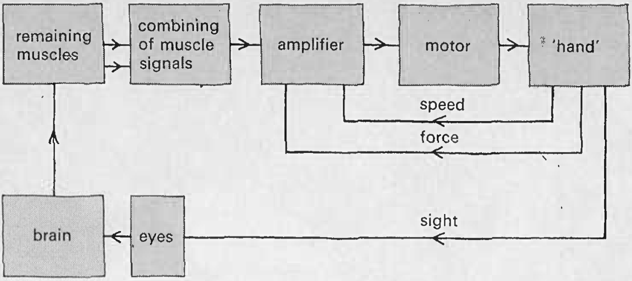


Figure 14
Three feedback loops in the artificial hand system.

wishes. One way to make the hand do what is required of it is to take signals from the muscles remaining in the amputated arm. Several such signals can be combined to give the proper motion of the hand (which would be controlled by several muscles if it were a real hand). There is a further feedback loop involved: the hand's user can see what it is doing, and his brain can control the muscles from which the signals operating the hand are taken. Such combinations of feedback loops within loops are common in electronics and in many other complex systems.

Lynxes eating rabbits

(See Tustin, 'Feedback'.) The Canadian lynx is valued for its fur, and fur trappers soon found that the lynx population is liable to rise and fall in a fairly regular rhythm. The rhythm is produced by feedback.

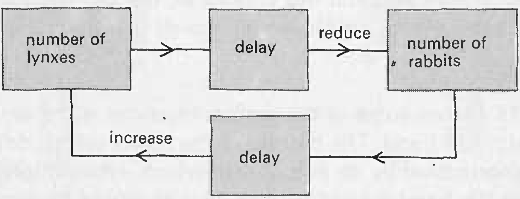


Figure 15
Lynxes eating rabbits: feedback loop.

Lynxes eat rabbits, so the more lynxes there are, the fewer rabbits there will soon be. But as rabbits are an important part of the lynxes' food supply, the fewer rabbits there are, the fewer lynxes can eat well enough to live.

If the effects of changes in one population on the other were quick to take effect, the two populations might settle down in equilibrium, with negative feedback keeping the lynx population under control. Any increase in the number of lynxes would decrease itself again by way of a decrease in their food supply: the principle being no different from James Watt's governor.

Actually, there are delays in the effects of a change in one population on the other. A drop in the supply of rabbits will take some time to lower the lynx population, and, although rabbits breed with proverbial speed, it will take time for their population to build up after a drop in the number of lynxes preying on them. The result is a cycle of oscillation, like that shown in figure 16.

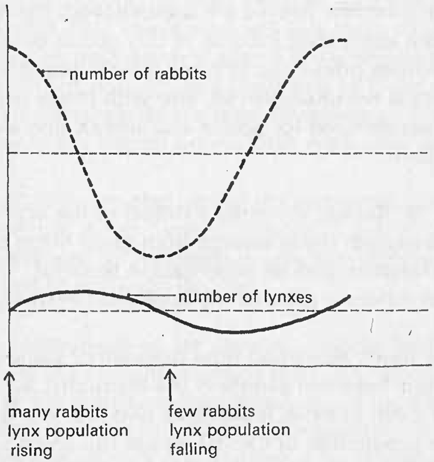


Figure 16
Oscillations of lynx and rabbit populations.

When there are many rabbits, the lynx population rises, but it reaches a maximum when the rabbit population is in decline. Later, rabbits are scarce, and the lynx population is falling. The oscillation is self-perpetuating: the result of negative feedback with delay.

Delays can be fatal to a negative feedback system which is intended to control something. If there are delays in the artificial hand control system discussed previously, the hand may go into oscillation whenever it is used to attempt to grasp something. It may be that the embarrassing side-stepping behaviour of two people meeting face to face in the street, as each moves aside to let the other pass, only to find that the other has moved the same way and is in front of him again, is the result of delays in the feedback system of observations of each other's positions and reactions to them.

Feedback, unemployment, and the economy

(See Tustin, 'Feedback'.) Capitalist economies, like the population of the Canadian lynx, are subject to periodic booms and slumps. In a boom, few people are unemployed; the many who are in work are using their income to buy goods or to invest in shares, whose prices rise as more people seek them. In a slump, more people are unemployed, and with fewer people in work, there is less demand for goods and shares, and share prices tend to be low.

The economist J. M. Keynes invented a model of the economy which can help to explain these swings from good times to bad and back. His explanation can be described in terms of feedback between different parts of the economic system.

Figure 17 is a very much simplified flow diagram of some of the interconnections between events in the economy, as Keynes supposed them to exist. It contains two important loops, one for the production of capital goods (machine tools, factories, plant, raw materials) and one for the production of consumer goods (food, clothes, television sets, cars, books, etc.)

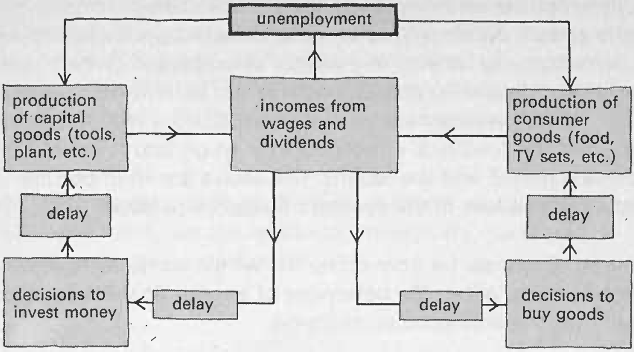


Figure 17
A simplified flow diagram of Keynes's model of a capitalist economy. It does not represent all the influences Keynes included in his model nor does it include the influence of one country's economy on another, or the effect of Government decisions.

Suppose now that people generally begin to invest rather more money than before, perhaps because they think 'good times' are coming. This investment will buy more capital goods, and more will be paid out in wages if more people can be employed to make them, and in share dividends to those whose extra capital is invested. So the level of economic activity, and of incomes in the capital goods loop, rises after some delay.

Now incomes are also part of the consumer goods loop. Bigger incomes may mean more purchases of goods, and, after a delay, will lead to increased production if more people can be employed to make the goods.

But because incomes are common to both loops, the increased activity in the consumer goods loop can, when it arises, increase the activity in the capital goods loop still further, by providing more money incomes for investment. Because the changes can amplify one another, a small change in investment can have large effects.

A boom of the kind described will reduce unemployment, as more people are employed to make the extra goods in demand. If there come to be very few people unemployed (which would seem very desirable) production may not be able to expand any more. Once investors see an end to expansion, they may invest less, and the feedback effects could then go into reverse. As with the lynxes and the rabbits, the delays are an important part of the causes of the system's tendency to oscillate.

This is, of course, far from being the whole story, even of what is understood about the behaviour of economic systems, and much yet remains to be understood.

Positive feedback

Some of the economic effects described previously involve a change in one direction in one part of a system being fed back later in such a way as to make the change go further in the same direction. Feedback with this effect is said to be *positive feedback.*

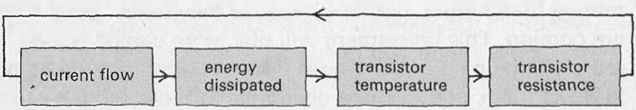


Figure 18
Feedback loop for thermal runaway.

A few simpler examples may help. The resistance of a transistor falls as it becomes warmer, as it may do if there is a current flowing in it. If the current increases as the transistor becomes warm, it may become warmer still. It is quite possible for this process to go on and on, until the transistor junction melts. Such thermal runaway can be avoided by keeping the transistor cool and by arranging, with resistors connected to it, that the energy dissipated in it does not rise as the temperature rises and the resistance falls.

Some people regard road building as an example of positive feedback. They would say that a new motorway does not just siphon off traffic from other roads, but encourages cars or lorries to be used when they would not otherwise have been, had the road not existed. Soon, on this argument, the new road will also be congested, and another new road will be wanted to relieve the load of traffic. Then this next new road, far from relieving the first, will attract its own extra burden of traffic, and so on.

Wind instruments, such as the flute or organ pipe, use positive feedback which, like the feedback through *RC* circuits in figure 6, is frequency-selective.

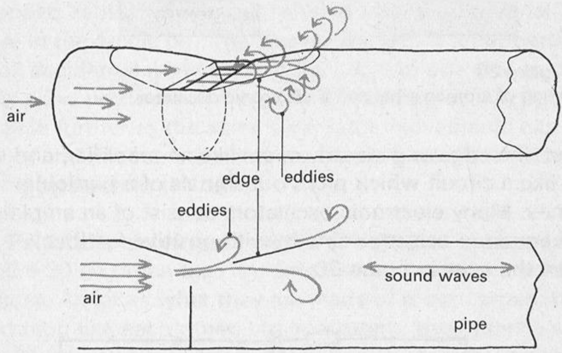


Figure 19
Organ pipe.

Air blown across the lip or edge of an organ pipe, as suggested in figure 19, will break away in eddies or vortices first on one side of the edge and then on the other. The alternating breakaway of the eddies of air produces a sound. If it were not for the rest of the organ pipe, the frequency with which the air breaks away would depend on the air speed past the edge. But the pipe responds freely to a sound whose frequency is at one of the pipe's resonant frequencies. Such a sound vibration, in the air stream near the edge, triggers off the formation of eddies above and below the edge at its own frequency.

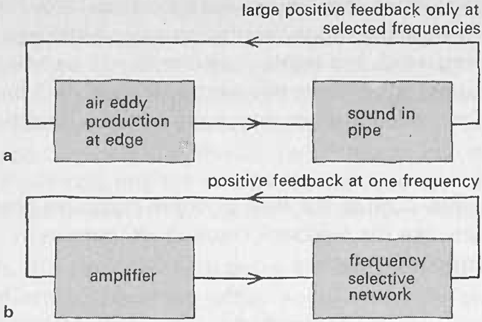


Figure 20
Comparison of a organ pipe: and **b** electronic oscillator.

In effect, the edge and air stream are like an amplifier, and the pipe is like a circuit which picks out signals of a particular frequency. Many electronic oscillators consist of an amplifier and a frequency-selective circuit, with positive feedback between them, as in figure 20.

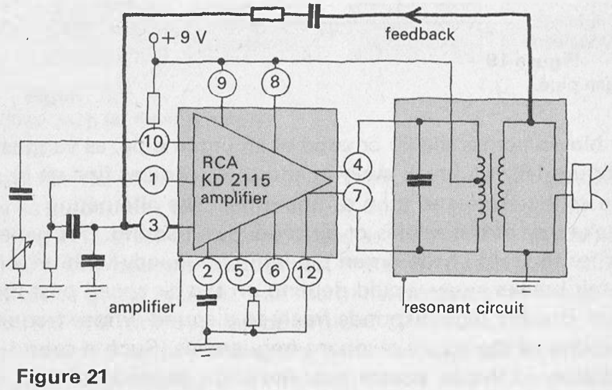


Figure 21
Oscillator using an integrated circuit amplifier.
Adapted from RCA (1970) Solid-state hobby circuits manual HM-91, *RCA Solid-State Division.*

Figure 21, for comparison with figure 20*b*, shows an audio oscillator circuit, using an integrated circuit amplifier. The resonant circuit is an inductor with a capacitor connected across it. The inductor is part of a transformer, which drives a loudspeaker, and the feedback returning to the input of the amplifier is taken from the loudspeaker circuit. (The other resistors and capacitors connected to the amplifier provide bias, or make it stable.)

Another example of positive feedback is the 'galloping' of suspended cables, which was referred to in the *Students' book*, Unit 4, in the article on 'The Severn Bridge'. If it happens that a small accidental movement of the cable to one side in a strong wind produces a change in the air flow which pushes the cable further to the same side, large movements can be built up, and the cable oscillates with a big amplitude from one extreme position to the other.

Problem-solving systems (analogue computers)

In figure 20 an organ pipe is compared with an electronic oscillator. As far as what they are made of is concerned, they are nothing like each other, but as systems, they share a strong resemblance. One advantage of thinking in terms of systems is that such resemblances are easier to see. Once seen, they can be exploited by building one system that may be cheap and easy to make, to represent another that is very costly to build.

For example, a chemical engineer might want to know the effect on a chemical plant of changes in the reaction conditions in one or more reaction vessels. In this case, it may be dangerous as well as expensive to try some modifications.

As suggested in figure 22 *b*, it may be possible to build an electronic system which behaves like the reaction vessel in figure 22*a*. If the reaction depends on temperature and pressure, but itself changes these factors, feedback loops representing their effects will be needed. Some of the partially reacted material may be returned to the vessel; if so, another loop can be provided.

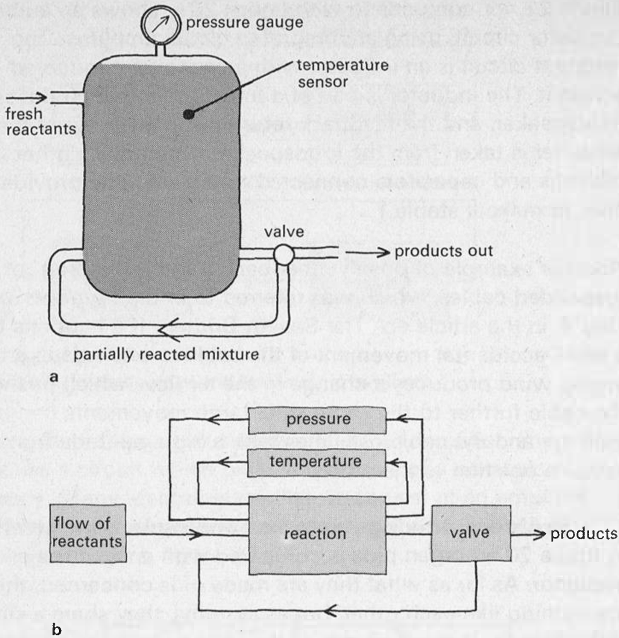


Figure 22
a A chemical reaction vessel.
b A possible system to simulate the behaviour of the reaction vessel.

One device which is much used in such systems is the *operational amplifier.* This is simply an amplifier which magnifies signals applied to its input by a very large factor, whether the input is a varying or a steady one, and which draws very little current.

An operational amplifier is always used with feedback. The simplest feedback system is shown in figure 23.

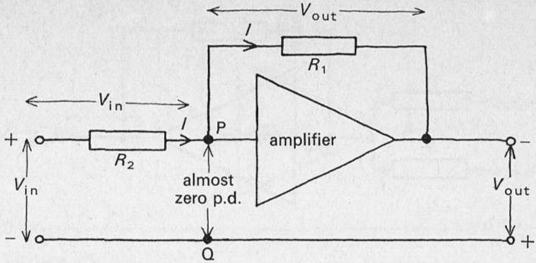


Figure 23
Operational amplifier with resistive feedback.

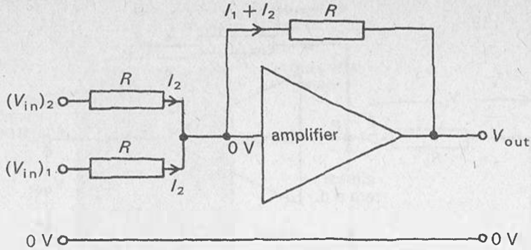
Suppose the amplifier produces at its output whatever appears across the input to the amplifier itself – that is, across PQ – magnified, say, 10 000 times, but reversed in sign. If the output voltage V_{out} *is moderate in size, the voltage across* PQ *must be* very small indeed. Thus P and Q are at nearly the same potential, and the p.d. across the feedback resistor R_1 must be nearly equal to V_{out}, and the p.d. across R_2 must be nearly equal to V_{in}.

Because the amplifier itself draws negligible current, almost the same current I must flow in R_1 and R_2.
Therefore

$$\frac{V_{out}}{V_{in}} = -\frac{IR_1}{IR_2} = -\frac{R_1}{R_2}.$$

The minus sign appears because V_{out} falls as V_{in} rises: the circuit is like an electrical see-saw with arms of length R_1 and R_2. The see-saw 'pivots' about point P, which always remains close to zero potential as long as the amplifier has a large gain.

Notice that the amplification, or gain, of the whole arrangement, $-R_1/R_2$, does not depend on the amplifier's own gain. This is a common feature of negative feedback circuits. Systems with feedback can often be made so that their performance depends very little on the behaviour of the electronic components in them, and almost wholly on the values of resistors and



$$I_1 + I_2 = -\frac{V_{out}}{R} = \frac{(V_{in})_1}{R} + \frac{(V_{in})_2}{R}$$

$$V_{out} = -\ [(V_{in})_1 + (V_{in})_2]$$

Figure 24
Summing amplifier.

capacitors connected in the circuit. This is a great help because components like transistors cannot easily be made in large batches all with the same properties.

If other input resistors are put in parallel with R_2, as in figure 24, the device becomes more useful. A similar argument to that for figure 23 shows that the output voltage is proportional to the sum of the voltages applied to the input resistors, if they are equal. If the input resistors are unequal, each input signal can be multiplied by a chosen factor before being added to the others.

This summing amplifier is needed for combining signals from different sources, if a complicated system is being built up. A summing amplifier would be needed to represent 'incomes' if an electronic analogue of the economic system, figure 17, were being built, as there are two inputs to the 'incomes' part of the system.

Just as useful is the result of feeding back from the output to the input through a capacitor, as in figure 25.

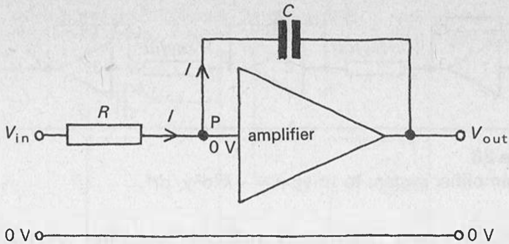


Figure 25
Integrating amplifier.

