BASIC ELECTRONIC CIRCUITS

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P.M. Buckley
Post Office Research Centre
Martlesham Heath

A.H. Hoskyns
Head of Physics
Sir William Collins School
Inner London Education Authority

Answers prepared by **Andrew Shewan**
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Preface

In the past, the teaching of electricity and electronics has more often than not been carried out from a theoretical and often highly academic standpoint. Fundamentals and basic concepts have often been presented with no indication of their practical applications, and all too frequently they have been illustrated by artificially contrived laboratory experiments bearing little relationship to the outside world.

The course comes in the form of fourteen fairly open-ended constructional experiments or projects. Each experiment has associated with it a construction exercise and an explanation. The basic idea behind this dual presentation is that the student can embark on each circuit following only the briefest possible instructions and that an open-ended approach is thereby not prejudiced by an initial lengthy encounter with the theory behind the project; this being a sure way to dampen enthusiasm at the outset. As the investigation progresses, questions inevitably arise. Descriptions of the phenomena encountered in the experiments are therefore given in the explanations. Although these were originally intended to be for the teacher's guidance they have been found, in fact, to be quite suitable for use by the student. In the explanations mathematics has been eliminated wherever possible, mechanistic descriptions of phenomena being preferred in all cases. Stress is thereby placed on concepts rather than on mere algebraic relationships. It is hoped that students of weak mathematical background will, as a result, not be prevented from following the explanations and deriving some benefit from these.

Another underlying aim of the course has been the avoidance of measurements for measurements' sake. All too often in the past practical work to the student has meant the taking of endless series of tedious measurements to verify some mathematical law. In this course, therefore, relationships are indicated initially in a qualitative way rather than in their exact quantitative form. Consequently, the brightness of a bulb serves as an adequate yardstick in most cases in the investigation of the behaviour of a circuit. Important quantitative relationships are given in the explanations, but the aim throughout has been that these should supplement the investigations rather than be the reason behind them. Despite the fact that measurements have been minimized, an important aspect of the course is the introduction to the use of common electrical measuring equipment. It is essential to the success of the course that the student should have full access not only to voltmeters and ammeters but also to signal generators and oscilloscopes.

A further benefit to be gained by avoiding the strictly quantitative approach is that the experiments are freed from the need to demonstrate mathematical relationships to a high degree of accuracy. The unrealistic nature of such contrived experiments is thus avoided. All the experiments in the course (like all circuits in the real world) display a variety of 'secondary effects'. Experience has shown, time and time again, that it is these secondary effects that capture the student's attention and imagination and stimulate further investigation. Again, on the grounds of realism and authenticity the circuits have not only been designed to reveal important electrical fundamentals but have also been chosen to illustrate as many as possible of the basic approaches to modern circuit design. Great care has been taken to use standard industrial components throughout, particularly ones that are commonly used in practice and are thus readily available.

There is, unfortunately, one important aspect of the course which cannot be put into print. This is the provision of skilled instruction on constructional techniques and, in particular, soldering. Wherever possible it is felt that professional instruction should be obtained; where this is not possible the onus for this will, unfortunately, fall on the teacher. Brief notes are included on this aspect although it is recognized that these will inevitably be inadequate for their purpose.

Acknowledgements

The authors would like to acknowledge the following examining bodies for permission to use their questions in Part 3 of this book;

Metropolitan Regional Examinations Board (M.R.E.B.) - from the Board's papers in Physics;
Oxford and Cambridge Schools Examination Board - O and A level Physics papers;
Scottish Certificate of Education Examination Board - SCE Physics Ordinary and Higher Grade;
University of London University Entrance and School Examinations Council - O and A level Electronics questions.

The assistance of Mr S. R. Elliot of the Post Office Research Centre is also gratefully acknowledged.

Introduction to the student

This book consists of fourteen circuits which form the basis of a number of fundamental electronic devices. If you wish to understand electronics you must make yourself familiar with these circuits, the components used to build them and the techniques for building and testing them.

One way of working through the course is to build each circuit yourself. Use the first page as a guide; it explains new words arising which you will need to understand, and symbols which may be new to you. Under the heading of guidance are brief hints for tests you can make. You should then read the explanation which describes the effects which you will have noticed and carefully explains them. It is best not to move on to a new circuit before giving the current one time to sink in.

If you cannot build the circuits, then draw them on paper fully. Think about the voltages in the circuit and how the current will behave and be controlled. Then read the explanations.

As you study each of the circuits build up a notebook. This should give test results and in it you should define each new word for yourself as carefully as possible. A glossary of terms used is given at the beginning of the book. In any case, when you start work on the circuits, begin to read Part 2. It deals with the basic components and will give you some idea how they are made and how they work.

The book provides a large number of recent questions in electronics from a wide selection of current examinations. If you can work through most of these successfully you will be fully prepared for most basic electronics papers and the electronics sections of examinations in Physics.

As you study the questions in Part 3 you will become aware that the form of questions has changed. Modern questions tend to ask about real electrical phenomena. They are therefore very useful to you, whether you are taking an external examination or not. Work through them, using the answers when there is anything you do not know or understand. The book is unique in providing detailed answers, included in Part 4.

If you are taking an examination, you are strongly advised as well to get a book of past papers, which are obtainable at CSE, O level, City & Guilds, A level or internal college level. If you have difficulty, write to the Cognitive Studies Trust. Information on obtaining components and test instruments is also available from the Trust by writing to:

The Correspondent,
33 Chepstow Court,
Chepstow Crescent,
London W11 3ED.

Abbreviations

The English and Greek letters used as abbreviations for electrical quantities are listed below with the symbols associated with them and the units used for measuring them. Most of them are defined in the text of the book, but it helps to see them in relation to one another before you begin to learn how they are used in understanding the circuits.

Quantity	*Symbol*	*Unit*
Charge	Q	coulomb, C
Current	I	ampère, amps, A (1A = 1 C/s)
Energy	E	joules, J
Power	P	watts, W (1 W = 1 J/s)
Voltage	V	volts, V
Resistance	R	ohms, Ω
Impedance	Z	ohms, Ω
Capacitance	C	farad, F
Inductance	L	henry, H
Frequency	f	hertz, Hz
Period	T	second, s

It is useful to be able to express multiples of these units without writing out the whole number either in words or as a decimal. It would be tedious to have to write a frequency of one million million hertz (1 000 000 000 000 Hz) every time one used the number. So we have available a system of prefixes and powers of ten which make it easier to express very large or very small numbers. A million, million hertz is one terahertz (1 THz) or 1×10^{12}Hz. Similarly, one millionth of a farad is a capacitance of one microfarad (1 μF) and one millionth of that is one picofarad (1 pF). It is common to read on a circuit diagram C_1 is a capacitor of 0.001 μF and then go to the component counter to find all the drawers labelled in picofarads so that you would need a capacitor of 1000 pF.

The prefixes and abbreviations for them which are commonly used are set out in the table below:

Tera	T	10^{12}	1000 000 000 000
Giga	G	10^{9}	1000 000 000
Mega	M	10^{6}	1000 000
Kilo	k	10^{3}	1000
Milli	m	10^{-3}	0.001
Micro	μ	10^{-6}	0.000 001

Nano	n	10^{-9}	0.000 000 001
Pico	p	10^{-12}	0.000 000 000 0001

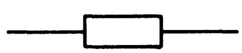
Example: a nanosecond, ns, is equivalent to 0.000 000 001 of a second.

Equivalent symbols

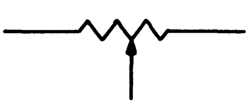
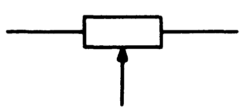
The components used in electronic circuits are given visual symbols so that they can be drawn out onto circuit diagrams. The symbols used throughout this book are those which the authors consider are most widely used internationally. They are identical with those agreed within the International Electrotechnical Commission. Unfortunately this also allowed alternatives to some of the common symbols and gave no indication as to which should be preferred. As a result the American Institute of Electrical and Electronics Engineers in a revision of their own standard of graphic symbols for electrical and electronic diagrams* and the British Standards Institution (B.S. 3939) adopted most of the I.E.C. alternatives as equivalent.

To get over the problem we have reproduced in the following pages some of the symbols which the I.E.E.E. and B.S.I. accept as equivalent and a few which we have not explained in the body of the book. (The difficulty can be illustrated with the symbol for a resistor. The American Standard allows the two alternatives showing the jagged line first. The British Standard shows the rectangular box first. We have tried in this book to use the genuine alternatives equally, some in the circuits, and others in the questions we have chosen and the answers to them. Obviously anybody wishing to work in electronics will want to become conversant with all the equivalent symbols.)

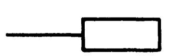
Resistor

 or 

(a) *Adjustable contact*

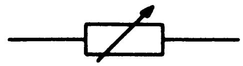
 or 

(b) *OFF (disconnect) position*

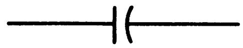
 or 

* 4 September 1975; 'I.E.E.E. Standards and American National Standards on Electrical and Electronics Graphic Symbols and Reference Designations' published by I.E.E.E. Inc., 345 East 47th St, New York, NY 10017, USA.

(c) *Adjustable or continuously adjustable (variable) resistor; rheostat*

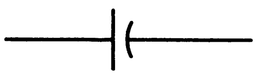
 or 

Capacitor

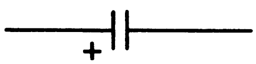
 or 

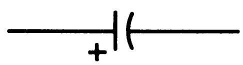
(a) *Variable capacitor*

(b) *Capacitor with identified electrode*

 or 

(c) *Polarized capacitor*



or


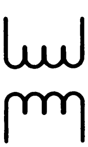
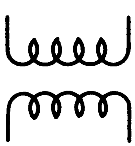
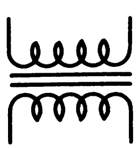
(d) *Variable capacitor with moving element indicated*

 or 

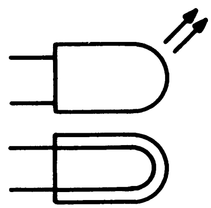
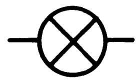
Inductors

,  or 

Transformers

 or  or 

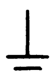
Lamp

 or 

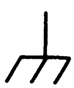
(The D shape is used when confusion with other circular symbols may occur.)

Battery

Ground (earth)

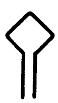
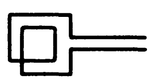


A direct conducting connection to earth.



A conducting connection to a chassis, frame, or a printed circuit board. The frame may be at substantial potential with respect to earth.

Antenna (aerial)

 or  or  or 

Direction of flow

 or 

 or  (Either way but not simultaneously.)

 or  (Both ways, simultaneously.)

Glossary

The words collected here are some of those which you might gather together in a notebook. Others are defined in the text and in the answers to questions.

Positive	(+) plus; a position of low electrical potential.
Negative	(−) minus; a position of high electrical potential.
Electromotive force (e.m.f.)	the difference in potential through which electrons are transferred in a battery.
Potential difference (p.d., volts)	(joules per coulomb) voltage difference, potential rise or drop, voltage rise or drop; V_{ab} is the work done in moving a unit positive charge from point a to point b. It is the difference in potential between a and b.
Series	components are in series when they are connected one after the other, so that the same current flows in turn through each of them.
Parallel	components are in parallel when they are connected side by side, so that the current divides between them and later re-unites.
Alternating current (a.c.)	a current that is alternately flowing in opposite directions.
Direct current (d.c.)	a current that flows in one direction only.
Reactance	the part of the impedance that is not due to pure resistance when an alternating e.m.f. is applied to a circuit. It is caused by the presence of capacitance or inductance. (Its symbol is X and it is measured in ohms.)
Frequency (hertz, Hz)	the number of cycles of an alternating current that occur in one second.
Rectification	the conversion of a.c. to d.c.
Impedance (Z) (Ω)	the effective resistance of a component to alternating current.
Root mean square (r.m.s.) value	the effective value of current or voltage in an alternating current. The r.m.s. value of a sine wave is the peak value divided by $\sqrt{2}$.

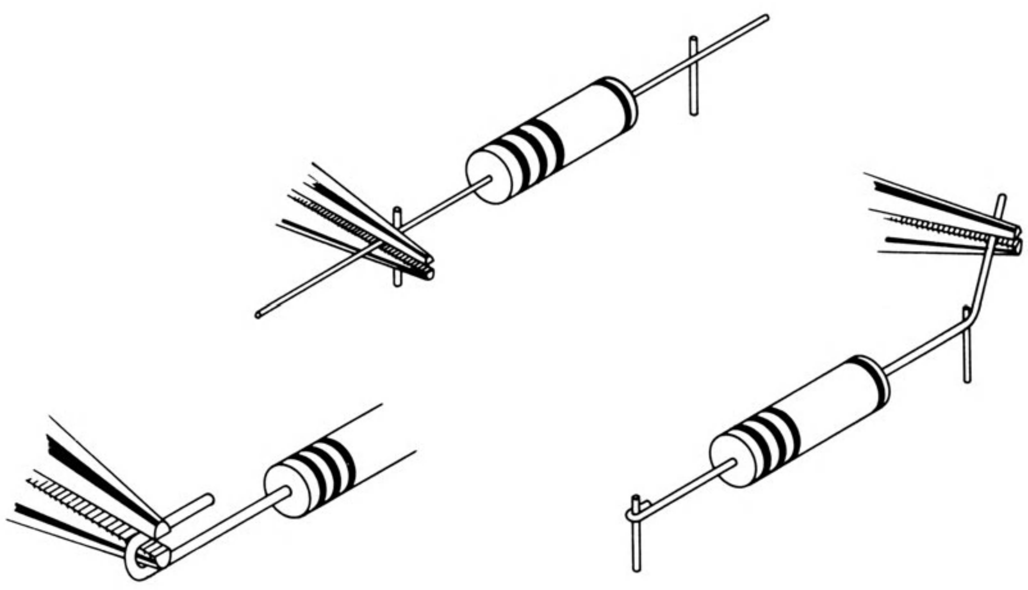
Out of phase	when two voltages are the same shape but displaced in time.
Current amplification	when a small current is used to control a large current.
Current gain	the ratio of the change in the larger current to the change in the small current controlling it.
Inductance (L), measured in henrys (H)	an electromagnetic property of a coil which affects its impedance.
Permeability	the property of materials used as cores in inductors, which tells us how strong the magnetic field will be.
Back e.m.f.	the induced e.m.f. caused by the changing magnetic field in a coil when an alternating current is flowing in the coil. It opposes the e.m.f. producing the current.
Resonant frequency	the frequency at which the impedances of L and C in a circuit are equal.
Voltage amplification	a small voltage used to control a larger voltage.
Voltage gain	ratio of output voltage change to input voltage change is the gain of the amplifier.
Primary winding	the coil in a transformer connected to the power supply.
Secondary winding	the coil in a transformer connected to the output.
Charge (Q) (coulombs)	stored electricity. A current flow of 1 C/s is 1 A.
Saturated transistor	when the transistor no longer behaves as an amplifier.
Electrical pulse	a voltage which switches between two discrete values.

PART 1
Basic electronic circuits

Soldering

Before you begin to build the circuits you will need to be able to arrange components on a board and solder them onto the pins cleanly. The circuit diagrams in this book are based on a rectangular paxolin board with a matrix of holes in it. Pins can be pressed into the board as shown in the constructional exercises. The component is fixed between the pins and then soldered. To get good electrical contact, clean, firm joints are important. The hints below will help you to ensure that you do not get what are called 'dry' joints, where electricity is not conducted through the joint.

1. Your soldering iron must be clean.
2. Measure carefully where to put the bend in the end of your component.

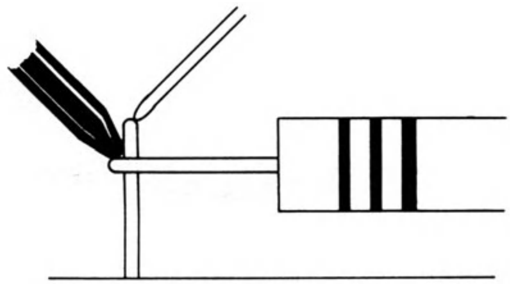


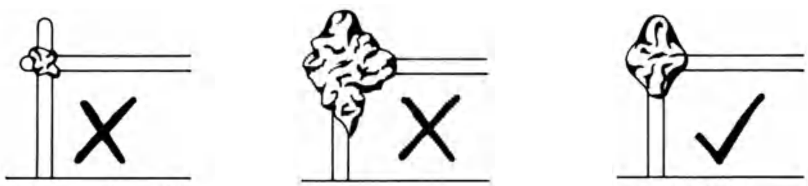
Bend the component end round the pliers rather than the pin.

Now bend the other end round the pin

Your component should sit firmly around the pins even before you solder it.

3. DO NOT melt solder onto the iron and take it to the joint. Put the hot iron against the joint and melt the solder on to the joint.



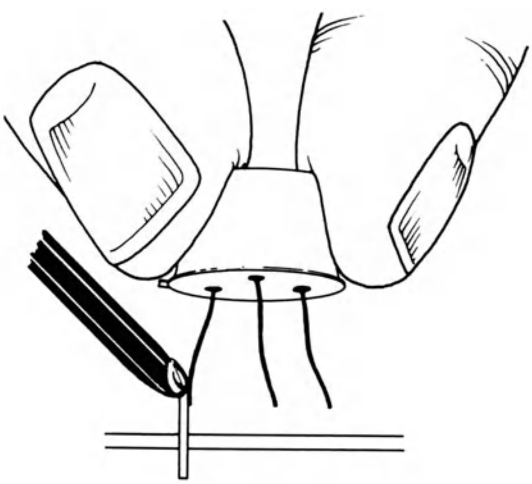


Too little solder *Too much* *Just right*

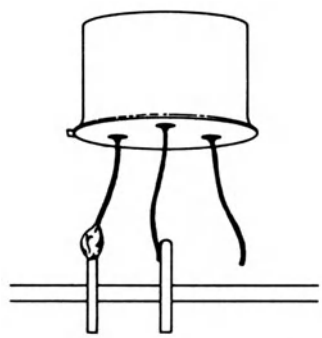
Your soldered joint should be shiny, not dull - the secret is to solder the joint quickly but carefully.

Soldering a transistor

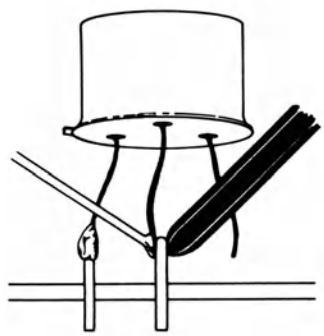
It is not always easy to solder on a transistor because heat from the iron may damage the component. The following is the technique favoured by the authors.



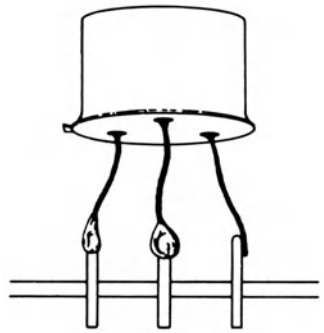
1. Solder one of transistor leads to pin without using fresh solder. Put solder on iron first.



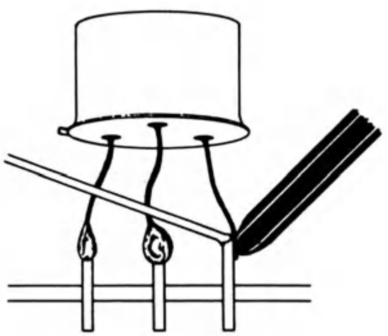
2. Bend transistor leads so that second lead touches second pin without holding transistor.



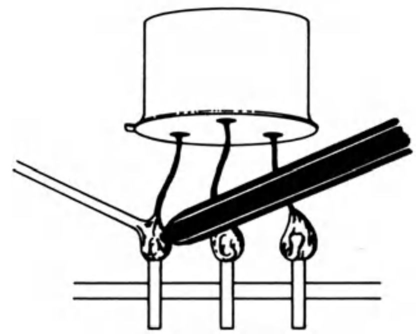
3. Solder second lead to pin using fresh solder and without holding transistor.



4. Bend third lead of transistor so that it touches third without transistor being held.



5. Solder third lead using fresh solder.



6. Resolder first lead using fresh solder - not too much.

CIRCUIT 1

Voltage and current

Collect all the components you need and then make and test this circuit

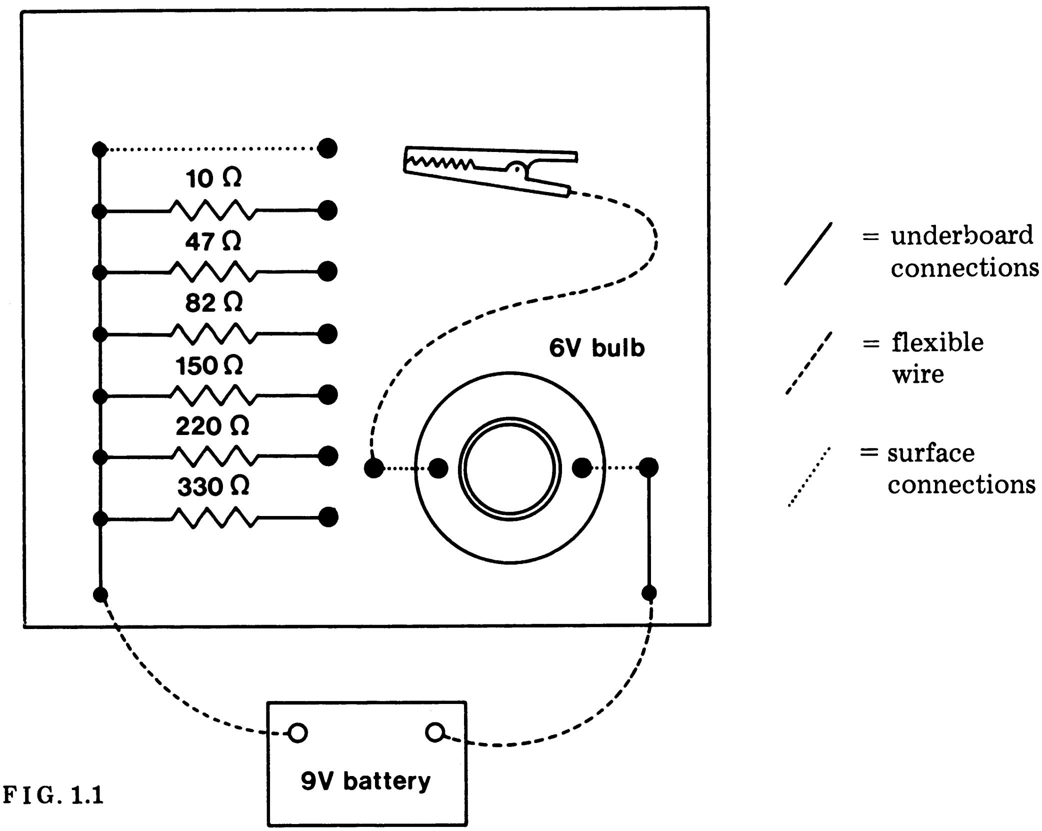
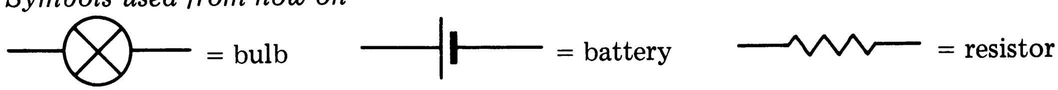


FIG. 1.1

Symbols used from now on



New words

Positive **Negative** **e.m.f.** **Potential difference**

Guidance

Use an *avometer* to measure the current and voltages in the circuit with the crocodile clip in different positions.