Suppose V_{in} rises sharply from zero. Current V_{in}/R flows in R, because P remains essentially at zero potential. If V_{out} was zero, there is no charge Q on C, and V_{out} remains zero unless C charges up. When V_{in} rises, the current V_{in}/R nearly all starts to charge C, since almost no current goes to the amplifier. V_{out} thus rises steadily, with a constant current charging C.

In general

$$-\frac{dV_{out}}{dt} = \frac{1}{C}\frac{dQ}{dt} = \frac{V_{in}}{RC}.$$

Thus

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

or $$V_{in} = -RC\frac{dV_{out}}{dt}.$$

The output is proportional to the time integral of the input. This circuit has for long been used in oscilloscopes and television sets, as a way of producing a steadily rising voltage for sweeping the electron beam across the tube face at a steady speed.

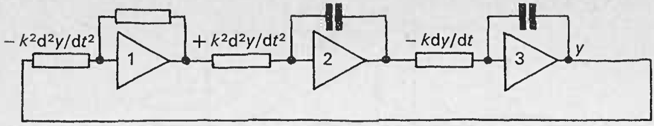


Figure 26
Operational amplifier system to solve $y = -k^2 d^2y/dt^2$.

Figure 26 shows two integrators and one amplifier with a gain of -1 (inverter), connected into a system to solve the equation $y = -k^2 \, d^2y/dt^2$. To see how the system achieves this, let the voltage at the output of amplifier 3 be y. Since 3 integrates, its input is $\left(-k\dfrac{dy}{dt}\right)$, where k depends on the resistor and capacitor connected to it. This is the output of amplifier 2, so its input is $-k\dfrac{d}{dt}\left(-k\dfrac{dy}{dt}\right)$ or $\left(+k^2\dfrac{d^2y}{dt^2}\right)$. Amplifier 1 reverses the sign, so its input is $-k^2\dfrac{d^2y}{dt^2}$. But the output of 3 is joined to the input of 1, and therefore the only values y can have must satisfy the equation:

$$y = -k^2 \frac{d^2 y}{dt^2}.$$

This is just one example, and it happens to be an equation that can easily be solved by other means. It represents a harmonic oscillator, and the system does oscillate if it is built. It is easy to build up more complicated systems to represent equations that are not as easy to solve, and such analogue computers are among the many useful tools for the engineer to have come out of the study and use of electronic systems.

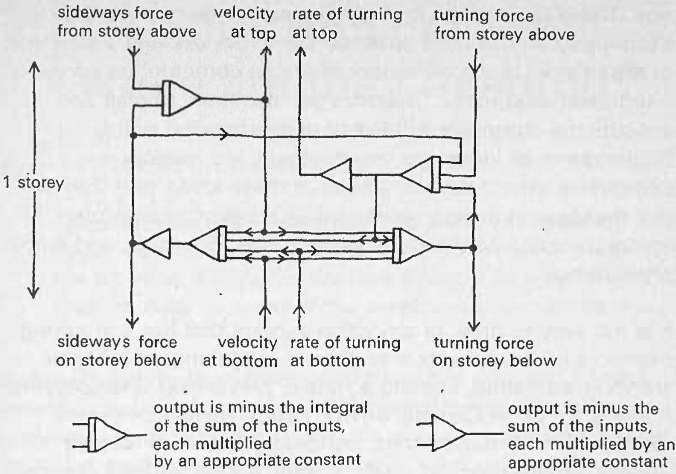


Figure 27
Operational amplifiers used to simulate the response of a building to an earthquake. The system represents one storey of a tall tower. Each storey can move and rotate, and exert a moving or turning force on those above or below it. The whole tower would be represented by as many such systems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

New names for new ideas

Many of the ideas discussed in the previous pages have only seen the light of day in this century. Indeed, scientific bookshops today have shelf after shelf filled with books whose titles include words such as *systems, feedback,* and *control,* while only thirty years ago hardly any books on these matters existed at all. Although the the ideas go back to devices like James Watt's governor, their flowering has been a product of our own time.

These new words represent new ideas; ideas born out of looking at things in a new way, as whole systems whose parts all affect one another. Much elegant mathematical theory has been developed for analysing systems and feedback, so as to be able to predict what a system will do, or to design a better one. The ideas and the theory have very wide applications. Biologists can use them to study the behaviour and self-control of organisms, or the behaviour of stable communities of interlinked organisms. Chemists can use them to plan and execute the automatic control of large chemical plant. Engineers of all kinds can use the tools, like analogue computers, which developed out of these ideas, and they can use the ideas in designing electronic systems, telephone communication channels, automatic machine tools, and many other things.

It is not easy to think of any other subject that has something fresh to say about matters as diverse as picking up a pencil, tracking a satellite, heating a house, preventing unemployment, hunting for fur in Canada, driving safely, using computers, designing radio transmitters, building good 'hi-fi' record players, landing aircraft safely, ironing a shirt without scorching it, and standing upright, to name but a dozen.

Microelectronics: Where are they heading?

by G. W. A. Dummer

Adapted from New Scientist *(1967),* ***34****, 544, 342–343.*

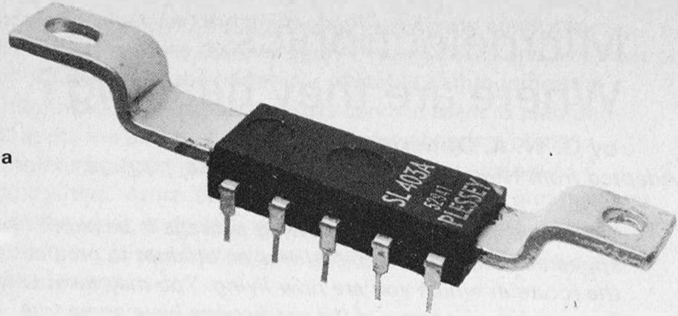
The article on which the following passage is based, appeared some time ago, and was an attempt to predict the future in which you are now living. You may be able to find out how far some of the predictions have come true.

In the whole history of electronics there has not been a faster growth than that evidenced by microelectronics. The first working circuits were made only six or seven years ago and yet today the market in the U.S.A. alone is $300 million and is expected to reach $550 million in 1970. It has been said by one leading figure in the microelectronics world that the pace of development is now so fast that it is impossible to forecast what a new factory will be making in two years' time. An 'avalanche growth point' has been reached, and the spread of microelectronics throughout the electronics industry is now inevitable.

The trend in practically all equipment design is to a module technology, using discrete component parts only where they cannot yet be avoided. The equipment designer, once suspicious of losing his job to the microelectronics maker, is finding that systems design can be more exciting because complexity can now be exploited to a degree not previously possible. The time from development to production has been shortened, and equipment which once took five years from design to production can now be completed in two.

The field of applications for microelectronics is now widening also. From the initial computer applications, with their comparatively easy digital 'on' or 'off' circuits, the extension to linear circuits able to operate on a continuously varying signal without distorting it has been accomplished.

a



b

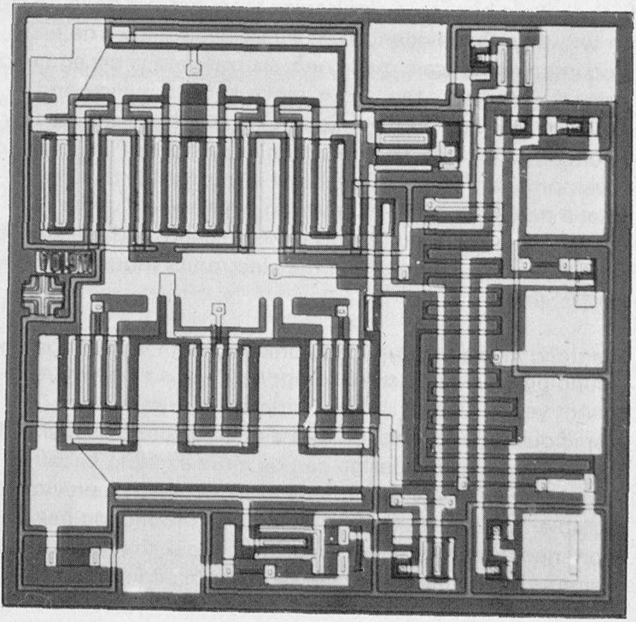


Figure 28
a The SL 403 integrated circuit package.
Photograph, Michael Plomer.
b An enlargement of the silicon chip inside the package. The chip is only 1.25 mm × 1.25 mm × 0.2 mm.
Photograph, The Microelectronics Division, The Plessey Company Ltd.

In the military field, many ground and airborne radar systems, missiles, and communications receivers for all three armed services are being developed in microelectronic form. Civil aviation applications such as flight-data recorders are now in use, and several interesting possibilities are opening up for the large domestic market – already complete radio and TV sets have been built experimentally with 90 per cent microelectronics. The automobile market is also very large, and vigorous steps are being taken by many countries to capture it. For example, microelectronic voltage regulators are already being used in the U.S.A. and we are likely to see a wider use of microelectronics in speedometers, motor regulators, windscreen wiper controls, tyre pressure sensors, and so on. Medical

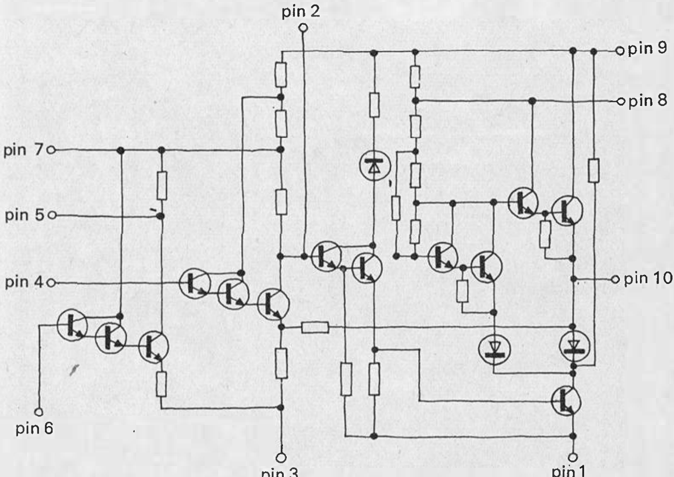


Figure 29
The circuit diagram of the SL 402 and SL 403 integrated circuit amplifier shown in figure 28.
After Gay, M. J. (1969) 'Integrated circuit: audio amplifiers', Practical electronics.

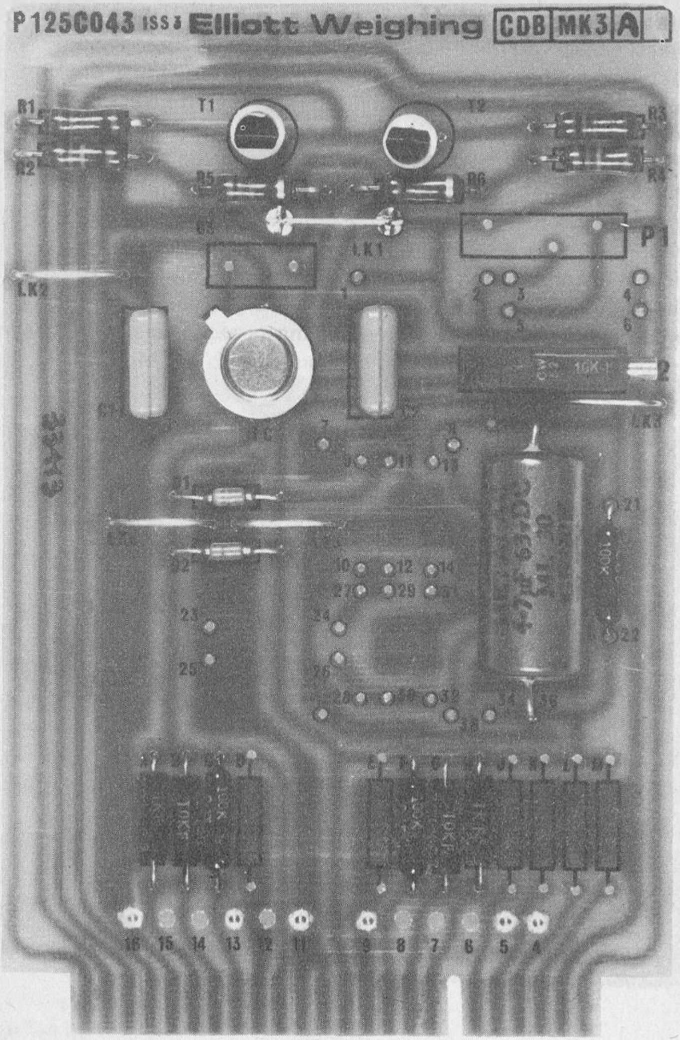


Figure 30
An integrated circuit operational amplifier mounted on a printed circuit board. The integrated circuit is the round object labelled IC, seen left of centre towards the top of the photograph.
Photograph, GEC–Elliott Precision Controls Ltd.

electronics is another field with obvious applications, in heart pacemakers and implanted devices. Even kits of parts for the American home electronics constructor now include integrated circuits.

The principle of integrated microcircuit construction is the vacuum-deposition upon a substrate, or diffusion into it, of patterns of material building up the circuit, instead of manufacturing discrete components and wiring them together. Enormous reductions in size are possible, as the active portions of transistors, resistors, and capacitors can be extremely tiny, and very closely packed; very accurate photographically produced masks are used to define the deposition patterns.

Many hundreds of integrated circuits can be built up on a small 'slice' of substrate (typically silicon, whose semiconducting properties can be locally controlled by the substances diffused into it). Diffusion methods give superior 'active' components (transistors and diodes), whereas deposition techniques produce better 'passive' elements (resistors, capacitors, and interconnections), so hybrid circuits combining the two techniques are widely used.

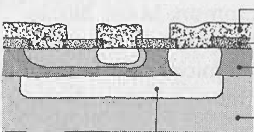


Figure 31
A section through part of an integrated circuit.

The problems – There are, however, practical difficulties in packaging microelectronics in order to make the best use of their inherently high reliability and, in certain cases, to realize the benefits of their small size. Their smallness is, in fact, a disadvantage in handling and connecting them up into complete equipment. To illustrate their size, over 9000 typical semiconductor integrated circuit chips (enough for a complete computer) will fit easily into a thimble (about 1 cm^3).

However, making the connections to these tiny circuits poses great problems. The usual method involves cutting the finished slice into a number of 'chips' each carrying one integrated circuit, attaching leads to each chip, and sealing it in a transistor-can or similar package. The cans are then assembled together on printed-circuit boards. Even with very densely packed boards, with two or more planes of interwiring, the thimbleful of actual working circuit is spread out over a volume about ten thousand times larger, and it is difficult to ensure that all the interconnections are sound.

There are two basic problems at present facing manufacturers of microelectronic equipment. These are the problems of yield and testing: reducing the number of defective circuits, and finding out which they are. Although costs have been reduced considerably over the last few years the final cost depends on how many working circuits can be produced from the initial silicon slices. The processes of manufacture of silicon integrated circuits are extremely precise and working tolerances of 0.002 mm are now common. Many highly accurate masks are necessary for the diffusion processes, and dust particles of less than about 0.25 micron are filtered from the air to maintain ultra-clean conditions for manufacture.

Of course, every care is taken to reduce the number of faults; nevertheless, scratches, pin-holes, and processing difficulties combine with the very tight tolerances to keep the yield down. Circuit testing also presents a formidable problem because of the very high packing densities of the circuits and their connections. Automatic probes can make connections to up to 40 points on a circuit and computers can calculate the working parameters of each individual circuit under test before automatically moving to the next circuit. This is obviously expensive and contributes heavily towards the total cost.

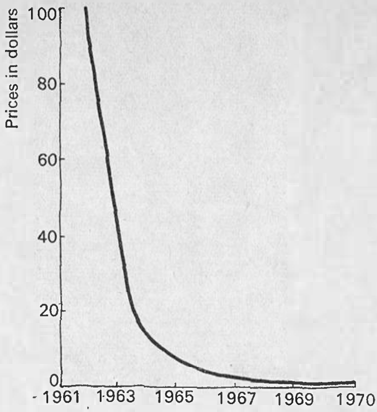


Figure 32
Estimated selling prices for integrated circuits, according to market analysis.

Figure 32 shows the expected reduction in world costs from 1962 to projected costs in 1970 made by market analysts. Once the cost comes below that of present consumer electronic component parts, the major breakthrough possible in radio and TV sets will necessitate a really massive attack on the production problem.

Likely developments – The future of microelectronics is difficult, almost impossible, to predict, for the whole field of semiconductor research is moving so fast in so many different directions. There are, however, some areas where it is possible to see the direction of advancement. Large-scale integration is now beginning to affect computer design and development. In this system several hundred circuits are made on a single slice of silicon. Instead of breaking them up and reconnecting them, a computer tests each individual circuit and only connects up the good ones. Again, process control and yield have an enormous influence on this very advantageous system.

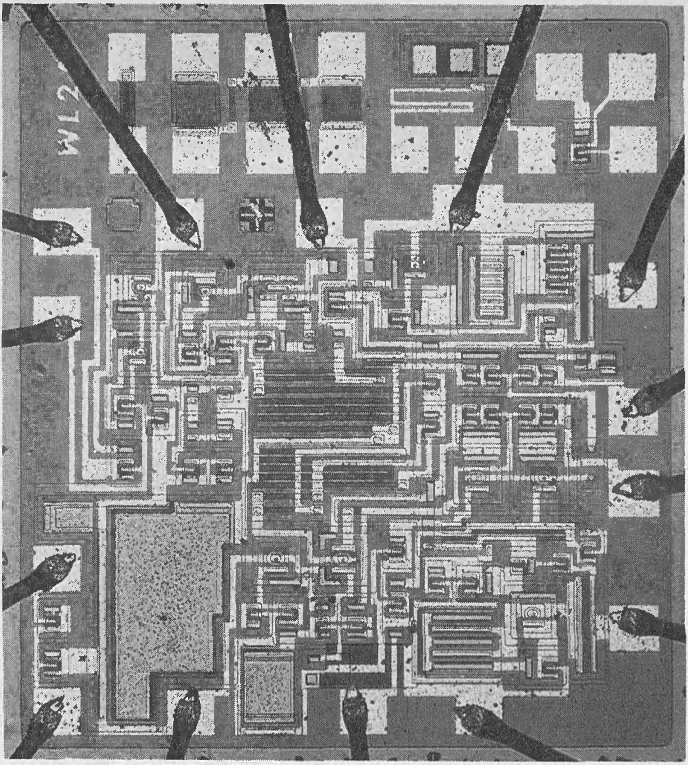
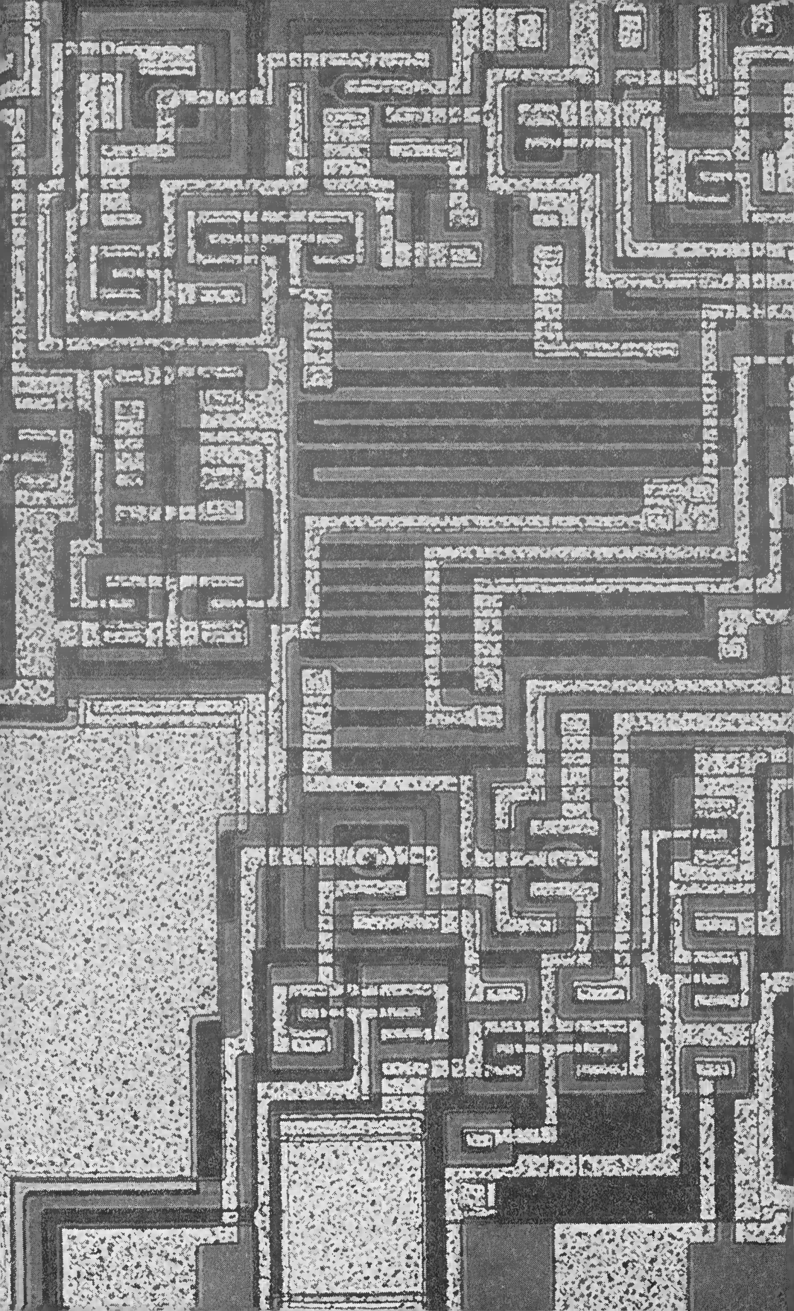
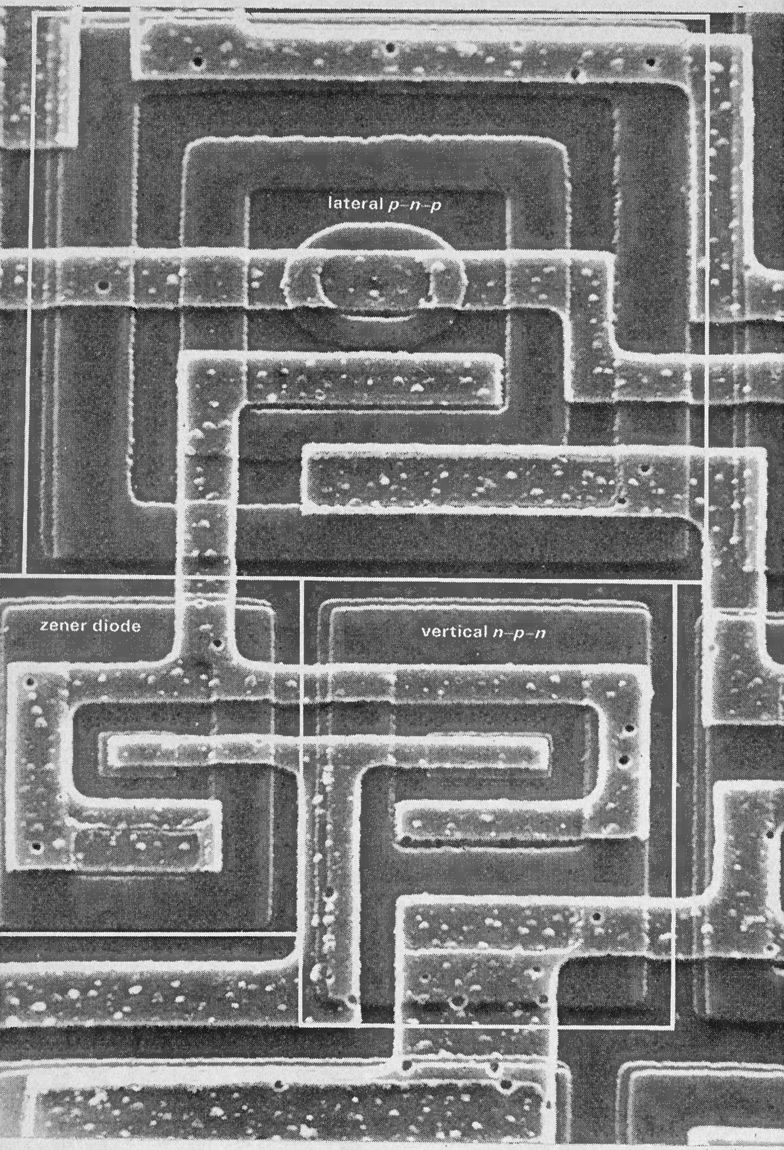


Figure 33
A large scale integration circuit.
a Magnified 110 times.
b Magnified 220 times.
Photographs, Allen Clark Research Centre. The Plessey Company Ltd.
(Continued)




lateral p–n–p
zener diode
vertical n–p–n

Computer design of integrated circuits is fast becoming a possibility. Simple circuits have already been designed by computers and the production masking patterns can now also be computer-designed. These techniques will undoubtedly be commercially developed soon. For very advanced techniques, the circuit may be 'drawn' on the substrate slice by a computer-controlled electron beam which locally hardens a protective plastic layer. The unhardened plastic can be dissolved away leaving an *in situ* plastic mask, which can itself be removed after deposition. Because of the need for higher and higher tolerances, the very high resolution of the electron beam offers advantages over photographic methods. Probably the highest possible packing densities yet envisaged will result from the use of this technique in conjunction with the scanning laser beam or the scanning electron microscope which can examine the process as it is carried out. There is, however, one fundamental problem; the electron beam or laser can only draw one circuit at a time whereas the present photolithographic process of masking makes hundreds or thousands of circuits at once.

The most exciting developments will almost certainly come from the exploitation of present research on semiconductor physics. Now that microwave frequencies can be generated by semiconductors, magnetrons, klystrons, and other vacuum tube devices of limited life may be completely replaced. Already airborne radar systems are being developed with no moving parts, the rotating scanner being replaced by a number of phased integrated circuit radiators. By paralleling some 600-odd integrated circuits, quite high output power pulses of around 50 kW peak power can be radiated at 10 000 MHz. Certainly, developments in this area have exciting possibilities.

Figure 33 (continued)
c A large scale integration circuit, showing the location of individual transistors and resistors. Magnified 1160 times.
Photograph Allen Clark Research Centre. The Plessey Company Ltd.

The upper frequency limit of transistors has been steadily rising, because the smaller and more accurate the active section can be made, the higher the attainable frequency; the present upper limit for reasonable power (say a few watts) is around 4000 MHz. The use of more precise integrated-circuit construction should raise this figure considerably, as also will the new series of self-oscillating semiconductor diodes (see *New scientist*, **34**, page 22). All these devices will have almost the same influence on the microwave market as the transistor had on the valve market, and one can expect an increasing development in this field.

Although a great many predictions have been made about the use of microelectronics in the medical field, this is bound to be a slow process because of the necessity for extensive verification of results before applying them to the human body. However, there is no doubt the pace will be increased by such developments as large-scale integration. One can envisage the time when the standard heart pacer device may be replaced by a large-scale integrated circuit which monitors the blood pressure and flow rate, automatically adjusting the parameters to keep the heart beating at the correct rate under all circumstances. This would be in effect a miniature computer or data processor embedded in the human body.

Questions

Questions 1 to 4

These questions are about *systems,* and the usefulness of thinking about complicated electronic circuits as systems made up of interconnected parts.

1 A *system* is a collection of parts, in which each part has a definite job to do, all the parts acting together to do whatever task is required of the system.

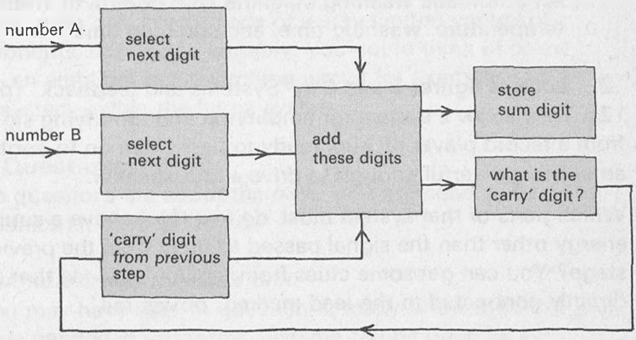


Figure 34
A system for adding pairs of numbers.

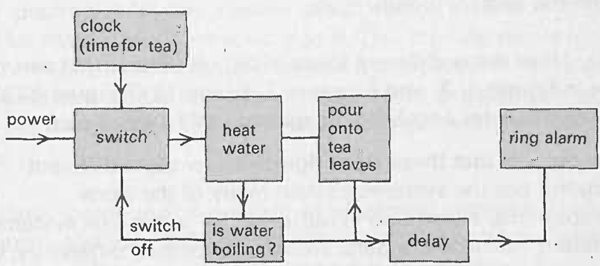


Figure 35
A system for making tea.

To illustrate the idea, figure 34 shows a system for adding up numbers, while figure 35 shows one for making tea automatically.

a Explain how the system for adding numbers works. That is, say what happens step by step. You need not say *how* a machine might achieve each step. That is another problem.

b Explain how the tea-making system works.

c Draw a similar system for one or more of these things:

Controlling cars at a pedestrian crossing.

A 'pop-up' toaster.

Drilling a hole to a required depth.

An automatic washing machine with control of water temperature, washing time, and spinning time.

2 Look at figures 5 and 6 in 'Systems and feedback' (page 12). They show a system for amplifying and modifying signals from a record player pickup, ready to pass them on to another amplifier, powerful enough to drive a loudspeaker.

Which parts of that system must, do you think, have a supply of energy other than the signal passed to them from the previous stage? You can get some clues from looking at those that are directly connected to the lead marked 'power rail'.

3 Suppose you are listening to a song on the radio. Trace the series of things which happen to this song signal on its way from the singers to you.

4 How many different kinds of circuit component can you see in figures 1, 3, and 5 (pages 7, 9, and 12)? Figure 36 shows the symbols for a resistor, a capacitor, and a transistor.

The point is that these three figures show quite different systems, but the systems contain many of the same components, connected in rather similar ways. The systems are different, because the parts are interconnected differently, and because the components (transistors, resistors, capacitors, and so on) are made to do different jobs in building up each part.

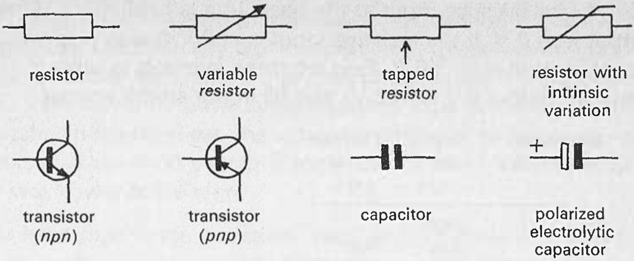


Figure 36

Much of Unit 6 is about building systems out of a small number of parts, each part being made of a very limited variety of components, connected suitably. You could think of one part – an amplifier or a switching circuit for example – as a mini-system within the larger system.

Questions 5 to 15

These questions are about the *basic unit* provided as part of the electronics kit used in Unit 6.

A note about the basic unit

As you may have seen in question 4, many of the different jobs that are needed in electronic systems can be done by a transistor or two, usually connected in a way that differs only a little from job to job. Because this is so, it is possible to provide in the electronics kit one module which can be used in many ways by altering the connections to it. This module we have called a 'basic unit' because it can be put together with others of its kind and with other simple components to build a lot of different things. It is the 'brick' with which other things can be made.

The name 'basic unit' is not one an electronic engineer would recognize, and you will not find any such thing in books about electronics. What you will find, and what the electronics engineer needs to know about, are parts of systems that do the jobs the basic unit can be adapted to do: switching, amplifying, producing or shaping pulses, and so on.

5 If one resistive input to the basic unit is held at +6 V, the output is at 0 V. If the resistive input is at 0 V (using just one input), output is at +6 V. Find what the symbols in table 1 stand for (either 0 V or +6 V) and fill in the empty spaces.

Symbols		Input	Output
+6 V	0 V	+6 V	0 V
		0 V	+6 V
...	...	high	...
		low	high
X	0	...	...
		0	X
...	...	1	0
		...	1
T	...	T	...
		F	...

Table 1

6 The basic unit has two inputs connected through resistors (the input going into a capacitor has later uses). Here is the output for combinations of inputs at 0 V or +6 V.

First input	Second input	Output
0 V	0 V	+6 V
0 V	+6 V	0 V
+6 V	0 V	0 V
+6 V	+6 V	0 V

Table 2

a Write down in words the necessary condition for the output to be high (+6 V), not low (0 V). *Harder:* Do it without using the word 'low', only 'high'.
b Suppose the customs officials at an airport decide to allow travellers through without inspection as long as they say they have nothing to declare, and they have not flown in from Paris. The decision is to depend on how the travellers press two switches. One is labelled 'Have you arrived from Paris?', the other 'Have you anything to declare?' Draw a circuit using a basic unit and two switches to light a lamp behind a sign saying 'Proceed'. Must the switches' +6 V position be marked 'yes' or 'no'?

7 The system shown in the answer to question 6 has the defect that the lamp saying 'Proceed' is lit as the passengers walk up to the switches, if these are at rest in the 0 V position. Add a third switch to the system so that, after the two question switches have been set, the sign only lights up as the passenger walks over the third switch (hidden in the floor), closing it, on his way towards the sign.

You have then made a system, '*Neither* from Paris, *nor* with anything to declare, *and* has passed the questioning point'.

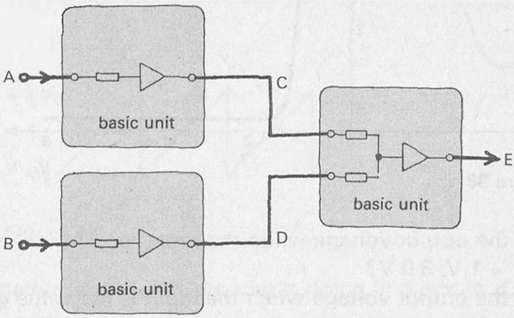


Figure 37

8 Suppose three basic units were connected as shown in figure 37. Complete table 3 showing what the outputs are for various inputs. Test your answer in the laboratory. What might such a system be used for?