EXPLANATION 1

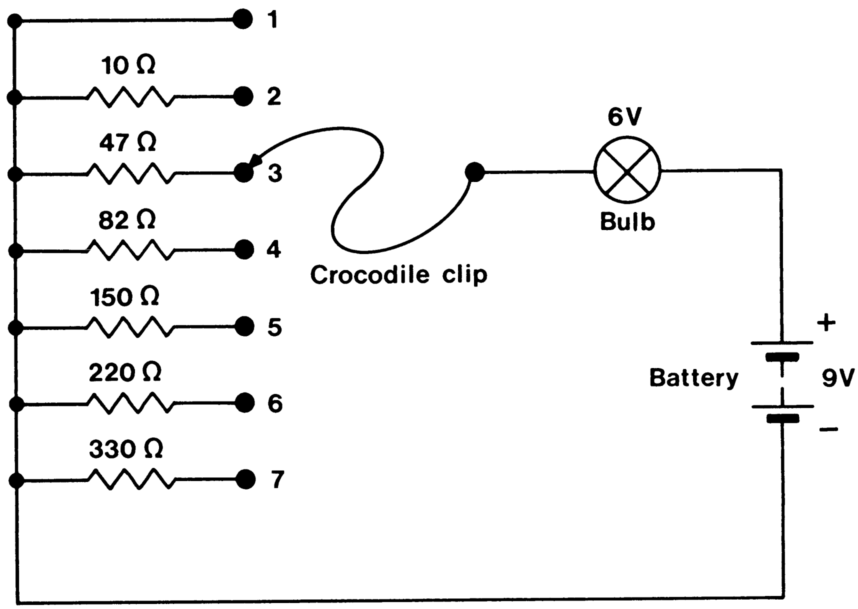


FIG. 1.2

1. Assemble the battery, bulb and resistors to make the circuit shown in Fig. 1.2.
2. Find out what happens to the bulb when the crocodile clip is connected in turn to points 1–7. You should notice that as the value of resistor to which the clip is connected is increased, the bulb becomes dimmer. In addition, when the clip is disconnected the bulb goes out altogether. The reason for this is that in order for the bulb to light up, electricity from the battery must flow through it. The electricity flows out of one side of the battery, round the wires in the circuit, through the components, i.e. bulbs, resistors, etc., and into the other side of the battery. Unless there is a complete path round the circuit through which the electricity can flow, and unless the bulb is part of this path, the bulb will not light up. The electricity that flows round the circuit is called *current.* Current is measured in amps* or milliamps (1000 mA = 1 amp). Current is made up of very small particles called electrons moving round the circuit from the *negative* terminal of the battery to the *positive* terminal. The negative terminal is said

* Amps is an abbreviation for amperes.

to be a position of high electrical potential for the electrons and the positive terminal a position of low electrical potential. The electrons move round the circuit because in any circuit they always move to the position of lowest potential. Thus the electrons coming out of the negative terminal move round the circuit to the positive terminal because it has a lower potential. Inside the battery, the electrons are transferred from the low potential of the positive terminal to the high potential of the negative terminal. To do this, energy has to be supplied to the electrons by the battery. The difference in potential through which the electrons are transferred in the battery is called the e.m.f.* of the battery. The energy thus supplied to the electrons is lost as they move round the circuit. This is usually dissipated in the components as heat (feel, for example, the heat from the bulb as electrons flow through it). The amount of current that flows round the circuit for a given e.m.f. in the battery depends on a quantity called *resistance.* This quantity represents the ease with which electrons can move to their position of lowest potential and hence determines the number of these that flow round the circuit. *Resistors* are components designed to have a certain resistance. Therefore, the reason for the bulb becoming dimmer when the clip is connected to resistors of high value is because the current lighting the bulb must also pass through the resistor, the total resistance in its path is large and, as a result, the current is small. Since few electrons are now travelling round the circuit, less energy is being transferred from the battery to the bulb in the form of light and heat.

3. An ammeter is a device for measuring current. To measure current, the current must flow through it. Connect an ammeter (*avometer*) into the circuit in such a way that the current flowing round the circuit also flows through the ammeter. Measure the currents when the crocodile clip is in the various positions 1–7. Demonstrate that as the bulb gets dimmer, i.e. as the resistor in series with it gets larger, the current gets smaller.

4. The difference in electrical potential between the positive and negative battery terminals should ideally be equal to the e.m.f. of the battery. *Potential differences* are measured in *volts.* Sometimes they are referred to simply as *voltages.* In the circuit we are testing, the e.m.f. of the battery and hence the potential difference across its terminals is 9 volts. As electrons move round the circuit their electrical potential becomes progressively lower. Thus, if an electron moving round the circuit, has reached some point at which it has lost 3 volts of potential, it follows that it still has 6 volts of potential to lose and that the potential difference between the positive battery terminal and this point is 6 volts and the potential difference between this point and the negative terminal is 3 volts. All potential differences through which the current flows must therefore add up to the potential difference between the battery terminals.

5. A meter for measuring potential differences is called a voltmeter. If the two wires from a voltmeter are connected to two points in a circuit, the voltmeter will measure the potential difference between these points. To confirm that the potential differences in a circuit always add up to the potential difference across the battery, use a voltmeter in the above circuit to measure the voltages across the resistors, bulb and battery when the crocodile clip is connected to each resistor in turn. You should find that the potential difference across the battery is always equal to the sum of the potential differences across the bulb and the relevant resistor. Notice that for low values of

* e.m.f. is an abbreviation for electromotive force.

resistor the voltage across the battery falls well below 9 volts. This is because there is a small amount of resistance inside the battery, and when large currents flow from the battery there is a significant voltage across this internal resistance. Since the sum of the potential differences across this internal resistance and the battery terminals is equal to the e.m.f., the voltage across the terminals drops below 9 volts.

CIRCUIT 2

Resistance

Collect all the components you need and then make and test this circuit

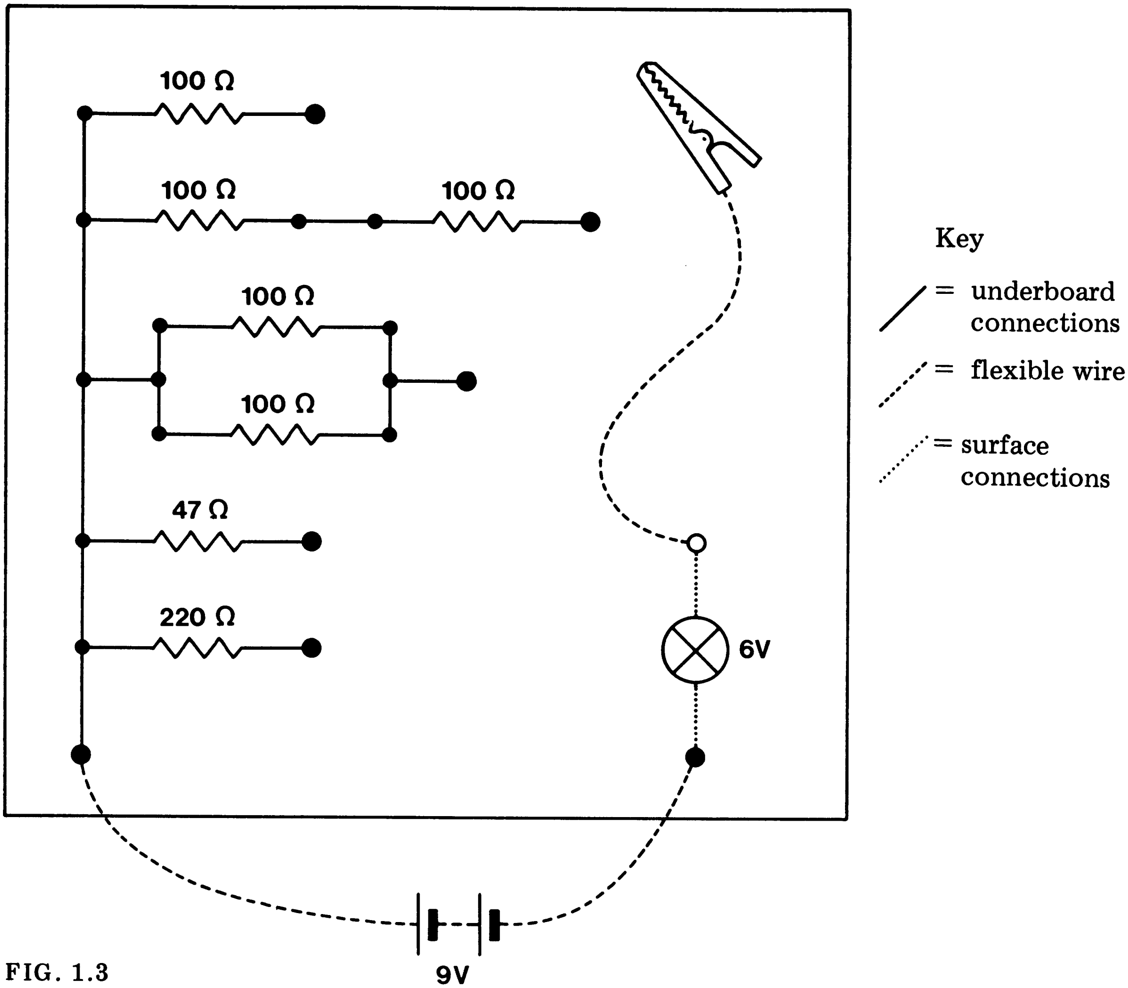


FIG. 1.3

New words:

Series **Parallel**

Guidance

With the crocodile clip in different positions measure the currents flowing in the appropriate resistors.

EXPLANATION 2

1. It was seen in Circuit 1 that the current that flows round a circuit for a given e.m.f. depends on the amount of resistance in the circuit. When there is more than one resistor in the circuit, however, the amount of current that flows from the battery depends on the way in which the resistors are connected together. To investigate the effects of different arrangements of resistors, build the circuit shown in Fig. 1.3 and observe what happens when the clip is connected in turn to the various points. It should be observed that when the two 100 Ω resistors, connected one after the other, are introduced into the circuit the bulb is dimmer than when the single 100 Ω resistor is used. Also, when the two 100 Ω resistors which are connected side by side are introduced it should be seen that the bulb is brighter than when the single 100 Ω resistor is used. In fact, the two resistors connected side by side should cause the bulb to light with almost the same brightness as when a 47 Ω resistor is used and the two resistors connected one after the other should result in the bulb lighting with roughly the same brightness as with the 220 Ω resistor in circuit. Components connected one after the other as in the above circuit are said to be connected *in series* and when connected side by side they are said to be *in parallel.*

2. By using an avometer, confirm that the current flowing from the battery is roughly the same when either two 100 Ω resistors are connected in series or a single 220 Ω resistor is used in their place. Similarly, show that two 100 Ω resistors connected in parallel can be replaced by a single 47 Ω resistor to give the same current. You will probably find the currents vary slightly. For them to be exactly equal, a 200 Ω resistor should be used instead of a 220 Ω and a 50 Ω used instead of a 47 Ω. These values, however, are not available for the type of resistor used in these circuits*.

It can be concluded from the above that, when resistors are connected in series, their total effective resistance in the circuit increases and, in fact, is equal to the sum of the individual resistances. In addition, for resistors connected in parallel their effective resistance in the circuit goes down and when the resistors are equal in value it is, in fact, halved. The reason for the resistance decreasing can be seen if the circuit is redrawn slightly (see Fig. 1.4). Each diagram is the same circuit drawn in a different way. In a parallel circuit, therefore, there are really two separate circuits (A and B in the diagram). Since there are two paths the current can take in flowing from one terminal of the battery to the other, twice the current can flow and this is, therefore, the same effect as having a smaller resistance in the circuit.

***See 'preferred' values, page 60.**

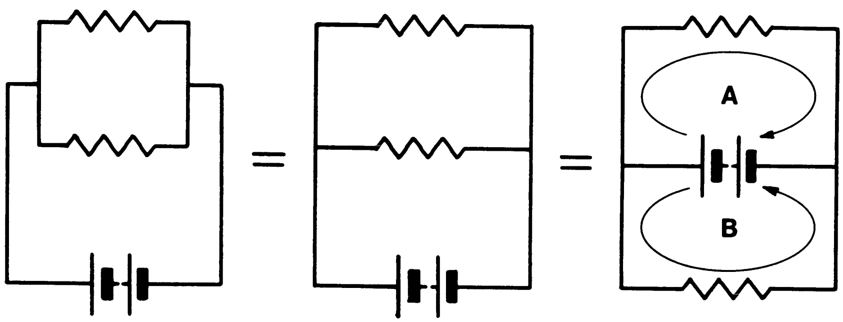


FIG. 1.4

Measure the current flowing through each of the 100 Ω resistors in the parallel branch and show that the current in each is, in fact, half the total current flowing from the battery.

In general, the voltage and current in a resistance are related by the formula

$$V = IR$$

(V is potential difference in volts, I is current flowing measured in amps and R is the resistance measured in ohms, Ω.) This formula is often referred to as Ohm's law.

For resistors added in series, the total effective resistance, R, is given by the formula

$$R = R_1 + R_2 + R_3,$$

and for resistors added in parallel it is given by the formula

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

R_1, R_2 and R_3 are the values of the individual resistors.

CIRCUIT 3

Alternating current

Collect all the components you need and then make and test this circuit

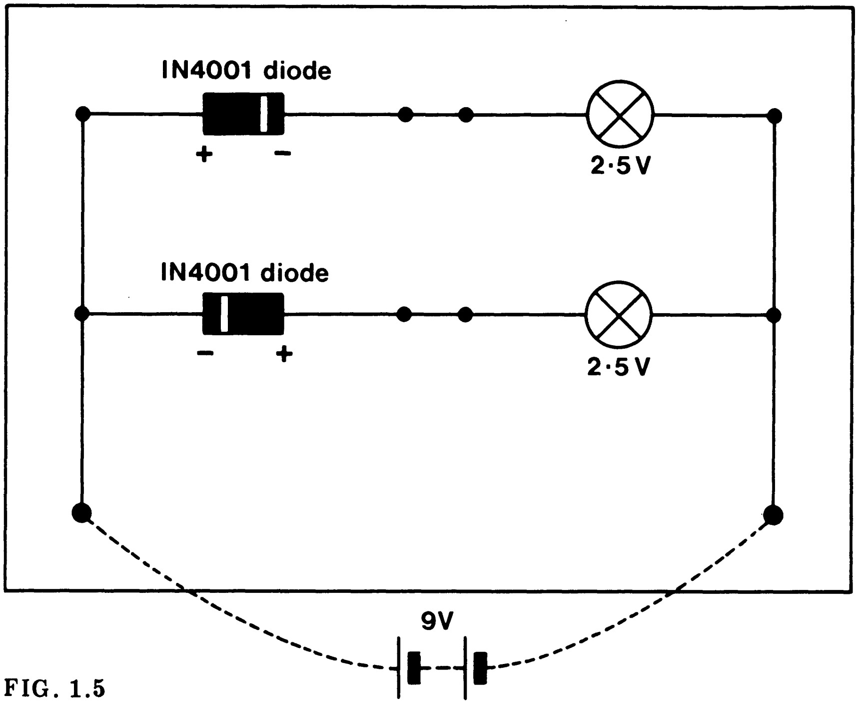
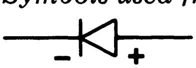
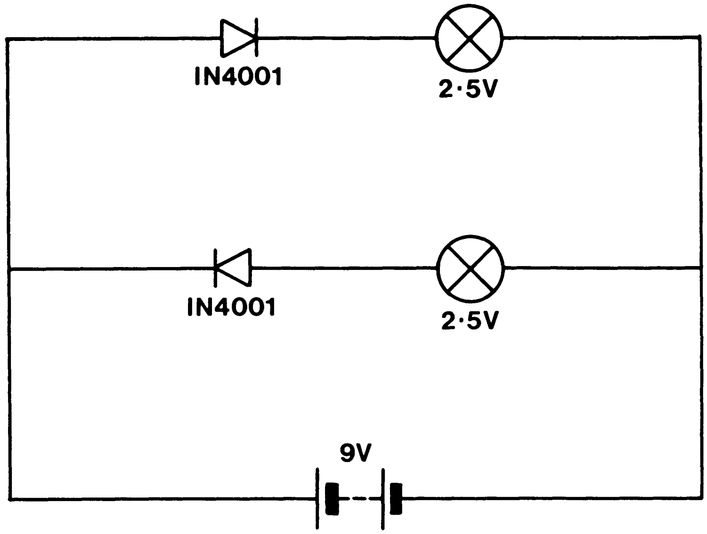


FIG. 1.5

Symbols used from now on

 = diode



This is another way of drawing the same circuit.

FIG. 1.6.

New words

Alternating current **Direct current** **Frequency** **Rectification**

Guidance

1. Find out what happens when the 9 V battery is replaced by a signal generator.
2. Use an oscilloscope to see how the voltages in the circuit change with time.

Note

Use the low impedance output terminals of the signal generator.

EXPLANATION 3

1. Find out whether reversing the battery connections in Circuits 1 and 2 alters the operation of the circuits in any way. It should be found that this has no effect. The reason is that reversing the battery connections reverses the direction of current flow round the circuit and since current can flow through resistances equally well in either direction the same current flows irrespective of the way the battery is connected.
2. Build the circuit shown in Figs. 1.5 and 1.6 and see what happens when the battery is connected to the circuit first in one direction and then in the other. It should be found that when the battery is connected, one bulb lights up and when the connections are reversed this bulb goes out and the other comes on. The reason for this is that the diode is a device which will only allow current to pass through it in one direction. When the battery, therefore, is connected in one way, only one of the diodes allows current to flow and consequently only the bulb which is in series with this diode lights.

The other diode which is connected in the opposite direction will not allow current to flow through it in the direction it wants to go in. Therefore, the bulb in series with this diode does not light up. On reversing the battery connections the situation is reversed. Now, the diode which previously allowed current to pass is preventing the current flowing through it and the other diode which previously did not conduct the current now allows it to flow. Thus the bulb that was initially on, goes off and the one that was off comes on.

It should be noted that although the electrons flow round the circuit from the negative battery terminal to the positive terminal, the convention is that the current itself flows from the positive to the negative or, in other words, in the opposite direction to the flow of electrons. The arrows on the symbol for the diode indicate the direction of conventional current flow through the diode.

3. Remove the battery from the circuit and in its place connect a signal generator.* Like the battery, the signal generator produces an e.m.f. which causes current to flow in the circuit. Observe what happens when the output level of the signal generator is turned up high and the frequency setting to its lowest position. It should be found that the bulbs in the circuit now flash on and off alternately. From this we can conclude that the current from the signal generator is flowing alternately in opposite directions. This implies that the e.m.f. from the signal generator is also changing direction.

A current that is alternately flowing in opposite directions is known as an *alternating current*, or simply a.c., and a current which always flows in the same direction is called a *direct current* or d.c. The current flowing from a battery is d.c. and that flowing from the mains is a.c. When an alternating current changes its direction of flow and then changes back to the original direction it is said to have gone through one *cycle*. The number of cycles of the current that occur in one second is called the *frequency* of the current. Frequency is measured in either *cycles per second* or *hertz*.

Turn the frequency of the signal generator up slowly to about 50 hertz. Notice that as the frequency increases the flashing becomes faster and faster, showing that the current is changing directions an increasing number of times per second. Eventually, as the frequency becomes sufficiently high the flashing will not be detected and both bulbs will then appear to be switched on all the time. Mains supply in fact produces a.c. at a frequency of 50 Hz. Lower frequencies would cause electric light bulbs to flicker but at 50 Hz this flickering is not noticeable.

4. Like a voltmeter, an oscilloscope is a device for observing electrical voltages. With an oscilloscope, however, very rapid changes of voltage can be displayed graphically on a screen. Connect an oscilloscope to the circuit and examine the voltages across both bulbs in the circuit, also the voltage at the output of the signal generator. When the trace moves upwards on the screen, a positive potential difference is present on the oscilloscope input terminals, similarly a downward movement of the trace implies the potential difference is in the opposite direction, or in other words is negative. You should find that the voltage at the output of the signal generator causes the trace to move both up and down indicating that its voltage is going both positive and negative. The voltages across the bulbs should cause the trace to be either always in the top half

* Connect the circuit to the low impedance output from the signal generator.

of the screen in the case of one bulb or in the bottom half in the case of the other bulb. This means that the voltage and hence the current in one bulb are always positive and in the other they are always negative. Notice that the diodes have caused the a.c. from the signal generator to flow in one direction only in each bulb, thus changing it to d.c. Converting a.c. to d.c. is called *rectificcation* and the diode is therefore sometimes referred to as a *rectifier.*

CIRCUIT 4

Capacitance

Collect all the components you need and then test the circuit at different frequencies

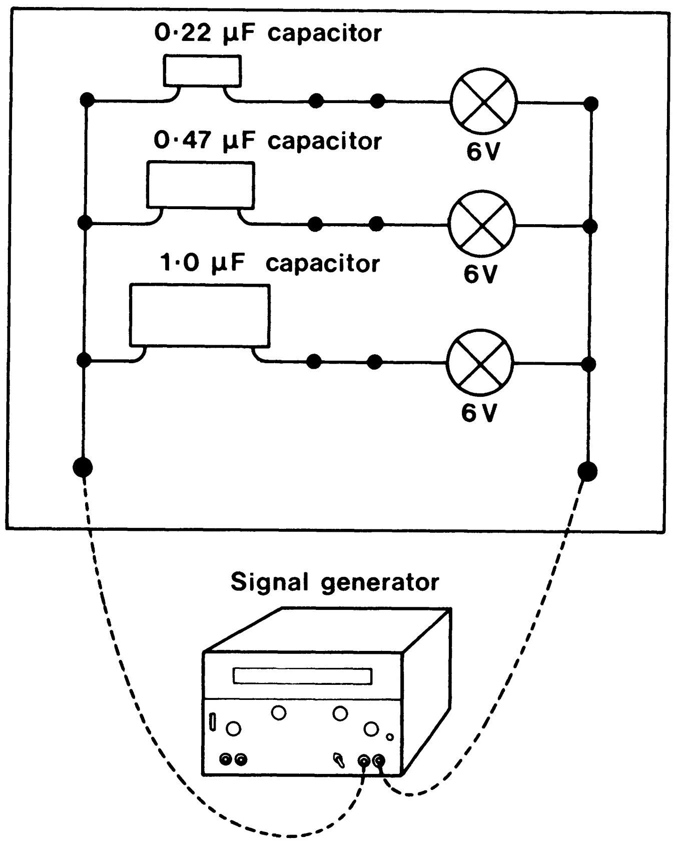
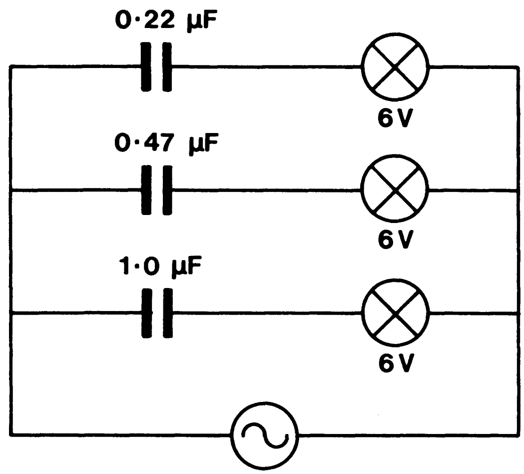


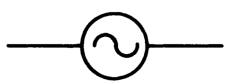
FIG. 1.7



This is another way of drawing the same circuit.