Input A	Input B	Output at C	Output at D	Output at E
0	0	1	1	0
1	0	0		
0	1			
1	1			

Table 3

9 The graph in figure 38 shows how the output voltage from a basic unit varies with input voltage.

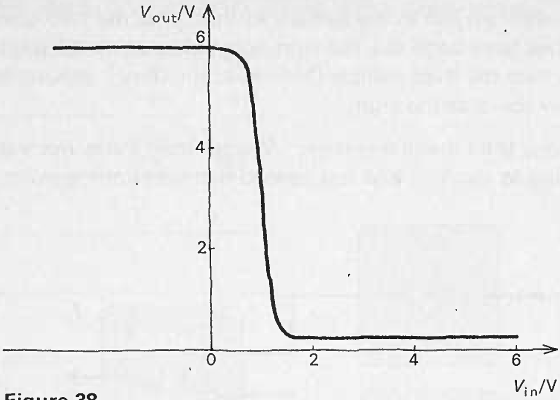


Figure 38

a What is the output voltage when the input is **1** +6 V, **2** +1 V, **3** 0 V?

b What is the output voltage when the input is the value given by **1** X, **2** Y, **3** Z, **4** P, **5** Q, **6** R, on the graph in figure 39?

c If a sinusoidal input voltage (as in figure 39) is used, how does the output voltage vary with time?

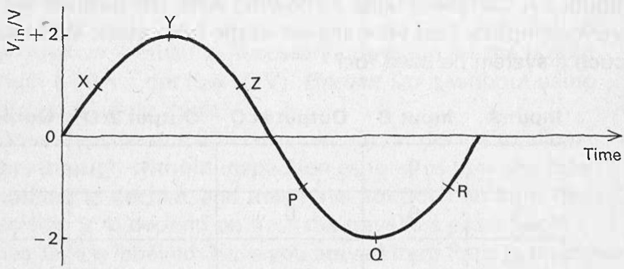


Figure 39

10 Figure 38, with question 9, shows how the output from a basic unit varies with the input voltage to the unit. What output would the unit give if fed with the signals shown in figure 40?

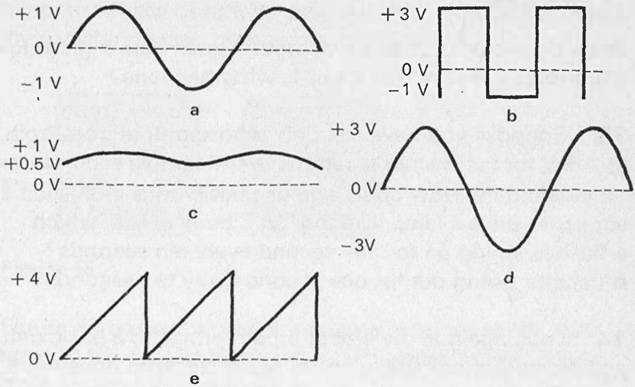


Figure 40

Give names to the jobs the unit is doing in **c** and in **d**.

11 Many scalers will count short, sharp +6 V pulses fed to them from a switch. Suppose you got the impression from the handbook provided with a scaler that it would also count short, sharp 0 V 'gaps' in a steady +6 V supply. How would you produce such 'gaps' with a basic unit?

12 An electronic circuit can be made which behaves as follows. When the input goes from high to low the output goes from low to high, stays there a short time, then goes low again. Figure 41 illustrates the idea.

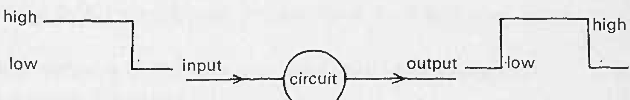


Figure 41

a Which input of the basic transistor unit must you use to get this result?

b Two such circuits are put in a row as in figure 42.

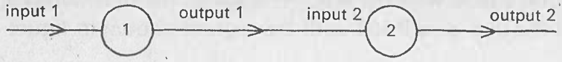


Figure 42

What does output 2 do when input 1 goes from high to low?
c If output 2 is joined to input 1, what happens?

13 Suppose you have a supply whose output goes from 0 V to +6 V for five seconds, returns to 0 V for five seconds, and so on indefinitely. How could you use basic units with such a supply to drive a lamp, like that on a buoy at sea, which
a flashes, going on for one second every ten seconds?
b occults, going out for one second every ten seconds?

14 Look again at the plot of input voltage to a basic unit against output voltage, given in figure 38, with question 9. What conditions must be met if the unit is to produce at its output an amplified version, which will be reasonably faithful, of an alternating voltage across its input?

15 Here are two possible views about what a basic unit does. The voltage across the output is controlled mainly by
a the *current* passing into the input
b the *voltage* across the input.
How could you test which view is more nearly correct?

Questions 16 to 19

These questions are about some combinations of basic units. The best way to think about what can be done by combining units is to have some in front of you, try your ideas out, and see what happens. These questions only add to that more important work, by providing some problems to think about.

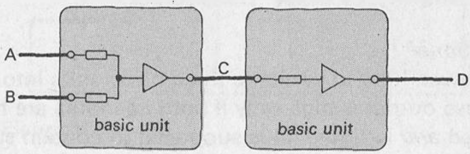


Figure 43

16 Figure 43 shows two basic units used as *nor*-gates, one connected to the output of the other. Complete table 4, giving the output of the combination.

A	B	C	D
0	1	0	...
0	1	0	...
1	0	...	...
1	1	...	...

Table 4

Write down in words the condition that D is high (1) in terms of whether or not A and B are high. Why is this called an *or*-gate?

17 This question is about a system, based on that in figure 43, with a strange new property. It is a very useful system, much used in computers.

Join D to A in figure 43, and forget input B. If A is low, what is C?

If A is low what is D? If A is low, and D is fed back to A, does A have to change?

If A is high, what is D? If D is fed back to A, does A have to change?

Suppose A is low and B is low, with D still fed back to A. The system will sit there, with A kept low by D just because A is already low. Now think of B being made high. C goes low. What happens to D? What happens to A. What happens to the circuit?

How would you get it back to the condition with A low? Why is the system called a bistable?

18 *Hard, optional*
Question 8 showed how to combine three basic units into an *and*-gate, whose output is high only if both its inputs are high. The box labelled *and* in figure 44 is supposed to contain such a combination. The other boxes, labelled *nor*, are basic units.

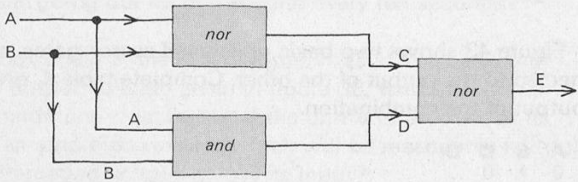


Figure 44

a Complete table 5 giving the outputs C, D, and the final output E, for various combinations of the inputs A and B. Note that A and B are fed both to the first *nor*-gate and to the *and*-gate.

A	B	C	D	E
0	0	1	0	..
0	1	..	0	..
1	0	..	0	..
1	1	0	1	..

Table 5

b In doing binary arithmetic, the sum of two digits is

$0+0=0$ carry 0
$0+1=1$ carry 0
$1+0=1$ carry 0
$1+1=0$ carry 1 (the sum is the two-digit number 10, or 2 in ordinary notation).

Table 6

What use would the system of figure 44 be in a computer?

19 What happens at the output of the system shown in figure 45 if a short, sharp positive going pulse arrives at the input?

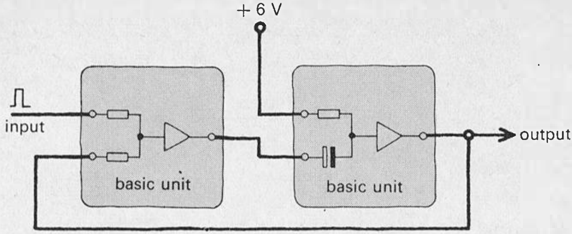


Figure 45

Questions 20 to 25 Feedback

20 Look back at questions 16 and 17. If two basic units are connected in a row, the first feeding the second, what happens to the output of the second if the input of the first starts to go from low to high?

Now suppose that the output is fed back to be the input of the first. If the input of the first starts to go high, what happens to it next? What happens later? What happens in the end?

This is called *positive feedback;* a change to the system drives the system further in the same direction.

21 Suppose the small local shop looks like running out of chocolate, and there isn't another shop nearby. Naturally, some people hasten to buy what they can before it is too late. Seeing this happen, others do the same. What happens? What has this to do with question 20?

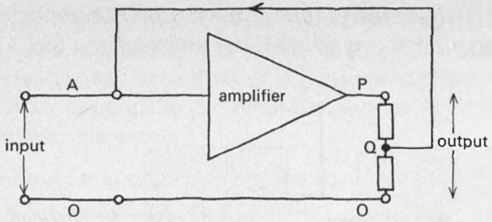


Figure 46

22 Suppose the amplifier shown in figure 46 has the following properties. If the input voltage across AO is 0.5 V and steady, the output across PO is 3 V and steady. If the input voltage rises, the output falls, and vice versa. (The device is not unlike a basic unit.)
The resistors across PO are chosen so that the voltage across QO is one-sixth of that across PO, being 0.5 V if the voltage across PO is 3 V.
The voltage across QO is fed back to the input.
a Suppose the input is at 0 V at one instant, and the output above 3 V. What will happen to the input because of the feedback?
b If the input goes over 0.5 V, the output goes below 3 V. What happens to the input next, because of the feedback?
c If the input is at 0.5 V, what does the system do next to the input?
d If the input goes under 0.5 V, what tends to happen?

This is called *negative feedback;* a system tends to stabilize itself because any change in the system is fed back in the opposite sense, to correct that change.

23 Many modern ships have stabilizers: fins sticking out under water from the hull like small aircraft wings (figure 47). If the ship rolls, a tilt-detecting device turns one fin one way and the other the other way to push the ship upright again as it travels through the water. Which way must the fins twist to stabilize the ship? What would happen if they twisted the other way? What kind of feedback is involved?

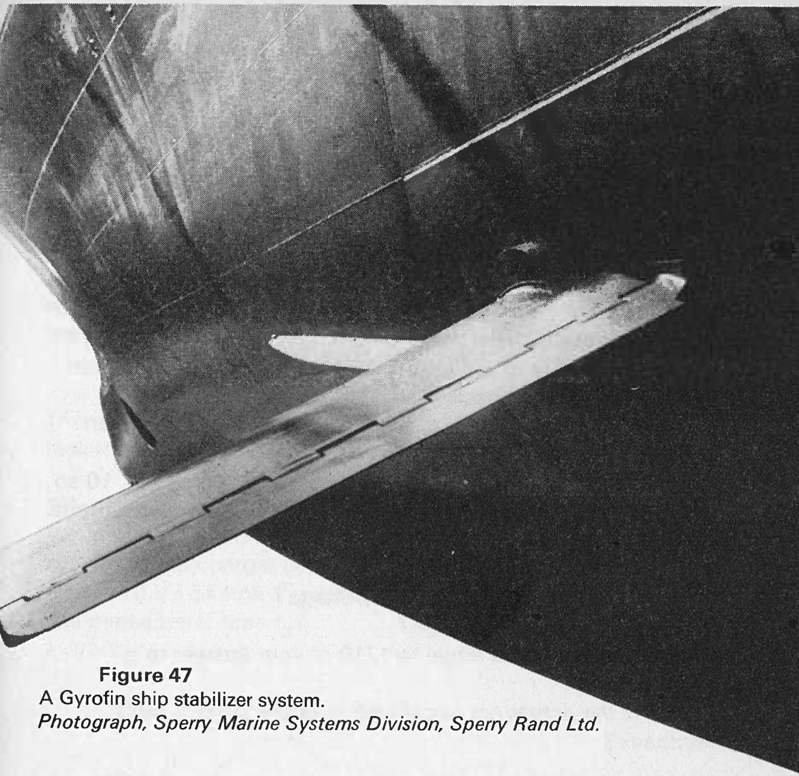


Figure 47
A Gyrofin ship stabilizer system.
Photograph, Sperry Marine Systems Division, Sperry Rand Ltd.

24 Suppose that the roll correcting system described in question 23 works in the proper direction, but that the tilt detector is sluggish, and the motors driving the fins take 30 seconds to move the fins appreciably. A ship rolling is a kind of oscillator, and has a natural period of oscillation. Suppose it takes 60 seconds for the ship to roll to one side, over to the other, and back again (one cycle). Will the stabilizing system still work?

25 *Hard, optional*

This question is about how negative feedback in amplifiers can be analysed, and also about some of its effects, which are very important to designers of electronic systems.

Think of an alternating current amplifier, whose output is an oscillation m times greater than its input. If the input has amplitude 1 mV, the output has amplitude m mV.

a Suppose the input is fed with 1 mV from outside, and with x mV fed back from the output, exactly out of phase with the external 1 mV supply. What is the net amplitude of the input to the amplifier?

b What is the output of the amplifier, given the input from **a**?

c If a fraction $1/p$ of the output is fed back to the input, what voltage is being fed back?

d The voltage fed back was what we called x in **a**. Write an equation relating x to p and m.

e Consider an amplifier whose gain m is 1000, with $p = 10$ so that one-tenth of the output is fed back. Let the external input be 1 mV.

What is the feedback voltage x?

f What is the effective, net input voltage?

g What is the output voltage?

h Is your answer to **e** equal to 1/10 of your answer to **g**? Should it be?

i What is the actual net amplification of the system, with feedback?

You may well think that this is a stupid arrangement, achieving a gain of about 10 in place of one of 1000. Suppose, though, that it is important to make an amplifier with a steady gain. Most transistors or integrated circuit devices (without feedback) are very sensitive to temperature. It is also impossible to manufacture all alike, and transistors come off the production line with gains that vary by at least a factor of two.

Suppose, then, that the amplifier gets hot, or is a sub-standard one, and that its gain is now only 500.

j What is the gain of the system with 1/10 negative feedback, now?

k The amplifier gain changed by 50 per cent. By what percentage did the system gain change?

l All amplifiers fall in gain at high frequencies, and many fall in gain at low frequencies. What will be the effect of negative feedback on the range of frequencies that the system with feedback will amplify about equally?

m Will a system with negative feedback cost more to achieve the same gain, than one without?

Questions 26 to 30

This group of questions examines circuits containing resistors and capacitors.

26 The curve in figure 48, shows one cycle of a sinusoidal variation of the p.d. V across a 100 μF capacitor.

a What is the charge, Q, on the capacitor when $V = +10$ V, 0 V, -10 V? Sketch a graph of Q against t. Is there a charge on the capacitor at time t_0?

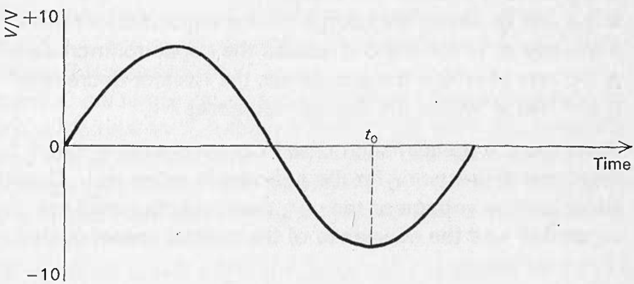


Figure 48

b When is the current flowing into or out of the capacitor at a maximum, and when at a minimum? Sketch a graph of current against time. *Is there any current at time t_0?*
c What other information is needed to give a rough estimate of the maximum current?

27 The capacitor in figure 49 is discharged and the switch is closed.

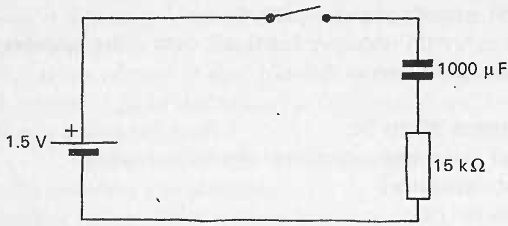


Figure 49

Immediately the switch is closed, what is
a the charge on the capacitor?
b the p.d. across the capacitor?
c the p.d. across the resistor?
d the current through the resistor?
e the rate at which the charge on the capacitor increases?
f *the rate at which the p.d. across the capacitor increases?*
g the rate at which the p.d. across the resistor decreases?
h the rate at which the current decreases?

What are the units in each case? Can you write down algebraic expressions for the answers in terms of *V, C,* and *R* if these are the voltage of the cell, the capacitance of the capacitor, and the resistance of the resistor respectively?

28 This question is about the response of the RC circuit in figure 50 to an input which suddenly rises to a high voltage V from zero, stays there for a while, and then goes suddenly back to zero.

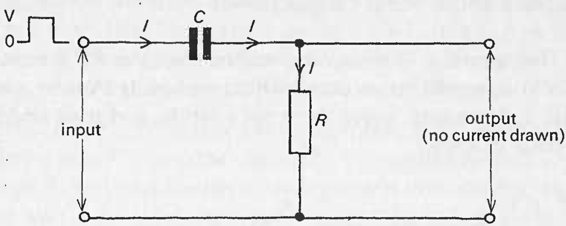


Figure 50

a The output of the circuit is equal to IR, where I is the current in the resistance R, and is therefore proportional to I. When the input voltage V comes on, if the capacitor is uncharged, there is no p.d. across the capacitor. What is the p.d. across R at that moment?

b What is the current in R at that moment?

c What was the current in R when the input was zero?

d The current I has jumped from zero to a high value. The capacitor begins to charge. The p.d. across the capacitor rises. Will it rise slowly or quickly if the capacitance C is large? Why?

e Will the p.d. across the capacitor rise slowly or quickly if the resistance R is large? Why?

f If R and C are large, the capacitor voltage takes a long time to reach a value near to V. It takes a time of the order RC seconds to come within about 2/3 of V. If the time constant RC is not long compared with the time the input pulse is steady at V, what will the output have been doing as the p.d. across the capacitor rose?

g If RC is about 1/100 s, and the input pulse is steady for 1/10 s, sketch the output pulse produced as the input pulse rises and stays steady.

h If RC is about 1 s, will the p.d. across the capacitor have risen much or little in 1/10 s?

i Explain why, in **h**, the output pulse will very nearly follow the shape of the input pulse (when RC is large).

This circuit can either almost follow its input, if RC is large, or 'differentiate' it if RC is small. By the last remark we mean that if the input suddenly changes, so that its rate of change is big, the output is big. A short, sharp rate of change of the input produces a short, sharp output pulse.

29 This question is about the response of the RC circuit shown in figure 51 to an input which suddenly rises to a high voltage V, from zero, stays there for a while, and then suddenly goes back to zero.

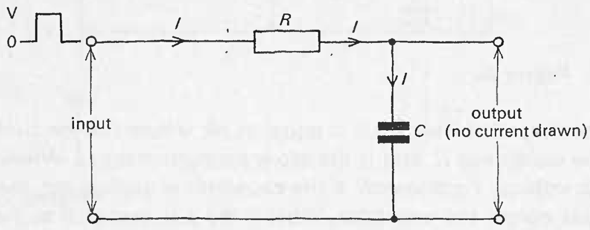


Figure 51

a The output of the circuit is equal to Q/C, where Q is whatever charge is on the capacitor, whose capacitance is C. The output voltage is proportional to Q. When the input pulse comes on, the capacitor is uncharged. What is the output voltage at that instant?
b What is the p.d. across R at that instant?
c What is the current in R at that instant?
d The current has jumped from zero to a high value, at the instant the input voltage comes on. The current charges the capacitor. What will happen to the output if the input voltage stays steady?
e If the p.d. across the capacitor rises, what happens to the p.d. across the resistor, if the input is steady?
f What happens to the current as the p.d. across the capacitor rises, if the input remains high and steady?
g If the input stays on for good, what does the output become in the long run? Sketch a graph.

h The time taken for the output to reach nearly the value of the steady input is of the order RC, as the output depends on the charging of a capacitor through a resistor (see question 28).
If RC is a short time, and the input switches on and off at long intervals, sketch the form of the output.
i If RC is 1 s, and the input stays on for only 1/10 s before going off, what will the output voltage have done in the time the input was on? Sketch a graph of the output voltage.

Either this circuit can almost follow its input, if RC is small, or, if RC is large, it will 'integrate' its input. By the last remark we mean that if the input comes on sharply and then stays steady, the area below the curve of input against time grows steadily, as suggested in figure 52. The output of the circuit grows at an almost steady rate, too.

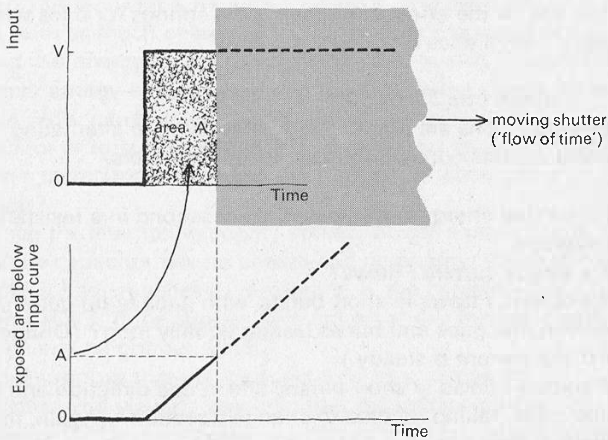


Figure 52

30 In Unit 2, a capacitor was compared with a spring.
The energy stored in a spring at tension F, if it is stretched by a distance x, is $\frac{1}{2}Fx$, or $\frac{1}{2}kx^2$. The stiffness of the spring, k, is the force per metre stretch, and $F = kx$. $1/k$ is called the compliance of the spring, being the stretch for a 1 newton force.

The energy stored in a capacitor at p.d. V, if it has been given a charge Q, is $\frac{1}{2}VQ$, or $\frac{1}{2}\left(\frac{1}{C}\right)Q^2$. C is the capacitance of the capacitor, the charge per volt across it, and $V = \frac{Q}{C}$.

a If the distance a spring is stretched corresponds to the charge on a capacitor, what does the tension correspond to?
b What does the capacitance correspond to? (Not the stiffness.)
c In question 29 a sharply rising and falling voltage input to a circuit containing a capacitor produced a gently rising and falling output across the capacitor. The bigger the capacitance, the smoother the output, or, at any rate, the slower it rises and falls. A sharply rising and falling motion of the wheels of a car running over a rutted road will tend to make the car body, mounted on springs fixed to the axles, move up and down. What will be the effect of changing the springs for ones with a greater compliance?

Questions 31 to 36

These questions are about energy dissipated in alternating current circuits containing resistors or capacitors.

31 **a** What energy is dissipated every second in a resistance R, on average,
1 if a steady current I flows?
2 if a current I flows in short bursts, with gaps of no current in between, the gaps and bursts lasting equally long? (During a burst the current is steady.)
3 if current I flows in short bursts, first in one direction and then in the other, taking no time to change direction? (Again, the current is steady during a burst.)
b What steady current would dissipate energy at the same rate as the current I in **2**, which comes in bursts?
c Suggest a reason why the current in **b** is called the root mean square current.
d The alternating current from the a.c. mains varies as $\sin\theta$. Figure 53 is a sketch graph of $\sin^2\theta$, over one cycle. The two lots of shaded areas are equal. What is the average value of $\sin^2\theta$ over one cycle?

e What steady current would dissipate as much energy in a resistor as an alternating current of maximum value I?

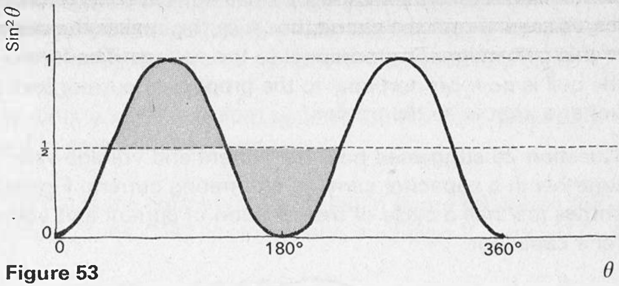


Figure 53

32 **a** This part is to be answered by guesswork, or 'intuition' as those who value the ability to guess right sometimes call it. A good steel spring is hit with a hammer, and the hammer flies back with as much energy as it had when going towards the spring. No energy is dissipated in this ideal spring, though the hammer energy was stored up temporarily in the spring. Now guess. How much energy is dissipated, warming up the capacitor or its surroundings as a lamp warms its surroundings, when a capacitor is connected to a supply of alternating current?

b When the alternating supply voltage across a capacitor is zero, the capacitor has no charge and no energy. When the supply voltage reaches its maximum, V, the capacitor has energy $\frac{1}{2}CV^2$. If the supply were cut off at this instant, could that energy be got out again?

c Now suppose that you connect a resistor across the capacitor, and cleverly vary it so that the voltage on the capacitor falls in exactly the way the alternating supply voltage would have decreased, had it continued. Where does all the capacitor energy go?

The energy given to a capacitor as the supply rises is given back to the supply as it falls.

33 An ammeter works because there is a force on a current in a coil placed between the poles of a magnet. The size of the force is proportional to the current, and it reverses direction if the current reverses.

The size of the force is proportional to the strength of the magnet. A wattmeter can be made by replacing the magnet with a fixed coil which carries a small current proportional to the voltage across the circuit, because this makes the strength of this coil-magnet proportional to the voltage. The force on the coil is now proportional to the product of current and voltage, that is, to the power.

Question 26 suggested how the current and voltage vary together in a capacitor carrying alternating current. Figure 54 shows just half a cycle of the variation of current and voltage for a capacitor.

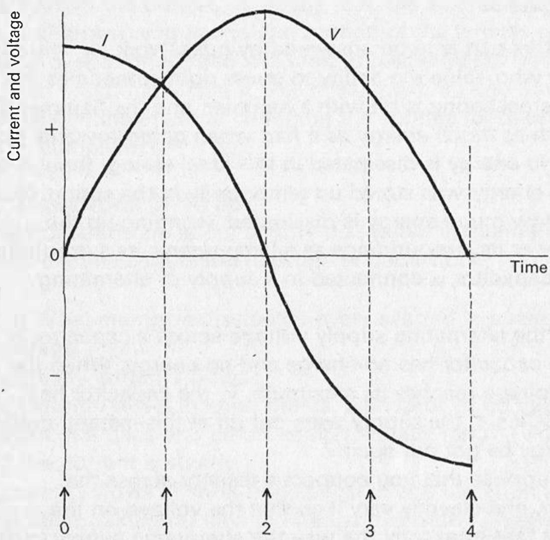


Figure 54

a Will there be a force on the wattmeter coil at time 2? Why?
b Will there be a force on the wattmeter coil at times 0 and 4? Why?

c At times 1 and 3 the magnetic field in the wattmeter will be exactly the same, for V has the same value at these times. How will any forces on the coil compare at these times?
d What does the average wattmeter reading seem likely to be, if it is set to measure the average power delivered to a capacitor by an alternating supply?
e Say what you think would be different if a lamp were now placed in series with the capacitor.

34 What is the current in the circuit in figure 55, when the deflection of the CRO spot indicates a voltage V across R?

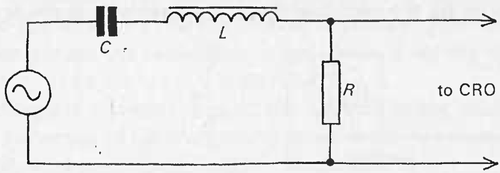


Figure 55

With $R = 10$ ohms and a voltage sensitivity of 0.1 V cm^{-1} the CRO shows a maximum deflection of 7.5 cm. What is the peak value of the current?

35 In figure 56, the oscilloscope's Y-sensitivity is set at 1 V cm^{-1}.

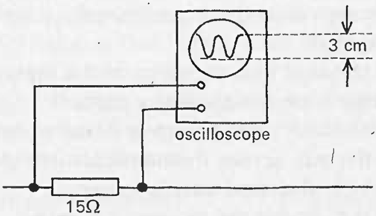


Figure 56

a What is the amplitude of the alternating voltage (the biggest voltage at any time during the cycle) across the resistor?
b What is the amplitude of the alternating current through the resistor?

c Does the biggest current flow through the resistor at the same instant that the biggest voltage is across it?
d What is the biggest rate at which electrical energy is used to warm up the resistor at any time during the cycle?
e What is the least rate at which electrical energy is used to warm up the resistor at any time during the cycle?
f Is there ever a time in the cycle when energy from the resistor is being transformed into electrical energy?
g What is the average rate at which electrical energy is used to warm up the resistor taken over many cycles? (Guess the answer if you are not sure.)

36 In figure 57 the oscilloscope's Y-sensitivity is set at 1 V cm^{-1}.

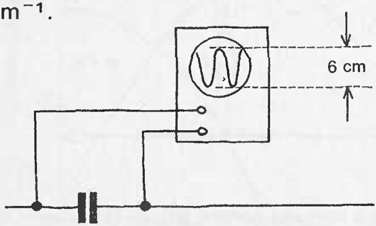


Figure 57

a What is the amplitude of the alternating voltage (the biggest voltage at any time during the cycle) across the capacitor?
b What is the voltage across the capacitor when the greatest charge at any time during the cycle is on the capacitor plates?
c When the greatest charge is on the capacitor plates, at what rate is the charge changing?
d What is the current 'through' the capacitor at the instant when the greatest charge is on the capacitor plates?
e What is the rate at which electrical energy is being transformed in the capacitor when the p.d. across the capacitor is 3 volts?
f What is the rate at which electrical energy is being transformed when the p.d. across the capacitor is zero?
g Is the energy stored in the capacitor increasing or decreasing while the p.d. across it is increasing?
h Is the energy stored in the capacitor increasing or decreasing while the p.d. across it is decreasing?
i What is the average rate at which electrical energy is being converted to other forms, taken over many cycles?

Questions 37 to 41

These questions are about circuits containing inductors and capacitors, and about electrical oscillations.

37 A capacitor is a circuit component that behaves like a spring. (See question 30.) An inductor is a circuit component that behaves like a *mass*. An inductor is a coil with little resistance, ideally with no resistance, often wound on an iron core. A current in the coil produces a magnetic field in the coil. If the current changes, the field changes. If the field changes, a *voltage is induced across the coil by electromagnetic induction.*

In an inductor, then, a *changing current* goes with a voltage across the coil. In a resistor, a steady current goes with a voltage across the resistor. In a capacitor, a steady charge goes with a voltage across the capacitor.

a If charge is analogous to displacement, while velocity is the rate of change of displacement, what is the mechanical analogue of electric current?

b How does the force F required to move a constant mass m depend on the rate of change of velocity dv/dt?

c For an inductor, the voltage V required to change the current I at the rate dI/dt is

$$V = L\,dI/dt.$$

where L is called the inductance of the coil.

To what mechanical quantity is the voltage analogous, for the analogy between a capacitor and a spring?

d What mass will require a force of 10 N to change its velocity at the rate 2 metres per second every second?

e What inductance will require a voltage of 10 V to change the current in it at the rate 2 coulombs per second every second (or 2 amperes per second)?

The unit of inductance, $V\ C^{-1}\ s^2$ is abbreviated to H, for henry, just as the unit of mass might be written $N\ m^{-1}\ s^2$, but is usually written kg, for kilogramme.

The inductance of a real coil is not necessarily constant, especially if the coil contains iron. For many purposes, the inductance of coils is constant enough for L to be a useful quantity, and for the analogy with constant mass to be a good one.

38 When the switch in figure 58 is closed, the current in the circuit rises to 0.5 A in the first 0.01 s. For this period, the rate of rise of current is very nearly steady. R is 0.1 Ω, and L has negligible resistance.

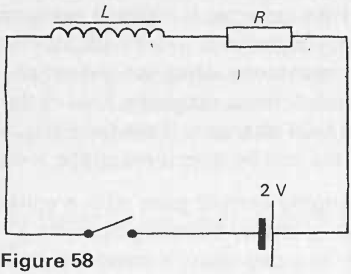


Figure 58

a What, approximately, is the inductance, L?
b How might the rise of current be observed?
c R is increased to 0.2 Ω and the experiment is repeated. Will the rate of rise of current double, halve, or be roughly the same as before?
d R is increased to 2 Ω. At what rate will the current rise initially? When the current is 0.5 A, will the current still be rising at a uniform rate? What will the rate of increase of current be at this stage?

39 Suppose that the input to the circuit of figure 59 is an alternating voltage of constant amplitude, but variable frequency.

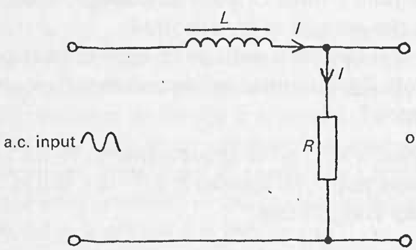
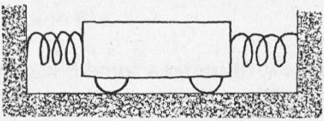
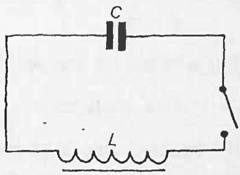


Figure 59

a If the frequency is doubled, what would happen to the maximum rate of change of the current drawn from the supply, if the maximum current stayed the same? (It does not, at constant voltage.)
b If R is small, nearly all the p.d. is across L, equal to the supply p.d. If this is unaltered, the rate of change of current must be the same as before, since V is given by $L\, dI/dt$. How can the rate of change of current be unaltered, though the frequency has doubled?
c If the maximum current has roughly halved, how has the maximum output p.d. changed?
d Why do you think such a circuit is often called a high frequency choke?



a



b

Figure 60

40 **a** Figure 60 *a* shows a trolley tethered between springs fixed to rigid walls. The trolley is pulled to one side, stretching and compressing the springs. The system has gained energy. Where is this energy?
b Figure 60 *b* shows a capacitor about to be connected across an inductor. The capacitor is connected to a battery, giving it a charge. The system has gained energy. Where is this energy?
c The trolley is released. What determines its initial acceleration?
d The switch is closed. What determines the initial rate of rise of current?
e In the middle position, is the velocity of the trolley constant, zero, or changing?
f When the capacitor has no charge is there a steady, a zero, or a changing current in the circuit?
g Because the trolley is still moving when the springs are not displaced, it soon does displace them. What effect does this have on the trolley's velocity?

h Because there is a current when the capacitor is uncharged, the capacitor soon becomes charged again. What effect does this have on the current?

i There comes a time when the trolley is at rest again, displaced from the centre by as far as it was to begin with, if there was negligible friction. How much energy has the system and where is this energy?

j There comes a time when the current is zero again, with the capacitor charged by as much as it was to begin with, if there was negligible resistance in the circuit. How much energy has the system, and where is it?

41 For a spring, if the spring has stiffness k, the tension F in it at extension x is

$$F = kx.$$

For a mass m, the acceleration $\mathrm{d}v/\mathrm{d}t$ under a force F is given by

$$F = m\,\mathrm{d}v/\mathrm{d}t.$$

If a mass is coupled to a spring, the frequency f of the oscillations is given by

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

For a capacitor, capacitance C, the voltage V across it when charge Q is on it is

$$V = (1/C)\,Q.$$

For an inductor, the rate of change of current $\mathrm{d}I/\mathrm{d}t$ under a voltage V is given by

$$V = L\,\mathrm{d}I/\mathrm{d}t.$$

If an inductor is connected to a capacitor, what expression might plausibly be written for the frequency of the electrical oscillations in the circuit?