FIG. 1.8

Symbols used from now on

 = capacitor  = signal generator (a.c.)

New words

Impedance **In phase** **Out of phase**

Guidance

1. Test the circuit with another 0.47 μF capacitor connected in series with the one in the circuit and then with it connected in parallel.
2. Investigate the effect of replacing the signal generator by a 9 V battery.
3. With the frequency of the signal generator at 2 kHz, measure the voltages in the circuit with an avometer and then using a double-beam oscilloscope compare the voltage across the signal generator with those across the capacitors.

EXPLANATION 4

1. Build the circuit shown in Figs. 1.7 and 1.8 and before connecting the signal generator see what happens when a 9 V battery is used in its place. It should be found that, no matter which way the battery is connected, none of the bulbs lights. This is because capacitors do not allow direct current to flow through them and no current, therefore, is able to flow into the bulbs.
2. Now replace the battery by the signal generator. Observe what happens as the frequency of the a.c. is slowly increased. It should be found that the bulbs now light, dimly at first, and increasingly brightly as the frequency goes up. Thus, although they will not conduct direct current, capacitors do allow alternating current to flow. Their

'effective resistance to a.c.' is known as *impedance* and it can be seen that this decreases with increasing frequency. The size of a capacitor is measured in terms of its *capacitance.* To explain how the impedance of a capacitor is related to its capacitance, notice that at any particular frequency in the above circuit the bulb that glows the brightest is the one connected to the largest capacitor. In general, therefore, the larger the value of a capacitor the smaller its impedance will be at any given frequency. Mathematically, the formula for the impedance* of a capacitor is given by

$$\text{Impedance } (Z) = \frac{1}{2\pi f C}$$

where Z is measured in ohms, frequency, f, in hertz and capacitance, C, in farads. N.B. 1 000 000 microfarads (μF) = 1 farad.

3. Connect another 0.47 μF capacitor in series with the one in the circuit. It should be seen that the brightness of the bulb connected to these two capacitors is now the same as that connected to the 0.22 μF capacitor. It follows, therefore, that when two 0.47 μF capacitors are connected in series their impedance is approximately the same as a single 0.22 μF capacitor. Thus, in general, capacitors connected in series are equivalent to a single capacitor of lower value. Mathematically, the rule for calculating the value of the single capacitor which is equivalent to a number connected in series is

$$\frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \quad \textit{series}$$

where C is the equivalent capacitance and C_1, C_2, C_3, etc., are the individual capacitances of the capacitors connected together.

Now connect the two 0.47 μF capacitors in parallel. It should be found that this time the two behave like a single 1 μF capacitor and it therefore follows that, when connected in parallel, capacitors are equivalent to a single capacitor of higher value. Mathematically the rule is

$$C = C_1 + C_2 + C_3 \quad \textit{parallel.}$$

Notice that the rules for adding capacitors together are the inverse of those for resistors. This can be explained by the fact that for capacitors, their impedances, like resistances, increase when added in series and decrease when added in parallel. When connected in series, therefore, the impedance of capacitors increases and when connected in parallel their impedance decreases. However, since an increase in impedance corresponds to a decrease in capacitance, this leads to the rules for adding impedances and capacitances being reversed.

4. Set the frequency of the signal generator to about 2 kHz and for each of the capacitors measure the voltage across it and the series bulb. Also, measure the voltage between the terminals of the signal generator. You should find that unlike d.c. circuits the potential differences across the components in this circuit do not add up to the

*The impedance of a capacitor can also be referred to as reactance.

supply voltage. This is, in fact, generally the case in a.c. circuits in which components other than resistors are present. The reason for this apparent contradiction is that the a.c. voltmeter measures a quantity called the r.m.s.* value of the voltage. This quantity is related to the largest voltage (either positive or negative) that appears at the output of the signal generator during the period of one cycle. Although the voltage across the capacitor and bulb *at any instant of time* add up to the voltage at the output of the signal generator, the largest voltages across each component in fact occur at different times during the cycle. By adding together the readings of the meter, therefore, across the two components, voltages which occur at different times are in effect being added. The sum of these voltages, therefore, in no way represents the reading that will be obtained at the output of the signal generator. This is generally the case in all a.c. circuits, the only exception being when the circuit is made up entirely of the same type of component, e.g. resistances. In such cases the maximum voltage across each component occurs at the same time and adding together the meter readings to get the supply voltage is then valid.

In order to demonstrate that the largest voltages across the bulb and signal generator occur at different instants of time, connect the circuit to a double-beam oscilloscope – this is the one which allows two voltages to be displayed on the screen at the same time. Connect up the circuit as shown in Fig. 1.9. Input 1 thus measures the voltage across the signal generator terminals and input 2 that across the capacitance.

The pattern of the oscilloscope screen should be similar to that shown in Fig. 1.10.

Since the two patterns are displaced horizontally, this means that the maximum voltages occur at different times. When two voltages are the same shape but displaced in time they are said to be *out of phase* and when they are not displaced they are said to be *in phase*.

* r.m.s. is an abbreviation for root mean square. A derivation of the r.m.s. value is given at the end of this section.

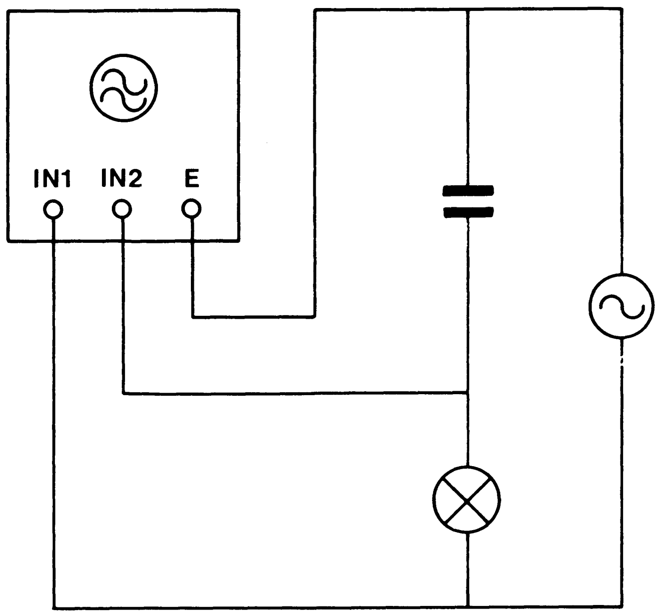


FIG. 1.9

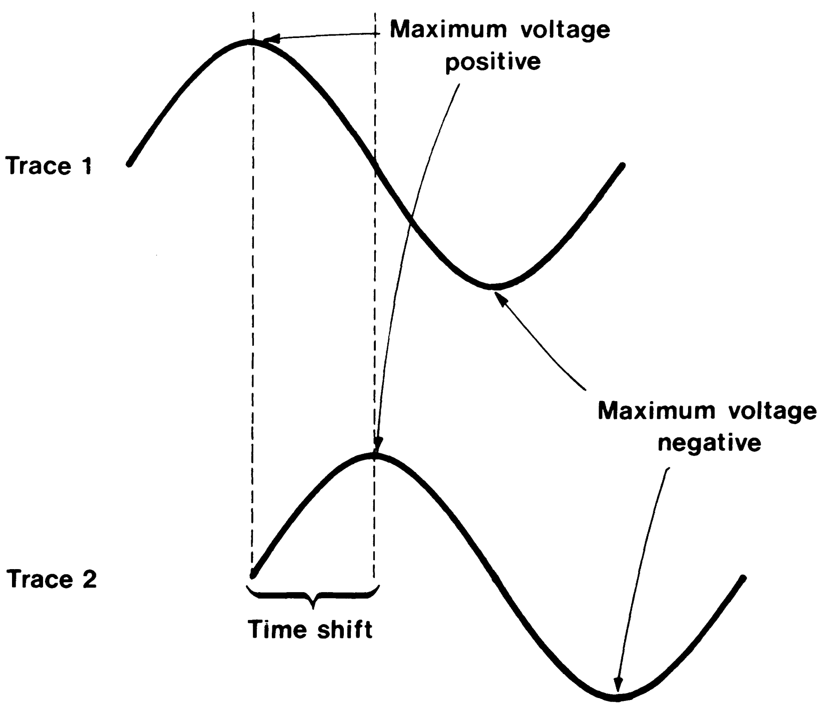


FIG. 1.10

Derivation of r.m.s. value

An alternating current, I, which has a sine wave variation, is given by

$$I = I_0 \sin \omega t,$$

where $\omega = 2\pi f$, f being the frequency and t the time. The peak value of the alternating current I is its maximum value I_0. The root mean square value is the square root of the average value of I^2 taken over one complete cycle. Since $I = I_0 \sin \omega t$, then $I^2 = I_0^2 \sin^2 \omega t$

$$= \tfrac{1}{2} I_0^2 (1 - \cos 2\omega t)$$

(from the identity $2 \sin^2 \theta = 1 - \cos 2\theta$).