Putting electronics to use

Different jobs the basic unit can do

The following is a list of different uses to which the basic unit can be put.

1 *Switch or inverter*

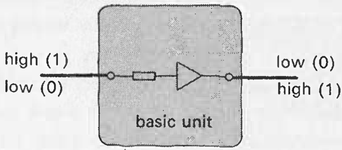


Figure 61a

2 *Squarer*

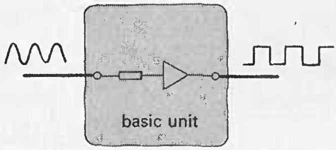


Figure 61b

3 *Nor-gate with two inputs*

Input 1	**Input 2**	**Output**
0	0	1
0	1	0
1	0	0
1	1	0

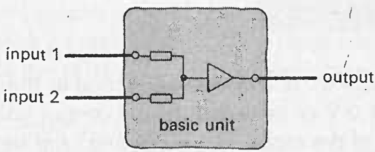


Figure 61 c

4 *Pulse producer or timer*

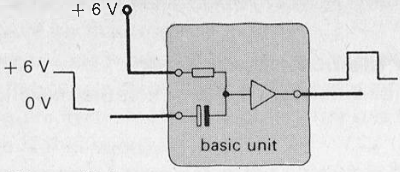


Figure 61d

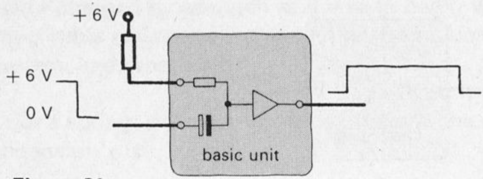


Figure 61e

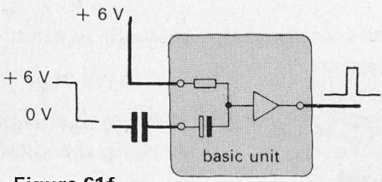


Figure 61f

To lengthen the output pulse, add a resistor, as in figure 61 *e*. To shorten the output pulse, add a capacitor, as in *f*.

5 *Voltage amplifier*

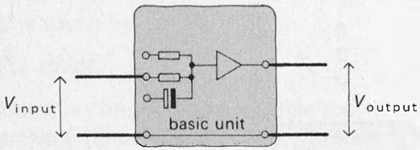


Figure 61 g

If the input voltage, figure 61 *g*, is somehow varied in the narrow range 0.5 V to 1.0 V or thereabouts, the output voltage is an amplified version of the input. The input need not be fed to a resistive input, but can go to the capacitative input of the basic unit. This will make it necessary to apply some steady voltage to one resistive input as well, since the mean level of the input through a capacitor, which does not pass direct current, is bound to be zero, while the input as a whole must average above zero for the unit to act as an amplifier. One of the practical problems suggested in the next list is about achieving this.

Practical jobs to try, using basic units

This is a list of things to try in the laboratory. Some of the combinations of basic units: the bistable, astable, the *and*-gate and amplifier will be used a good deal in later work.

a *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.

b *Make a lamp go on from a + 6 V input*

Use two basic units to make a lamp come *on* when the input to one unit goes from 0 V to +6 V.

c *Make a lamp flash on for a moment from an input rising from 0 V to +6 V.*

d *Make short sharp spikes*

Turn an alternating supply into short sharp 0 V to +6 V and back spikes. It helps if you square the input first.

e *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.

f *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, to test the system.)

g *Make an or-gate*

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

h *Make a bistable system*
Two units can be interconnected 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. Make such a system.

i *Make a system 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.

j *Make an astable that produces an audible tone*
Speed up the astable (**i**) and make it produce a tone in an earpiece.

k *Make an and-gate*
Use three basic units to make a system that has two inputs, and one output that is high only when both of the inputs are high.

l *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 output can be obtained if the input is allowed to vary over the right range by controlling the current to another input. Recall the graph, figure 38, of input voltage against output voltage.

m *Hard. Make a monostable circuit*
Half way between the bistable (**h**) and the astable (**i**) there is a system made of two basic units, in which one unit is on (output high) whenever the system is undisturbed by inputs from outside, but in which the other unit can be switched on for a short time by a suitable input to the system.

n *Hard. Make an amplifier with two stages of amplification*
Add another stage to the amplifier (**l**).

o *Hard. Investigate the effect of strong negative feedback on an amplifier*
See what the system in figure 62 does when it is given step-like inputs going from 0 V to +6 V and from +6 V to 0 V. Try square pulses and sinusoidal input too.

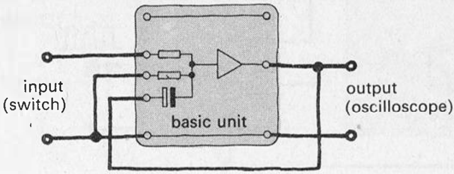


Figure 62

p *Hard. Make a parity, or 'same' gate*
Three basic units make an *and*-gate (**k**). The electronics kit contains an *and*-gate module with this combination inside it. Use an *and*-gate module and three more basic units to make a system that gives a high output only when both of two inputs are the same, that is, both high or both low. Question 18 nearly gives an answer.

Five ways of making square pulses

The diagrams in figure 63 show circuits for making square pulses, long and short, single and in trains. They will be useful for feeding pulses into circuits containing capacitors, resistors, and inductors, to see how these circuits modify the pulses.

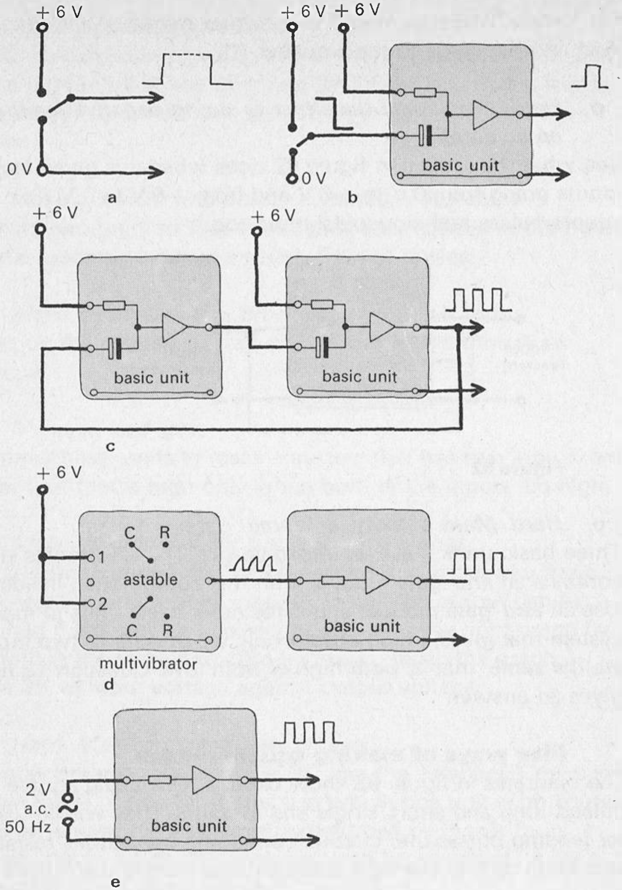


Figure 63
Five ways of making square pulses.
a Switch.
b Basic unit as a pulse producer.
c *Two basic units as a slow astable.*
d Fast astable, squared with a basic unit.
e Basic unit squaring a sinusoidal input.

Suitable component values for *RC* and *LR* circuit experiments

If you supply square pulses from the sources shown in figure 63 to circuits containing resistors and capacitors or inductors, it is convenient to start off with component values for which the circuits behave interestingly. Figures 64 and 65 suggest such values, for several possible circuits, and for different rates at which pulses are supplied. Of course you should vary the sizes of the component values. These figures are just meant to help you to start.

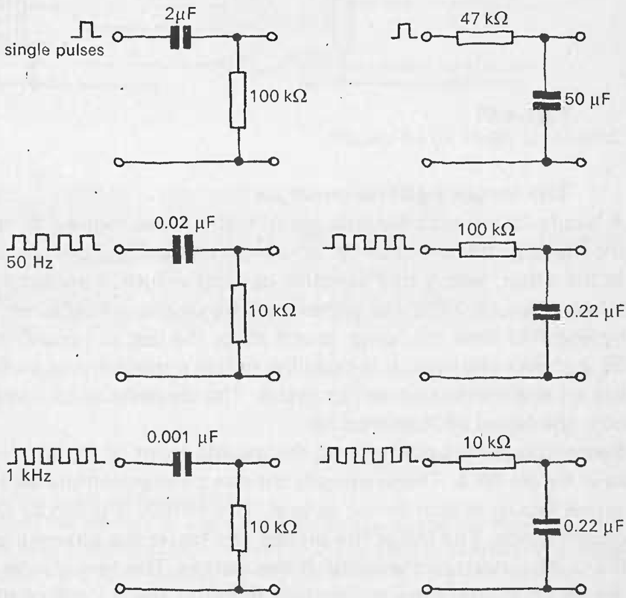


Figure 64
Component values for *RC* circuits.

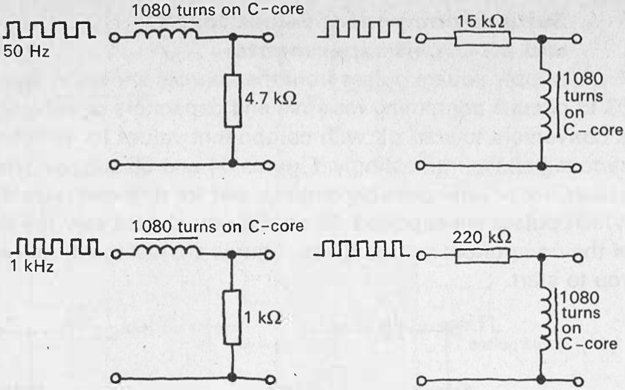


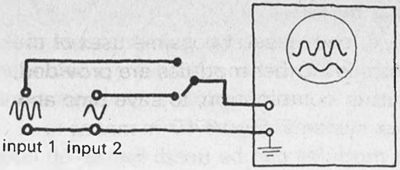
Figure 65
Component values for *LR* circuits.

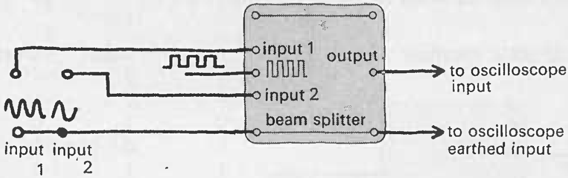
The beam splitter module

A single-beam oscilloscope could display two signals at once if the input to the beam could be switched rapidly from one signal to the other, taking tiny samples of each in turn. If samples are taken often enough, the signals will be displayed quite well, not having had time to change much since the last sample. Figure 66 *a* shows the idea. It is possible to use a mechanical switch, but an electronic one can be faster. The electronics kit contains one, the beam splitter module.

Switching pulses are fed into the middle input of the module, as in figure 66 *b*. These operate diodes connecting the two signal inputs in turn to the output. The output is taken to an oscilloscope. The faster the pulses, the faster the alternation of the connections of the input to the output. The two inputs to the beam splitter have a common terminal, the 0 V rail of the module, also shared with the output. If the sources have earthed terminals, these should be joined to this common terminal, as should the earthed input terminal of the oscilloscope.

Figure 66 *c* shows how square switching pulses can be supplied to the beam splitter module. A multivibrator module, with both its switches to ' C ', and its two inputs (not the trigger input) joined to the +6 V rail, acts as an astable, emitting pulses at about 2.5 kHz. A basic unit squares the pulses, and passes them on to the beam splitter module.





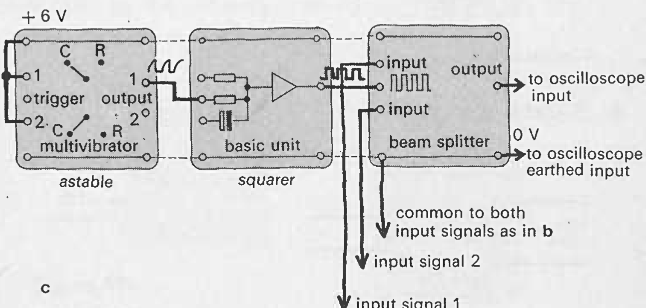


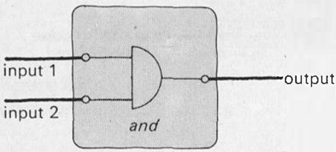
Figure 66
Uses of the beam splitter module.
a A switch mechanism for a two beam display (a means, not shown, is needed to keep the two displays apart on the screen). **b** Connection of inputs to the beam splitter. **c** Supply of switching pulses to the beam splitter.

Neither input signal may exceed about 1 V amplitude, or part of it will be clipped off, because the whole display on the screen can only represent a few volts from top to bottom. Varying the oscilloscope gain will not only alter the vertical size of each trace, but will also alter the space between the traces. If the gain is turned up to inspect a small signal on the lower trace, the upper trace will be off the top of the screen.

Electronic building bricks

Figure 61, pages 75 and 76, shows several possible uses of the basic unit from the electronics kit. Other modules are provided, mostly containing basic units in combination, to save time and trouble in making complex systems. Figure 67 is meant to remind you of how these modules can be used. Figure 68 adds some circuits containing resistors, capacitors, and inductors, which can also be used as parts of systems.

a *And-gate module*



Input 1	Input 2	Output
0	0	0
0	1	0
1	0	0
1	1	1

Figure 67a

b *Bistable module*

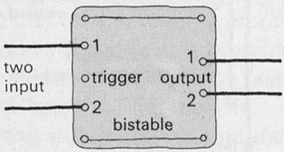


Figure 67b

Outputs 1 and 2 go alternately high and low as pulses are fed to inputs 1 and 2 in turn.

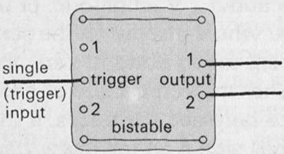


Figure 67c

Outputs 1 and 2 go alternately high and low as pulses arrive in sequence at the trigger input.

c *Multivibrator module*

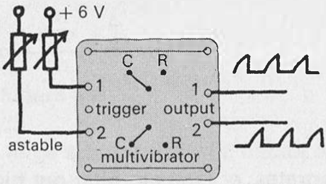


Figure 67d

A chain of pulses emerges from each output. The frequency is controlled by the resistors connected to the inputs. The switches must be at C.

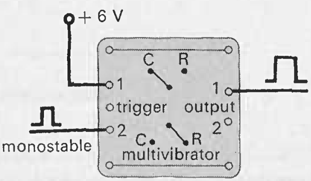


Figure 67e

A pulse of fixed length emerges from the output when any rising pulse comes to the input. One switch is at C, the other at R.

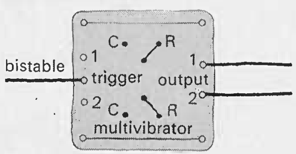


Figure 67f

With the switches at R, the module behaves exactly like the bistable module.

Useful *R, C, L* circuits for parts of systems

1 *Integrating RC circuit*

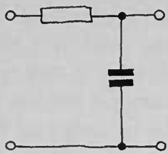


Figure 68a

If *RC* is large, the circuit integrates, or tends to filter out high frequency signals.

2 *Differentiating RC circuit*

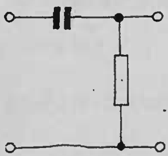


Figure 68b

If *RC* is small, the circuit differentiates, or tends to block low frequency signals.

3 *Integrating LR circuit*

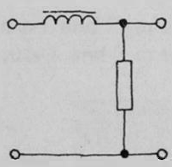


Figure 68c

If *R* is small and *L* large, the circuit integrates, or tends to block high frequency signals.

4 *Differentiating LR circuit (not much used)*

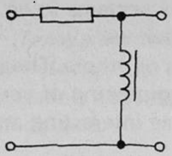


Figure 68d

If R is large and L small, the circuit differentiates, or tends to filter out low frequencies.

5 *Oscillating or resonant parallel LC circuit*

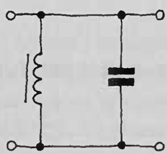


Figure 68e

The circuit oscillates, with frequency given by $2\pi f = \sqrt{1/LC}$. There is a large voltage across it and only a small net current through it at the resonant frequency.

6 *Series LC circuit*

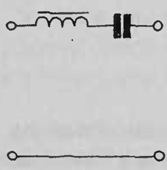


Figure 68f

The circuit may be useful. It has a small voltage across it for a large current through it at the resonant frequency f, also given by $2\pi f = \sqrt{1/LC}$.

Building electronic systems

Using the electronic building bricks shown on pages 84–7, it is possible to construct a very large number of systems to do a wide variety of jobs. The suggestion below will, we hope, start you off. No doubt you will think of others. The idea is to let you try some electronic systems engineering of your own, trying to build a system that does some interesting and potentially useful job.

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

2 *Make a low pass filter*
A device to reduce the high pitched scratching sounds from a worn record is wanted.

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.

4 *Make a crossover filter*
A device that passes high frequencies to one loudspeaker ('tweeter') and low frequencies to another ('woofer') is wanted.

5 *Make a bleeper that emits an audible tone when a button is pushed and released*

6 *Make a binary adder*
Use three bistables and three indicators to make a binary counter, to count from 0 to 7 pulses.

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.

8 *Make six flashes in a row*
A device that emits just six short flashes after a button is pressed is wanted.

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

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

11 *Illumination control or warning*
Use a photo transistor to produce a warning tone when the light level is low. Then try high.

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

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.

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

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

16 *Sound operated lamp*
Make a lamp come on in response to a sound.

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

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.

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.

20 *Blind student's illumination meter*
This system is similar to the one for **19**.

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.

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

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.

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.

25 *Traffic lights*
Make red, amber, and green lamps flash in traffic light sequence.

26 *Decoding binary numbers*

A binary counter (see **6**) produces an output 0 to 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.

27 *A binary adder*

Make a system to add the two digits A and B together to give a SUM and a 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 =	0	and	1

28 *A ring counter*

A way of counting pulses is to make them light lamps in rotation. If there are ten lamps numbered 0 to 9, one has 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).

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 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 experiment would be to discover what rate of success is achieved, and how many trials are needed to attain a given success rate.

30 *Playing tunes*

The electronics kit can be used to play tunes. One can either make a simple organ with a keyboard (switches or push buttons) controlling a series of notes, or one can arrange that a system itself selects notes of the proper pitch, duration, and sequence to play a tune.

To our knowledge, systems so far built with the kit have played the call-sign 'B–B–C', and the first lines of 'Colonel Bogey', 'Three blind mice', and 'Oh, come, all ye faithful'.

Answers

1 a Suppose the numbers are 1342 and 5768. Select the end digits of each number (2 and 8). Add them; there is no carrying to do yet. The sum is 10. Store the digit 0 as the first digit of the answer, and carry the digit 1 to the next step. Select the next two digits (4 and 6). Add them, and the 1 carried over, getting 11. Store 1 and carry 1. Then continue. A better system would have a stopping device that turned the adding process off when all of the incoming digits (carry as well) became zero. Without it a mindless computer would go on for ever, producing the answer (to be read from the right)

........000000000000000000000000000000000007110

b When the clock reaches a preset time it switches on the power to a heater immersed in cold water. When the water boils, the heater is switched off. The water-boiling signal also operates a device that pours the water onto the tea leaves. After a suitable delay for the tea to infuse, a 'tea ready' alarm is rung. The human part of the system then adds milk and sugar.

c Figures 69 to 72 show systems, or parts of systems, to do the suggested jobs.

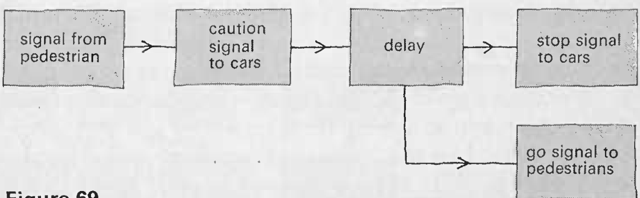


Figure 69
Part of a system for controlling cars. Other parts should be added to operate go and stop signals for cars and pedestrians.

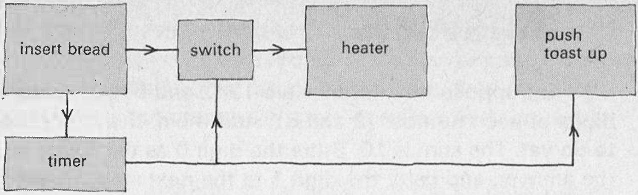


Figure 70
A system for a 'pop-up' toaster.

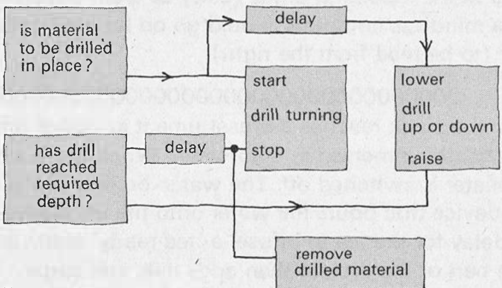


Figure 71
A system for drilling holes.

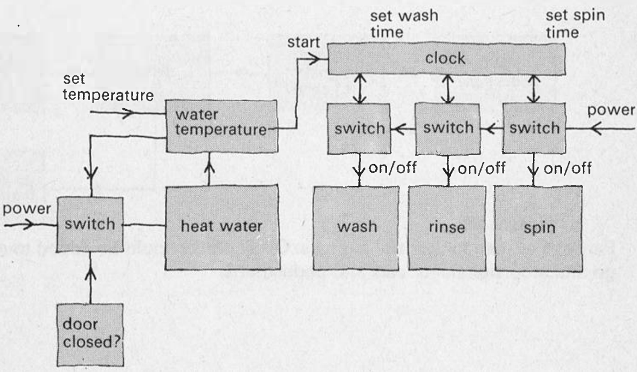


Figure 72
A system for an automatic washing machine.

2 The two blocks marked 'amplifier' make the signal larger, presumably adding to the energy it carries, and so they require a source of external energy, which comes from the power supply. The job of the amplifier is to arrange that this extra energy is added to the signal without changing the pattern of the oscillations. Both amplifiers, and no other parts of the system, are directly connected to the power rail.

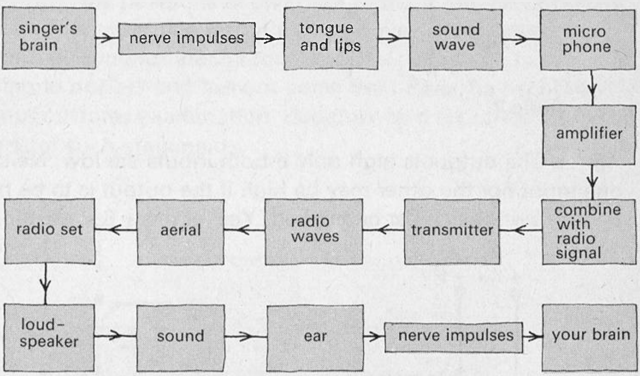


Figure 73

3 Figure 73 shows a series of things happening to the song.

4 Apart from a lamp, figure 1 contains only resistors, transistors, and capacitors. Figure 3 adds to these switches a relay device (the box with a cross on it), one or two diodes, and the counting tubes. Resistors, capacitors, and transistors are in the majority. Figure 5 again consists entirely of these three components.

Most mains operated devices also contain a transformer, and coils (transformers or inductors) are to be found in such devices as radio sets and transmitters.

What is remarkable is the smallness of the number of components involved in doing so many different jobs.

5

Symbols		Input	Output
+6 V	0 V	+6 V	0 V
		0 V	+6 V
high	low	high	low
		low	high
X	0	X	0
		0	X
1	0	1	0
		0	1
T	F	T	F
		F	T

Table 7

6 **a** The output is high only if both inputs are low. Neither one input nor the other may be high if the output is to be high.
b Both switches must be marked 'Yes' at the +6 V position.

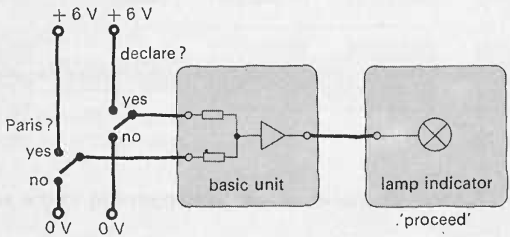


Figure 74

Figure 74 shows a suitable system. The table of inputs and outputs can be set out in many equivalent forms other than that given in the question. For example:

I have something to declare	I have come from Paris	He may proceed
No	No	Yes
No	Yes	No
Yes	No	No
Yes	Yes	No

Table 8

or:

Input 1	Input 2	Output
0	0	1
0	1	0
1	0	0
1	1	0

Table 9

Such tables are called 'truth tables', even though they often record only the positions of switches or the presence of pulses, because they were first introduced as a way of analysing how the truth of complex statements like, 'If a passenger has nothing to declare and has not come from Paris, he may proceed without customs examination' depends on the truth or falsity of parts of such statements.

7

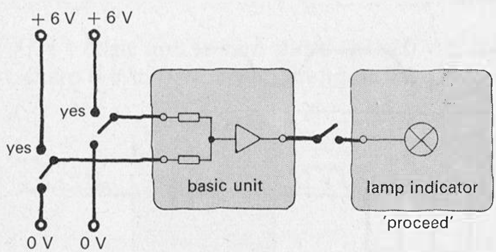


Figure 75

Figure 75 shows a way of inserting a switch to achieve the desired result. At some stage in Unit 6 you will use an electronic device that tests whether both of two signals are present.

8

A	B	C	D	E
0	0	1	1	0
1	0	0	1	0
0	1	1	0	0
1	1	0	0	1

Table 10

The system gives a high output only when both A *and* B are high. It is called an *and*-gate, while the basic unit might be called a *neither-nor*-gate, usually *nor*-gate for short.

'*And*' was what was needed in question 7. *And*-gates have an interesting use in computer arithmetic, done in the binary number scale in which 0 1 2 3 4 ... reads 0 1 10 11 100 ..... . The sum 1+1 =2 becomes, in binary form, 1+1 = 10. In question 1, you may have considered the sum and carry digits produced when two digits are added. In 'ordinary' arithmetic, 7 + 7= 14, and 4 is the sum digit while 1 is the carry digit. In the binary sum of two digits, the carry digit is only 1 if both digits to be added are 1s. The *and*-gate is just what is needed to calculate this digit, if 1s are represented by +6 V pulses and 0s by no pulses.

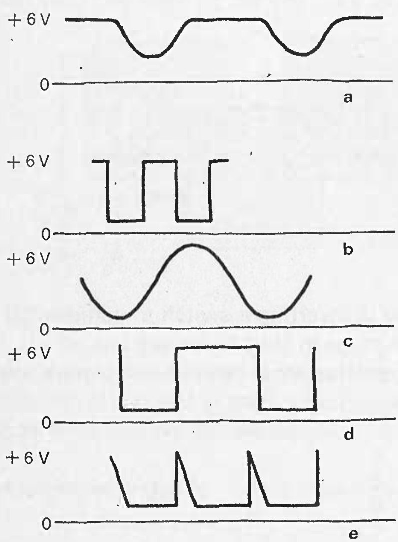


Figure 76

9 a **1** Nearly 0 V.
2 About +2 V.
3 +6 V.
b 1 about +2 V.
2 Nearly 0 V.
3 About +2 V.
4 +6 V.
5 +6 V.
6 +6 V.
c The sinusoidal input comes out square.

10 See figure 76.

In *c*, the unit is an amplifier; in *d* it is a squarer or clipper.

11 Use a basic unit to turn short, sharp 0 V to 6 V pulses into short, sharp 6 V to 0 V gaps, as in figure 77.

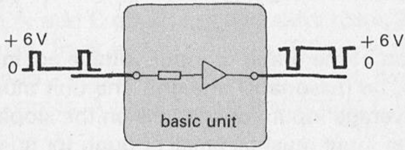


Figure 77

12 a The capacitative input (bottom one).
b A short while after input 1 goes from high to low, output 2 goes from low to high, stays there a short while, then goes low again, as in figure 78.

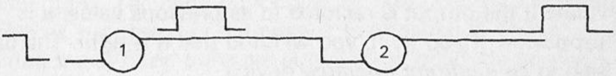


Figure 78

c When the output of 2 is fed back to the input of 1 the circuit oscillates. The end of the pulse emitted by 2, coming back to the input of 1, starts the process over again, then again, and so on.

13 See figure 79.

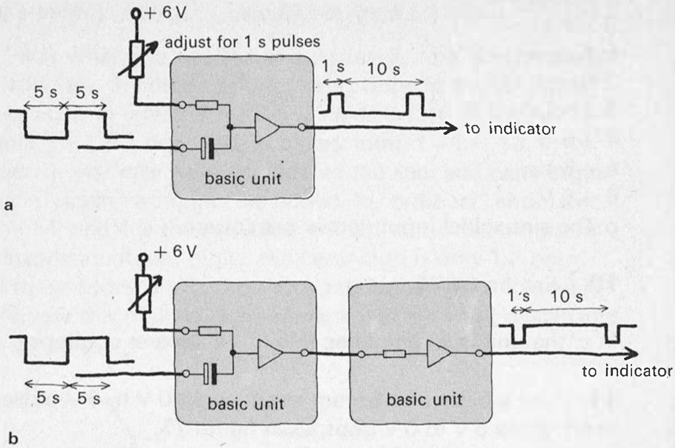


Figure 79

14 The sloping part of the graph of input voltage against output voltage must be reasonably straight. The unit must be biased so that the average input voltage falls on the sloping part of the curve. The input must be small enough for no part of the input voltage, plus bias, to fall outside the sloping part of the curve.

15 Try putting extra resistance in series with the input, and keeping the input voltage the same. If the output stays constant (as it would for the electrometer for example), **b** is supported. If it falls, try raising the voltage until the current has its former value. If the output is restored to its previous value, **a** is supported. If you try it, you will find that a is right. The unit is said to be a *current operated* device.

16

A	B	C	D
0	0	1	0
0	1	0	1
1	0	0	1
1	1	0	1

Table 11

D is high if A or B is high, or if both are. The term *or*-gate comes from the condition for D to be high, if A *or* B is high *or* both are.

17 If A is low, C is high.
If C is high, D is low.
If D is low, and fed back to A, which is low, no change occurs.

If A is high, C is low.
If C is low, D is high.
If D is high and is fed back to A, which is high, no change occurs.

If B is made high, C goes low, and D goes from low to high. If D is fed back to A, which was low, A goes high too, to be the same as D. Now A is high, D is kept high, and the system has 'flipped' over into a new state.

To make A low again, give the second basic unit a high input, alongside its other input C. D goes low, A goes low since D is fed to A, and C goes high and stays there. The system has 'flopped' back to where it was. This is sometimes called the 'flip-flop' circuit, or the bistable circuit, because it has two stable states, A high, C low; and A low, C high.

18 a

A	B	C	D	E
0	0	1	0	0
0	1	0	0	1
1	0	0	0	1
1	1	0	1	0

Table 12

b The system could be used to generate the sum digit of a pair of binary digits. The carry digit could be produced by a separate *and*-gate as suggested in the answer to question 8. These combinations of basic units are sufficient to build the adding-numbers system suggested in question 1, though for binary numbers, not numbers in the scale of ten, as in that question.

19 When the input to the first unit rises, the output from it drops. This input to the second unit makes its output rise, stay steady for a time, and then fall (see figure 80). The output from the first unit would have risen again, when the short input pulse finished, except for the fact that the output pulse from the second unit is taken round to the input of the first. This holds the first unit on (its output low) until the output pulse is finished. The system emits a pulse of standard height and length as each input pulse arrives. It is useful for reshaping pulses to a standard shape, particularly in computers where pulses represent digits in binary arithmetic, and may become flattened or rounded as they pass through the various devices adding, combining, or delaying them.

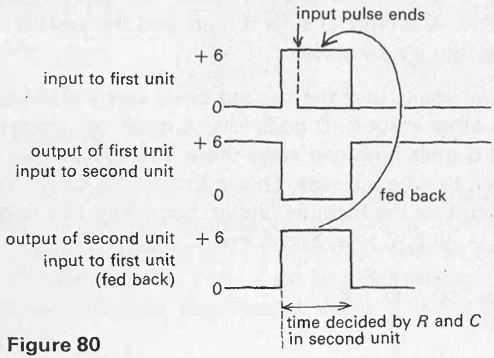


Figure 80

20 If the input of the first rises, its output falls, and the output of the second, to which this is the input, rises.

If the input of the first unit rises a little, the fed back output of the second unit makes it rise further, and then further. Ultimately, the inputs and outputs are driven as far as they can go, usually to 0 V or +6 V if that is the power supply voltage.

21 Two sorts of thing happen, at least. Thinking there will be a shortage, people buy more than they usually do, to stock up. This either produces an actual shortage, or a stronger belief that there will be a shortage, and people buy even more. Soon the belief that there will be a shortage generates a shortage. Also, even if the shop rations people, more people are likely to buy, and more and more buy as they hear of the coming shortage or see the queue, again reinforcing the effect of an initial apparent shortage.

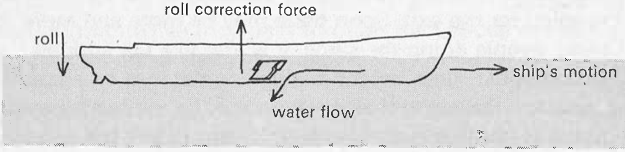
It is all rather like one man in a building shouting 'fire' and running for the exit. Soon there may be more and more and more people doing the same. It is also like the sudden catastrophic 'runs' which happen sometimes on a country's currency. Believing that its value may be reduced (devalued) in terms of another currency, people start to sell the currency so as not to be holding too much if the value goes down. If there are many sellers and few buyers, a reduction in price looks to be more necessary. So more sell, which makes yet more think the price will come down, and so on. The run can sometimes only be stopped by reducing the price of the currency – the very change that was expected, produced by that expectation.

Positive feedback like this is used in electronic circuits. It will tend to drive the input and output of the circuit as high or low as they can go. Often it makes a circuit oscillate from one extreme to the other.

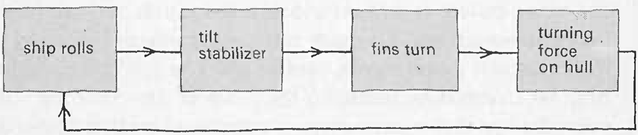
22 **a** The voltage across QO is over 0.5 V and is fed back to the input, which rises.
b The voltage across QO goes under 0.5 V, so the input tends to go down.
c The output is 3 V, the voltage across QO is 0.5 V, which is fed back to the input, which is already at 0.5 V. Nothing happens.
d The voltage across QO goes over 0.5 V, which sends the input up.

23 The leading edge of the stabilizer on the side that rolls downward must turn up so that water flowing against its tilted surface pushes the ship upright. The fin on the upward rolling side must twist so that its leading edge goes down, and water flowing over it pushes that side of the ship back downwards.