Now the average value of $\cos 2\omega t$ over one cycle (i.e. through 360°) is zero. It follows that for a sine wave variation of current,

$$I_{\text{r.m.s.}} = \frac{1}{\sqrt{2}} I_0$$

$$= 0.71 \times \text{peak value}$$

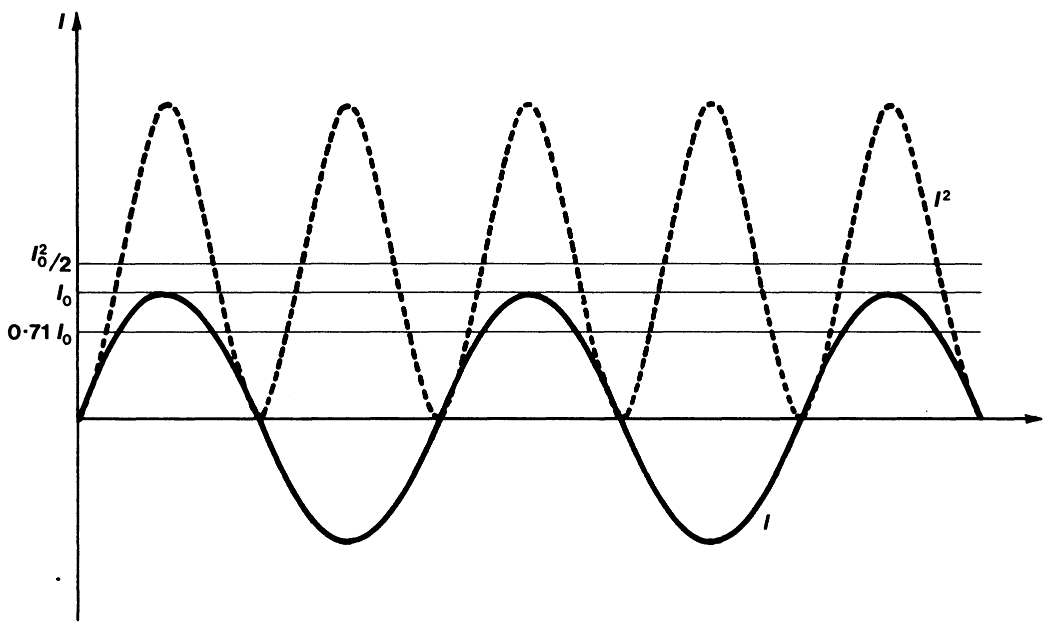


FIG. 1.11

CIRCUIT 5

The transistor

Make and test this circuit. Be careful when soldering the transistor

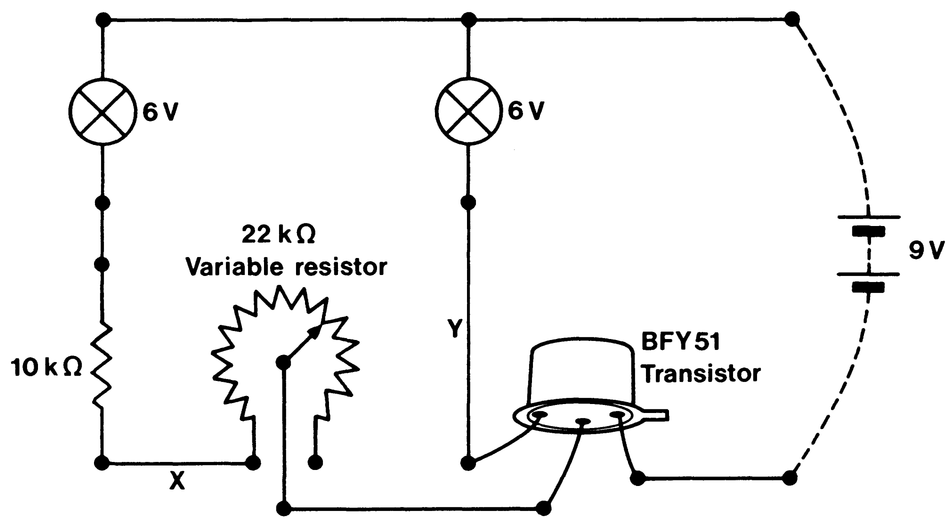
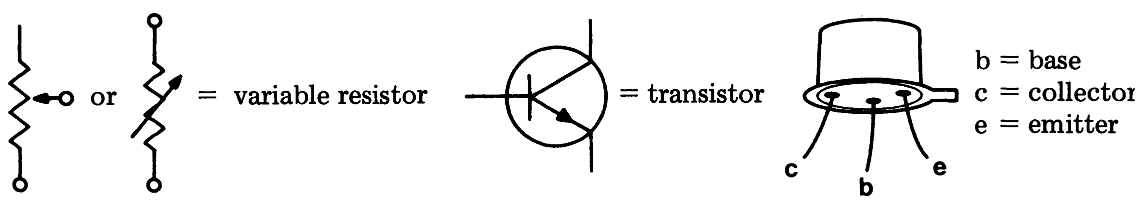
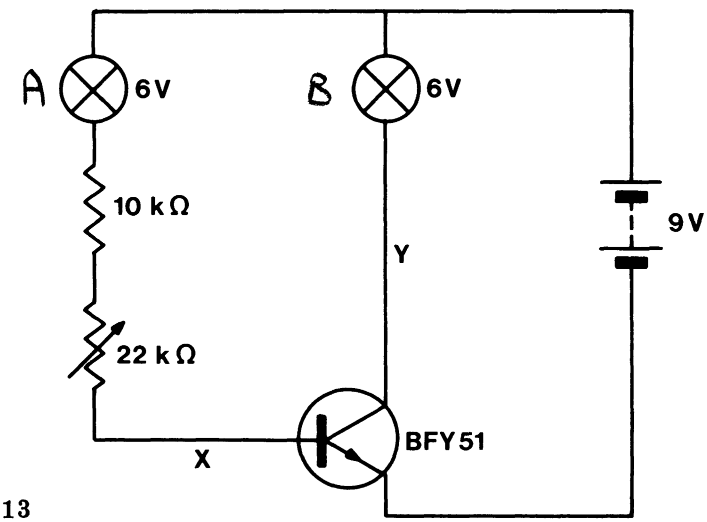


FIG. 1.12

Symbols used from now on





This is another way of drawing the same circuit.

FIG. 1.13

New words

Current gain   Current amplification

Guidance

Measure the currents at X (base circuit) and Y (collector circuit).

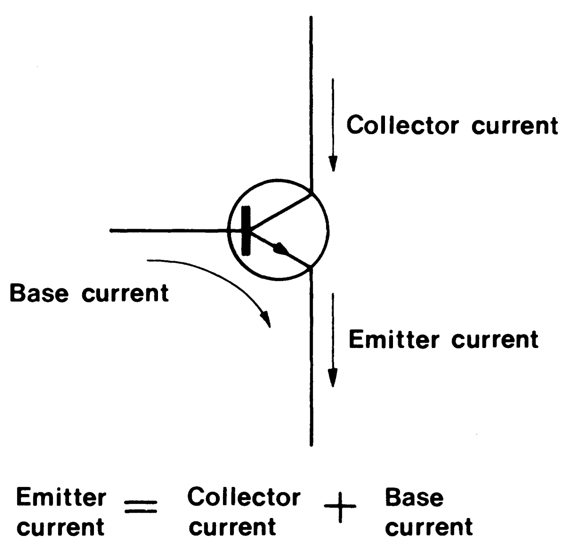


FIG. 1.14

EXPLANATION 5

1. Build the circuit shown in Fig. 1.13 and observe what happens when the variable resistance is altered. Notice that although the brightness of bulb B changes, bulb A does not light. The reason why bulb A does not light is that even with the variable resistor set to no resistance (0 Ω) there is still a 10 kΩ resistor in series with bulb A and this is too large to allow enough current to pass through the bulb to light it.
2. Remove bulb A from its holder and see what happens. It will be seen that even though the bulb does not appear to be doing anything in the circuit, without it bulb B will not light. Since no current can flow into the base of the transistor when bulb A is removed we can conclude that unless current flows into the base, no current can flow into the transistor's collector, i.e. bulb B will not light.
3. To see whether there is any relationship between the base and collector currents, put ammeters into the circuit at points X and Y. Measure the currents at these points for various settings of the variable resistor. You should observe that when the variable resistance becomes large in value both the base and collector currents become smaller and that as the variable resistance becomes smaller in value the currents get larger.
It will be seen that as the base current increases, even though the collector current is much larger in value it increases proportionately. It follows, therefore, that a small current is being used to control a large current in the sense that small changes of current in the base circuit are producing large changes of current in the collector circuit. The transistor is therefore acting as a *current amplifier.* The ratio of the collector to the base current in the transistor is called the *current gain* of the transistor (denoted as β or h_{fe}). From the measured values of current at points X and Y, calculate the current gain of the BFY 51 transistor; it should be about 100 and should vary slightly from one transistor to another.
4. For various brightnesses of bulb B measure the voltage between the base and emitter of the transistor. You should observe that no matter what the currents in the transistor, when the transistors act as an amplifier, this voltage remains substantially constant at about 0.6 volts. This is the same for all transistor amplifiers.
5. Put an ammeter in the circuit at point Z and measure the current. You should observe that under all conditions the collector current and emitter current are always roughly equal. The emitter current should, in fact, be slightly larger since the base current as well as the collector current flows through the emitter (Fig. 1.14).

CIRCUIT 6

Inductance

Wind 100 turns of wire onto a ferrite rod. Test at different frequencies.

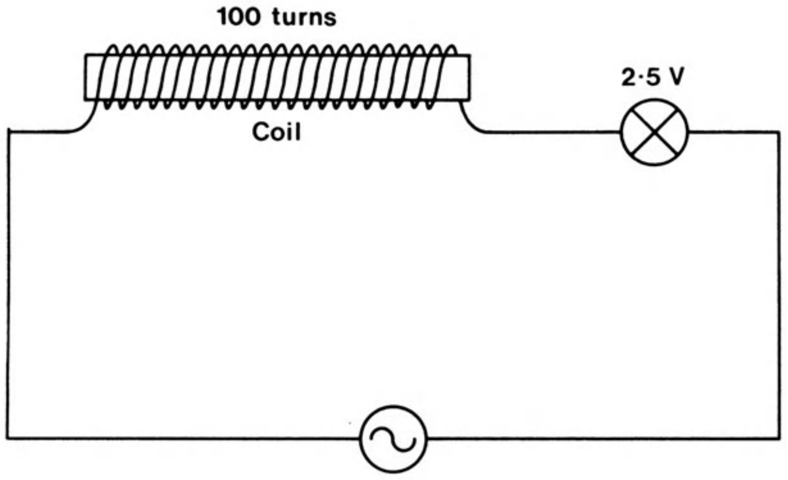
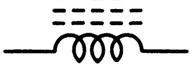


FIG. 1.15

Symbols used from now on

 = coil

New words

Inductance **Permeability** **Back e.m.f.**

Guidance

1. Find out whether changing the number of turns and the material of the core changes the electrical properties of the coil.
2. Use a double-beam oscilloscope to compare the voltage across the signal generator terminals with that across the coil.

EXPLANATION 6

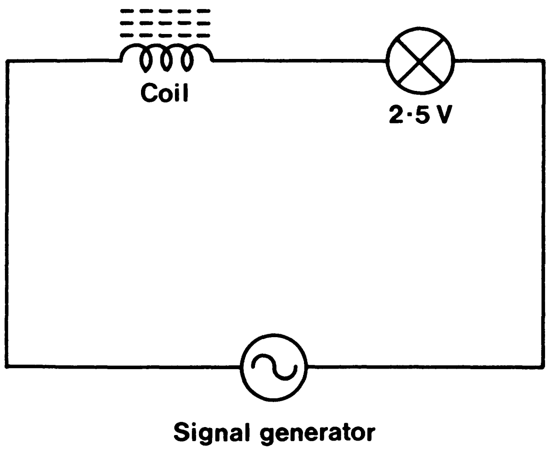


FIG. 1.16

1. Wind 100 turns of plastic-covered wire onto a ferrite rod of about 4 in. long, sticking the ends of the winding to the rod with sellotape to prevent unravelling. A coil of wire like this is known as an *inductor*, a *choke*, or simply a *coil.*
2. Connect the coil in circuit as shown in Fig. 1.16. Change the frequency of the signal generator over its entire range and observe what happens. You will notice that the bulb lights up at low frequencies but that as the frequency is increased beyond a particular value the bulb dims and eventually goes out. This indicates that as the frequency increases the current in the circuit decreases and that the resistance of the inductor to alternating current therefore increases with increasing frequency. As with the capacitor, this resistance to a.c. current is known as *impedance.* Unlike the capacitor, however, it can be seen that an inductor's impedance does not decrease but increases with increasing frequency.
3. The impedance* of any coil of wire depends not only on the frequency of the current through it but also upon a property of the coil called its *inductance.* In fact, the formula for a coil's impedance is given by

$$Z = 2\pi fL$$

where Z = impedance (Ω), f = frequency (Hz) and L = inductance. Inductance is measured in henrys (H).