If the fins twisted the wrong way, a small roll of the ship would be amplified, and might turn it right over. To stabilize, the feedback must be negative, a roll producing a change that reduces the roll.



a



b

Figure 81
a Direction of twist of a stabilizer (see also figure 47, page 59).
b The roll correcting system.

24 No, it will not work. The stabilizers take effect just as the ship has, 30 seconds later, rolled over to the other side, where their effect is to make the roll worse, not correct it. Delay can often be fatal to a negative feedback control system.

25 **a** $1-x$.
b $m(1-x)$.

c $\dfrac{m(1-x)}{p}$.

d $x = \dfrac{m(1-x)}{p}$ so that $x = m/(p+m)$.

e 1000/1010 mV = 0.99 mV.
f 1 − (1000/1010) mV = 1/101 mV.
g 1000 (1/101) mV = 9.9 mV.
h Yes. It should be, since **g** is the output, and **e** is the feedback voltage, 1/10 of the output.
i 1 mV input from outside emerges as 9.9 mV output. The system gain is 9.9.
j Replacing 1000 by 500 for *m* gives 9.8 mV for the output if the the input is 1 mV. The gain is now 9.8.
k About 1 per cent.
l In the system above, if the amplifier gain fell from 1000 to 500 as the frequency was increased, the system gain would fall by only 1 per cent. The effect of negative feedback is to extend the frequency response of an amplifier, at the price of reducing its gain. Engineers call it 'trading gain for bandwidth'.
m The system with negative feedback will need more stages of amplification to achieve the same gain, and so will be more expensive, quite apart from the cost of the extra feedback components. Everyone who buys a good quality record player amplifier pays this price, which is worth paying for the flat frequency response, and for the greater freedom from distortion that negative feedback also provides.

26 a When $V = +10$ V, $Q = 10^{-3}$ C.
When $V =$ zero, $Q =$ zero.
When $V = -10$ V, $Q = -10^{-3}$ C (this is time t_0).
See figure 82.

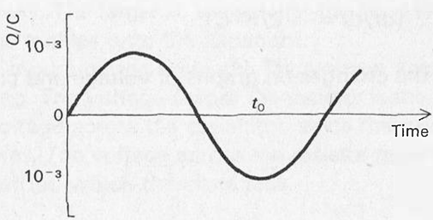


Figure 82

b The current I has a maximum when the rate of change of charge, dQ/dt, is greatest. The current is a minimum when the rate of change of charge is (momentarily) zero, which happens as the charge goes past its greatest value (of either sign). See figure 83. At t_0 the current is zero.

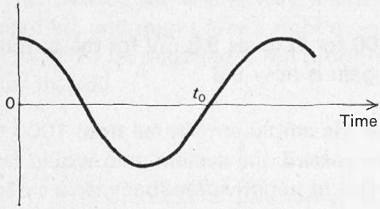


Figure 83

c To estimate the magnitude of the current, the time scale would be needed. For example, if the complete oscillation took 0.04 s, the charge would rise and fall from zero to its greatest magnitude in 0.01 s, requiring an *average* current of 10^{-3} A.

27 a Zero.
b Zero.
c 1.5 V.
d 10^{-4} A. ($I = V/R$.)
e 10^{-4} A or coulombs per second. ($dQ/dt = V/R$.)
f 0.1 V s^{-1} ($dV/dt = V/RC$).
g 0.1 V s^{-1} ($dV/dt = -V/RC$).
h 6.7×10^{-6} A s^{-1} ($dI/dt = -V/R^2C$).

Figure 84 shows the changes on graphs of voltage and current against time.

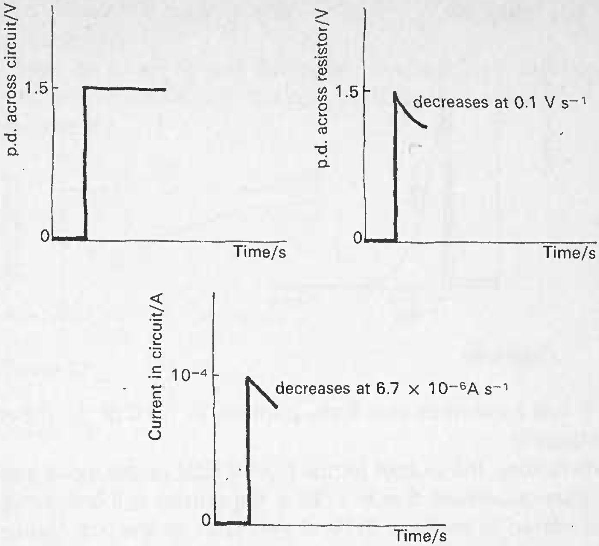


Figure 84

28 a Equal to the input V.
b V/R.
c Zero.
d Slowly. The current I starts by being V/R. The bigger the capacitance, the slower this steady trickle of charge raises the p.d. across the capacitor, which is equal to Q/C when charge Q has been delivered.
e Slowly. The larger R, the smaller the current I, and the slower charge trickles onto the capacitor.
f The input voltage is steady. The voltage across the capacitor is rising. The voltage across the resistor is the input voltage less the voltage across the capacitor, since the two components are in series. The voltage across the resistor must be falling. It is the output, which therefore falls.

g See figure 85.

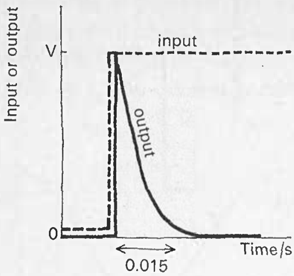


Figure 85

h It will have risen very little, perhaps to 1/10 of the input voltage *V*.

i As before, the output jumps from 0 to V as the input goes on. It then decreases. But in 1/10 s, the output will only have decreased to perhaps 9/10 of the input, as the p.d. across the capacitor has only risen by about 1/10 of the input. The output looks like figure 86.

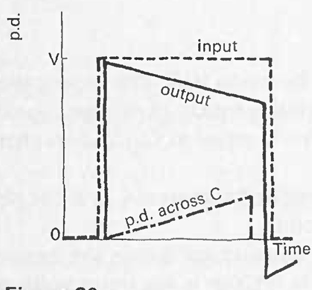


Figure 86

29 a Zero.

b *V*.

c *V*/*R*.

d The output will rise, as the p.d. across the charging capacitor rises.

e The p.d. across the resistor falls.

f The current falls.

g The capacitor charges, and the input rises, but more and more slowly as the current falls. In the end, the output reaches the input voltage *V*.

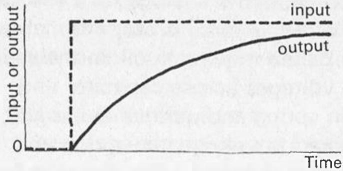


Figure 87

h See figure 88.

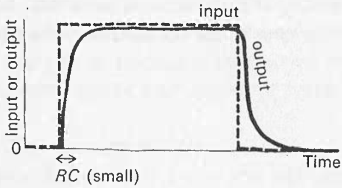


Figure 88

i The output will have risen to perhaps 1/10 of the input. Since the p.d. across *R* will hardly have fallen (down to 9/10 V) the current will have remained nearly steady, and so the p.d. across the capacitor will have risen almost linearly, as charge trickles onto it at an almost constant rate.

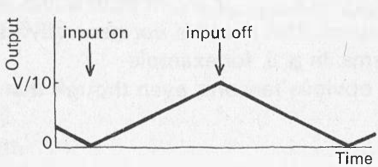


Figure 89

30 a The voltage across the capacitor.
b The compliance.
c The car body will move up and down less far, and rise and fall more slowly.

To draw out the full analogy involves some subtleties, which there is no room to develop here. The analogy for a resistance is a damping device whose frictional force is proportional to velocity of motion – like a piston moving in oil. In the series circuit of question 29, the voltages across capacitor and resistor add. If the forces in spring and damper are to add, as they must if force is compared to voltage, the spring and damper must be in parallel, not in series. (The forces in ropes pulling in one line are all equal, and do not add up. Forces in ropes pulling side by side on the same thing do add up.) In the circuit, the inputs and outputs are voltages. In the spring and damper for a car, the interesting inputs and outputs are displacements, not forces. So one must be careful in using the analogy.

31 a 1 I^2R.
2 $I^2R/2$.
3 I^2R.
b $I/\sqrt{2}$.
c Its square is the average, or mean, of the square of the varying current. So it is the root of the mean of the square of the varying current. The usual abbreviation is r.m.s.
d 1/2.
e $I/\sqrt{2}$.

Note. It happens that $I_{\text{r.m.s.}} = I_{\text{maximum}}/\sqrt{2}$, in both **b** and **e**, though for different reasons. This result is *not* generally true for all varying wave forms. In **a 3**, for example $I_{\text{r.m.s.}} = I_{\text{maximum}}$ for fairly obvious reasons, even though the current 'alternates'.

32 a 'None' is the obvious guess, if only from the way the question was put.
b Yes, by connecting it to a lamp or a motor, for example.
c All the energy is dissipated in the resistor. Of course, it doesn't matter how the voltage falls, whether quickly or slowly, linearly or sinusoidally. We suggested the sinusoidal variation to make it seem more like the case where the capacitor is connected to an alternating supply.

33 a No, the current is zero.
b No, the voltage is zero, so the coil is not in a magnetic field.
c The forces are equal and opposite, as the current is the same size at both times but reverses its direction.
d Zero.
e The wattmeter would give a reading. It must, as the lamp would light and would be dissipating energy. If it does, the current and voltage across the two together can no longer have the phase relationship shown in figure 54, for that phase relationship gives zero average force on the wattmeter coil.

34 The current is V/R.
If the deflection is 7.5 cm, the voltage is 0.75 V. The current is 0.075 A.

35 a 1.5 V. (Not 3 V, which is the peak to peak voltage.)
b 0.1 A.
c Yes.
d 0.15 W.
e Zero.
f No.
g 0.075 W.

36 a 3 V.
b 3 V.
c Zero.
d Zero.
e Zero.
f Zero.
g Increasing.
h Decreasing.
i Zero.

37 a Velocity.
b $F = m\,dv/dt$.
c Force.
d 5 kg.
e 5 henries, written 5 H.

38 a The p.d. across R is only 0.05 V when the current is 0.5 A, so the p.d. across L is very nearly 2 V. The rate of rise of current is 50 A s^{-1}, so the inductance is 2/50 H, or 0.04 H, approximately.
b Connect an oscilloscope across R.
c The p.d. across R when the current is 0.5 A is still only 0.1 V, so that the p.d. across L is still not much under 2 V. The rate of rise of current will be much the same.
d When the current is 0.5 A, the p.d. across R is 1 V, leaving only 1 V across L. The rate of rise of current must now be about half what it was when there was nearly 2 V across L, being now about 25 A s^{-1}.

39 a The same maximum current would have to be attained from zero in half the time, so the rate of change of current would have doubled.
b The time for the change of current has halved; to keep the rate of change constant, the maximum current must have halved, so that half the change happens in half the time, at the same rate.
c The maximum output p.d. is the maximum p.d. across R, which is IR if I is the maximum current. As the latter has halved, so has the output p.d. Of course this only works out so simply if R is very small, so that IR is not an appreciable part of the input p.d. Nevertheless, the output as a fraction of the input always falls as the frequency is raised, in this circuit.
d Less of a high frequency input appears across the output, than of a low frequency. The high frequencies are 'choked off'. The circuit is used to discourage unwanted mains frequency voltages from mixing with steady (zero frequency) voltages in devices which draw their power from the a.c. mains.

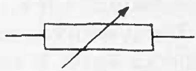
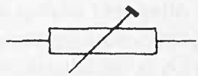
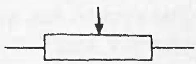
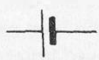
40 a Stored in the springs.
b Stored in the capacitor.
c The force exerted by the springs and the mass of the trolley.
d The voltage across the capacitor and the inductance of the coil.
e The velocity is momentarily constant, because there is no net force on the trolley.
f The current is momentarily constant, because there is no voltage across the coil.
g The springs begin to exert a force, slowing down the trolley.
h A voltage builds up across the capacitor, and the current decreases.
i The system has as much energy as before, stored in the springs again. If energy is conserved, one could infer that the trolley had energy equal to the total energy, when it was in the centre position, and the undisplaced springs had no energy. This is, of course, the trolley's kinetic energy, $\frac{1}{2}mv^2$.
j The system has as much energy as before, stored in the capacitor again. If energy is conserved, one could infer that the inductor had energy equal to the total energy, when the capacitor was uncharged and had no energy. The energy of an inductor is the electrical analogue of kinetic energy, and is given by $\frac{1}{2}LI^2$.

41 $2\pi f = \sqrt{1/LC}$.

Information and data

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 here.

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

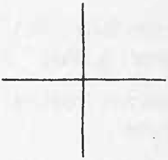
galvanometer

Signal lamp

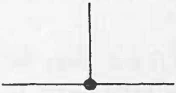
Lamp for illumination

Wires, junctions, terminals

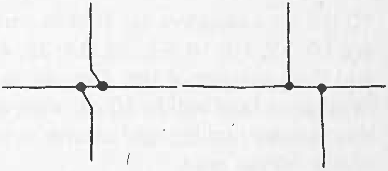
crossing of wires, no electrical contact



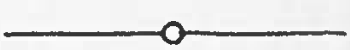
junction



double junction



terminal



Coding for values of resistors

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 90.

Figure 90

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 in place of R for Ω, or M for MΩ, again in place of R. 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.

Time constants of circuits

RC circuits

The discharge of a capacitor through a resistor follows the equation

$$Q = Q_0 e^{-t/RC}$$

The product *RC*, whose units are seconds, is called the time constant of the circuit. After a time equal to *RC*, the charge Q has fallen to a fraction e^{-1} of its original value Q_0; that is, to 0.37 or 37 per cent of this value. After a time $2RC$ the charge has fallen to 13 per cent of its original value; after $3RC$ to 5 per cent, and after $4RC$ to less than 2 per cent.

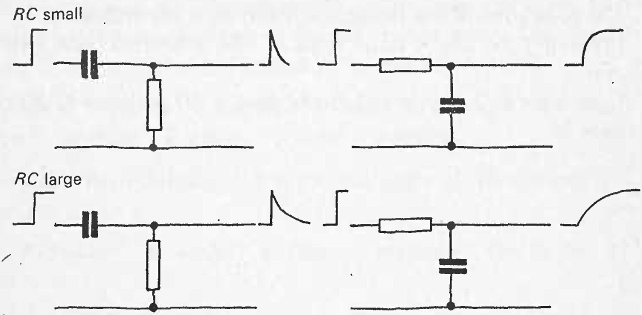


Figure 91
Effect of time constant on the response of *RC* circuits to step inputs.

Figure 91 shows the consequences of all this for some *RC* circuits.

LR circuits

The current in an *LR* circuit also has a time constant, and decays or grows according to an exponential law. In the circuit of figure 92 *a*, if the input is a falling step, the current decays according to the equation:

$$I = I_0 e^{-\frac{t}{L/R}}$$

If, as in figure 92 *b*, the input is a rising step, the current grows according to the equation,

$$I = I_0\,(1 - e^{-\frac{t}{L/R}})$$

The time constant is L/R, measured in seconds if L is in henries and R is in ohms.

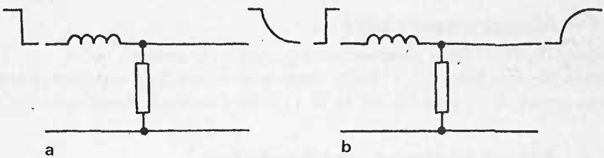


Figure 92

LC circuits

The parallel circuit shown in figure 93 oscillates or resonates at a frequency f given by,

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

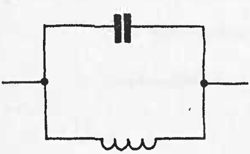


Figure 93
LC circuit.

Books and further reading

About transistors

Bennet, G. A. G., (1968) *Electricity and modern physics* (MKS version). Edward Arnold.
Brophy, J. J. (1966) *Semiconductor devices.* Allen & Unwin.

About computers

Benrey, R. M. (1965) *Understanding digital computers.* Iliffe.
Brand, M. and Brand, T. (1970) *Analogue computers.* Edward Arnold.
Hollingdale, S. H. and Tootill, G. C. (1970) *Electronic computers.* Penguin.

About systems and feedback

Tustin, A. (1952) 'Feedback.' *Scientific American* Offprint No. 327.

About practical circuits

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.
RCA (1970) *Solid-state hobby circuits manual HM*-91. RCA Solid-State Division.
Sjobbema, D. J. W. (1961) *Using transistors.* Macmillan.

Reprint

McLean, F. C. (1966) 'Colour television.' A *Science journal* reprint. Not available at the time of writing, but due to be re-published in Nuffield Advanced Physics (1972) *Physics and the engineer.* Penguin.

Index

Where significant information is contained in an illustration or diagram, the page reference is italicized.

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

Additional contribution from:
G.W.A.Dummer

This *Students' book* begins with a summary of Unit 6, *Electronics and reactive circuits*, followed by chapters on 'Systems and feedback' and 'Microelectronics: where are they heading?' The next chapter contains questions on the main work of the Unit, which has four themes: 'Electronic building bricks', 'Circuits containing capacitance', 'Circuits containing inductance', and 'Building electronic systems'. The chapter, 'Putting electronics to use', suggests systems the student can build. There follow answers to the questions. The book ends with a list of relevant background reading and notes on symbols and data used in the Unit.

Published by Penguin Education

14 0827137