To find out which factors contribute towards a coil's inductance, first adjust the frequency of the signal generator until the bulb just goes out and make a note of this. Now reduce the number of turns on the coil to 50 and see what happens to the bulb at the same frequency. It should be found that the bulb now glows, whereas before it was extinguished. A larger current than before must therefore now be flowing through the bulb and the coil's impedance must consequently have decreased. Since our measurements have been made at one frequency, the reduction of the impedance can

* The impedance of an inductor can also be referred to as reactance.

only be explained by a lowering of the coil's inductance. In general, therefore, reducing the number of turns on a coil reduces its inductance and hence its impedance.

Now wind a similar coil of 100 turns around a piece of wood instead of ferrite and repeat the above experiment with the coil in circuit. Notice that the bulb now stays on for all frequencies. If the signal generator could provide much higher frequencies, eventually the bulb would go out as the frequency was increased. However, at the frequencies within the range of this signal generator, the impedance of the coil is much too low to prevent the bulb lighting up. The inductance of the coil must therefore have drastically been reduced by replacing the ferrite core with one of wood. In general, for the inductance of a coil to be fairly high, its core must be made of a magnetic material.

We can conclude, therefore, that when making a coil which is to have a high inductance, a large number of turns should be used and a material like ferrite which has good magnetic properties should be used for the core.

The behaviour of an inductor can be explained by the fact that electric currents and voltages and magnetic effects are closely related to each other. Thus, when a current flows in an inductor the current causes a magnetic field to be set up in the core of the inductor. When the current through the inductor is direct current, the resulting magnetic field is constant and does not change in strength, whereas if alternating current flows in the coil the fact that the current is constantly changing in strength and direction causes the resulting magnetic field to also change in strength and direction. Changing magnetic fields always cause induced e.m.f.s to appear in conductors passing through the magnetic field and therefore in the case of the coil, when an alternating current is flowing an induced e.m.f. is produced in the coil by the changing magnetic field in the core. When a direct current is passed through the coil, however, the magnetic field produced does not change in strength and in this case, therefore, no induced e.m.f. is obtained. The induced e.m.f. is called a *back e.m.f.* because in all circuits the back e.m.f. opposes the main e.m.f. in the circuit; in our case the alternating e.m.f. from the signal generator. The result of the opposing e.m.f. is that the total e.m.f. acting in the circuit is reduced and as a result the current flowing is also reduced. We interpret this as an increase in the impedance of the coil when a.c. is used in place of d.c.

As the frequency of the a.c. increases, the magnetic field in the coil changes more rapidly and a larger back e.m.f. is obtained. This leads to a smaller net e.m.f. acting in the circuit, a smaller current flowing and hence a larger impedance for the coil. This is the reason, therefore, why increasing the frequency leads to an increase in the impedance of a coil.

If the core is made from magnetic material, the field in the core will be strong, whereas if it is non-magnetic, the field will be weak. The property of the material in the core that tells us how strong the magnetic field will be in these circumstances is called the *permeability* of the material. For a high permeability material such as ferrite, at any given frequency the magnetic field in the core is much stronger than if a low permeability material such as wood were used. For ferrite, therefore, a greater back e.m.f. is obtained and hence a higher impedance. Since the impedance at any frequency is increased, it follows that the coil's inductance must have increased.

It can be seen, therefore, that increasing the permeability of the core leads to an increase in inductance of the coil.

Similarly, increasing the number of turns on the coil increases the back e.m.f. produced since not only do more turns lead to a stronger magnetic field being set up in the core but also the extra turns lead to the changing magnetic field producing a larger back e.m.f. An increased back e.m.f. in turn leads to a higher impedance, and hence higher inductance. Increasing the turns on the coil therefore gives rise to a rapid increase in the coil's inductance.

4. Confirm that direct current does not lead to a back e.m.f. being produced by observing that the bulb lights up with full brightness when the signal generator is replaced by a 9 V battery and that the bulb's brightness is unaffected by short-circuiting the inductor, i.e. connecting its ends together.

5. As in Circuit 4, the phase of the voltage and current in the circuit may be examined on a double-beam oscilloscope. It should be found that as in the case of the capacitor the voltages in the circuit are out of phase. In fact, if the frequency is adjusted so that the bulb is not lit, the voltage across the inductor is then nearly equal to the voltage from the supply and the waveforms on the oscilloscope then represent the waveforms of the voltage and current across the inductor. This is because the voltage waveform across the bulb is the same as the current waveform through it and since the same current must flow through the bulb and the inductor, the voltage waveform across the bulb and the current waveform in the inductor are therefore the same. It should furthermore be seen that the two waveforms are shifted apart by a quarter of a cycle and that the voltage waveform is a quarter of a cycle ahead of the current, i.e. is to the left of the current waveform on the screen. One complete cycle is often divided into 360°; we then talk of the voltage in the inductor leading the current by 90°.
If the measurement is repeated with a capacitor in place of the inductor, it should be found that in the capacitor the current now leads the voltage by 90°.

CIRCUIT 7

Tuned circuits

Wind a 100-turn coil and connect this first in series (Circuit A) and then in parallel (Circuit B) with a 1 μF capacitor.

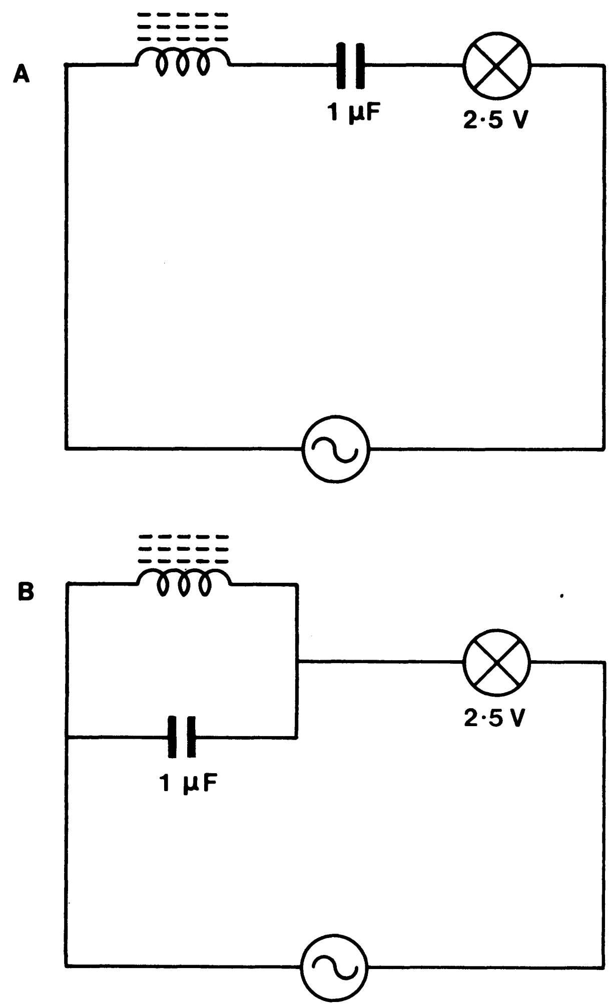


FIG. 1.17

New word

Resonant frequency

Guidance

See what effect using different values of capacitor and inductor have on the resonant frequency.

EXPLANATION 7

1. Make an identical coil to that used in Circuit 6 by winding 100 turns of plastic-covered wire onto a ferrite rod.
2. Connect up the coil in series with a 1 μF capacitor and bulb to a signal generator as shown in Circuit A in Fig. 1.17 above. Vary the frequency of the signal generator over its entire range, observing what happens to the bulb. It will be noticed that the bulb only lights up for a band of frequencies around 7 kHz. This is because at low frequencies the high impedance of the capacitor prevents the bulb lighting while at high frequencies the situation is reversed and it is the high impedance of the inductor at these frequencies that prevents the bulb from coming on. It is only for frequencies in the middle of the range when the impedances of the inductor and capacitor are approximately equal that the bulb lights.
3. Replace the 1 μF by a 0.1 μF capacitor and repeat the experiment above. Notice that now the range of frequencies over which the bulb lights up is higher and is centred on about 20 kHz. This is because the 0.1 μF capacitor has a higher impedance at any particular frequency than the 1 μF capacitor so the frequency at which the inductor's impedance will be equal to that of the capacitor will be higher than before.
4. Now connect up the 1 μF capacitor in parallel with the inductor as in Circuit B in Fig. 1.17 and again see what happens to the bulb as the frequency is varied. Replace the 1 μF by the 0.1 μF capacitor and repeat the experiment. Notice that with the capacitor and inductor in parallel, the bulb lights up for all frequencies except a band centred on 7 kHz for the 1 μF capacitor and 20 kHz for the 0.1 μF capacitor. These effects can again be explained in terms of the changes in the impedances of the inductor and capacitor with frequency. At low frequencies the low impedance of the inductor allows a large current to flow in the circuit, thus causing the bulb to light; at high frequencies the inductor's impedance is high but the capacitor's impedance is low and a large current thus flows through the capacitor allowing the bulb to light. It is only for frequencies at which the impedances of the inductor and capacitor are approximately equal that the bulb dims. Notice that the frequencies around which the bulb dims for the inductor and capacitor connected in parallel are the same as the frequencies around which the bulb lights when the two are connected in series. These frequencies are those at which the impedances of the inductor and capacitor are exactly equal. Mathematically, they are given by

$$f = \frac{1}{2\pi\sqrt{(LC)}}$$

with f in hertz, L in henrys, and C in farads.*

Decreasing C by a factor of 10 thus increases f by a factor of $\sqrt{10} \simeq 3$. This should have been confirmed by the observations above. The frequency at which the impedances of the two components are equal is called the *resonant frequency* of the circuit. Circuits with inductors and capacitors arranged in the above way are known as *resonant circuits.* They are also often referred to as *tuned circuits.*

* This can be derived as follows. The impedance of the inductor $Z_L = 2\pi fL$. The impedance of the capacitance $Z_C = \frac{1}{2\pi fC}$. At the resonant frequency

$$Z_L = Z_C, \quad \therefore \quad 2\pi fL = \frac{1}{2\pi fC}$$

$$f^2 = \frac{1}{4\pi^2 LC}$$

$$\therefore \quad f = \frac{1}{2\pi\sqrt{(LC)}}.$$

CIRCUIT 8

Transistor amplifier

Modify Circuit 5 as shown in Fig. 1.18.

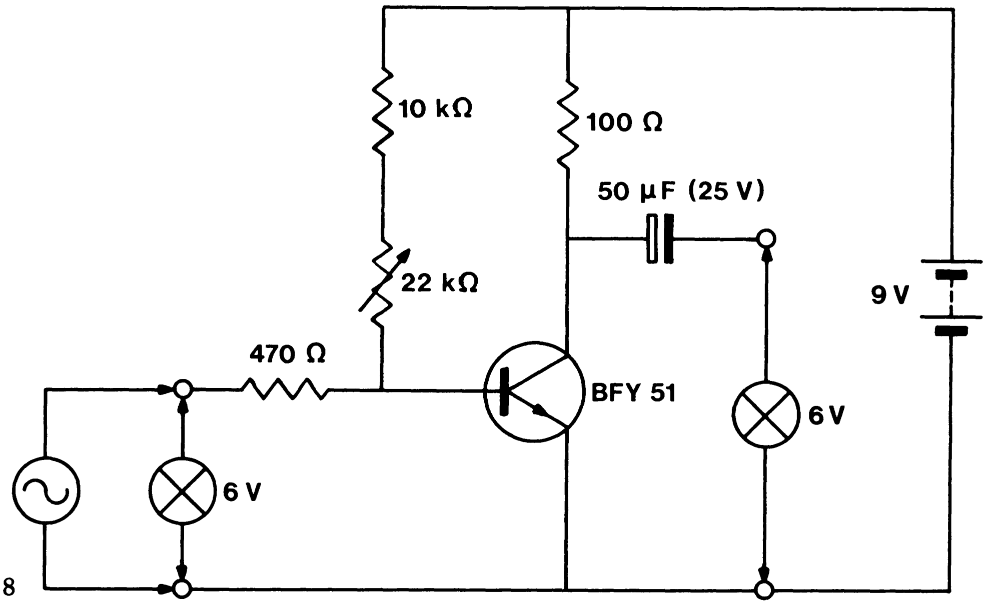


FIG. 1.18

New words

Voltage amplification   **Voltage gain**   **Decoupling capacitor**

Guidance

1. Adjust the 22 kΩ potentiometer to obtain a potential difference of 4.5 volts between the collector and emitter.
2. Compare the brightness of the bulb in the circuit with the brightness of a bulb connected directly across the signal generator terminals.
3. Use an avometer to calculate the gain of the amplifier. (Do not allow the output voltage to be greater than about 3 V r.m.s.)
4. Connect two earphones; one across the bulb, the other directly across the terminals of the signal generator.

EXPLANATION 8

1. Build the transistor circuit shown in Fig. 1.18. The circuit is basically the same as Circuit 5 except that the bulb in Circuit 5 has now been replaced by a 100 Ω resistor and a 470 Ω resistor has been added at the input to the circuit and a 50 μF capacitor at its output.
2. First, put an avometer across the 100 Ω resistor and by adjusting the variable resistor make the voltage roughly half the voltage of the battery, i.e. 4.5 volts.
3. Connect the circuit to the low impedance output terminals of the signal generator and set the frequency of this to about 1000 Hz. You should find that of the two bulbs, the bulb at the output of the circuit is brighter than that connected at the input. Notice also that the brightness of both bulbs depends on the output voltage from the signal generator and that the input voltage to the circuit is therefore controlling the brightness of both. Using an avometer confirm that the voltage across the output is, in fact, larger than the input voltage. It follows, therefore, that the circuit is causing a small voltage from the signal generator to control a larger voltage across the bulb at the output. The circuit is therefore acting as a *voltage amplifier.*

The circuit shows that although the transistor is basically a current amplifying device it can, nevertheless, be used to amplify voltage. The way in which this is achieved can be explained as follows: when the signal generator is connected to the circuit an alternating voltage appears across the 470 Ω resistor, and since the resistor is connected to the base of the transistor an alternating current flows through the resistor, into the base, out of the emitter and back to the signal generator. Notice that since the base-emitter voltage of the transistor must always remain at about 0.6 volts, little or no alternating voltage will appear on the base itself, and the voltage across the 470 Ω resistor must therefore be equal to the output voltage of the signal generator. From Circuit 5 it will be recalled that since the transistor behaves as a current amplifier, small changes in base current produce much larger changes in collector current. In the above circuit, therefore, the changes in base current caused by a.c. flowing across the base-emitter junction of the transistor cause a similar but much larger alternating current to flow between the collector and emitter. Some of this current flows through the capacitor and bulb and the result is that the latter lights. The voltage across the bulb will in general be dependent on the value of the collector resistor, the resistance of the bulb itself and the value of the capacitor. Since the currents in this part of the circuit, however, are much higher than the input current, the voltages at the output are also correspondingly higher than the input voltage and voltage amplification is thus obtained.

At high frequencies the 50 μF capacitor has a low impedance and there is, therefore, only a small voltage drop across it. When this is the case the voltage across the bulb is nearly the same as the voltage between the collector and emitter of the transistor and the circuit then behaves as if the bulb were connected directly to the collector. The capacitor then has no effect on the amplifier. Without the capacitor, however, direct current as well as alternating current would flow through the bulb and the purpose of the capacitor is therefore to prevent direct current from the battery flowing through the bulb when no signal is being fed into the amplifier. A capacitor used in this way is called a *decoupling capacitor.*

4. In an amplifier, the ratio of output voltage change to input voltage change is called the *voltage gain* or simply the *gain* of the amplifier. In general, therefore,

$$\text{voltage gain} = \frac{\text{change in output voltage}}{\text{change in input voltage}},$$

but when a.c. from a signal generator is being used, since a voltmeter, in effect, measures the amount the alternating voltage changes, the voltage gain of the amplifier is then simply the output voltage meter reading divided by the input voltage meter reading.

Use an avometer to measure the input and output voltages of the amplifier and from these calculate the gain of the amplifier. Calculate the gain for several settings of the signal generator output voltage but do not allow the output voltage of the amplifier to be larger than about 3 volts r.m.s. as the transistor then no longer acts as an amplifier and false values for the gain would therefore be obtained.

5. See what happens to the voltage gain as the frequency of the signal generator is decreased. Notice that it too decreases. This is because at low frequencies the decoupling capacitor's impedance becomes significant and the voltage drop across it prevents the voltage across the bulb being as large as the voltage across the collector–emitter of the transistor. Confirm this by measuring the voltages across the capacitor and bulb at different frequencies and see how one gets larger as the other gets smaller. From this it can be seen that if the amplifier is to be used to amplify low frequencies, a large capacitor must be used so that its impedance at these frequencies is small.

CIRCUIT 9

Transformer

Make a transformer with a primary winding of 100 turns and a secondary winding of 100 turns.

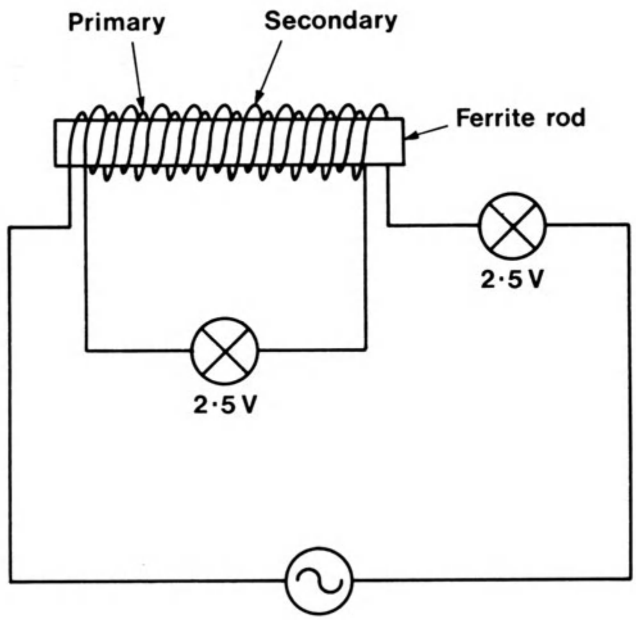


FIG. 1.19

Or, diagrammatically,

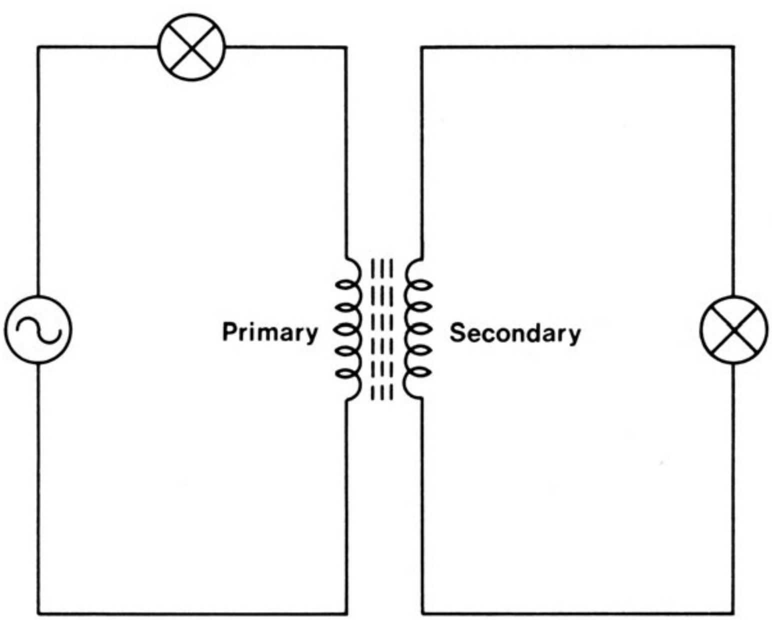


FIG. 1.20

New words

Primary winding **Secondary winding**

Guidance

1. Show that at high frequencies the circuit acts as a transformer.
2. Disconnect the bulb in the secondary and observe the effect on the bulb in the primary.
3. Show that the transformer only works with a.c. and not d.c.
4. Connect the bulb in the primary in parallel with the transformer instead of in series and investigate the effect of changing the number of turns on the secondary. Use an avometer to measure the voltages across the primary and secondary.

EXPLANATION 9

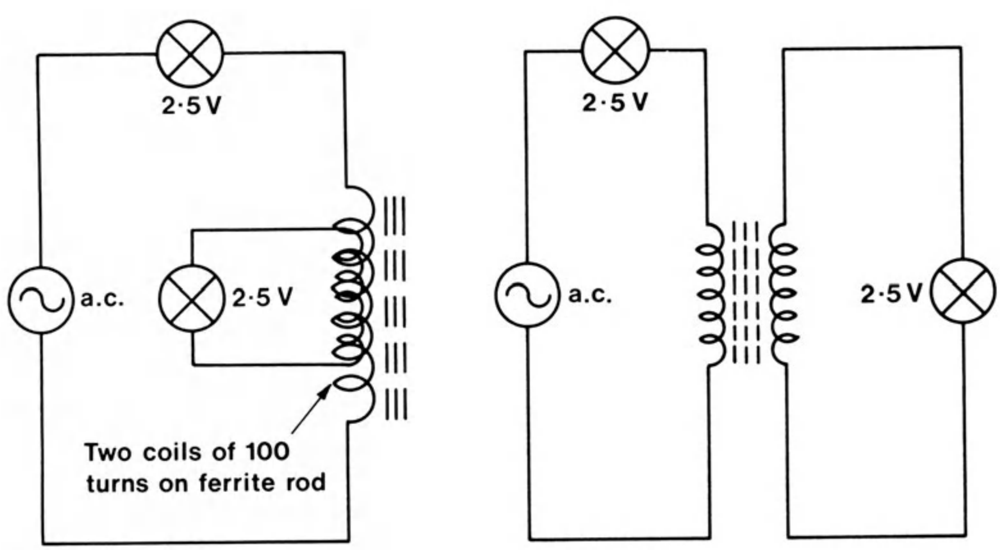


FIG. 1.21a FIG. 1.21b

1. Connect Circuit 6 to the signal generator and check again what happens at different frequencies.
2. Wind another coil of wire on top of the first, again of 100 turns. Connect the ends of this second coil to a bulb holder. Again connect the first coil to the signal generator via a bulb as in Circuit 6. The circuit of Fig. 1.21a illustrates this arrangement. Another way of drawing this is shown in Fig. 1.21b.
3. Switch the signal generator on at low frequencies and see whether the circuit behaves the same way as Circuit 6.

4. Turn the frequency of the signal generator up higher and see what happens. Does the bulb on the first coil behave the same as did that in Circuit 6? Notice that the bulb connected to the second coil now lights even though there is no connection between the wires in the first and second coil. This is because the two coils are now acting as a *transformer.* The first coil (the one connected to the power supply) is called the *primary* and the second coil (the one connected to the bulb) is called the *secondary.*
5. See what happens when the bulb connected to the secondary is removed. Notice the bulb in the primary goes out. This is because if no current flows in the secondary of a transformer then none can flow in the primary, hence the bulb in the primary cannot light up. At low frequencies the bulb in the primary *does* light up. This is because the two coils are not now behaving like a transformer.
6. Does the transformer work on d.c., i.e. using a battery instead of a signal generator? It will be seen that it does not; in fact a small transformer like this will only work at high frequencies.
7. Now connect the transformer to the signal generator as shown in Fig. 1.21c.

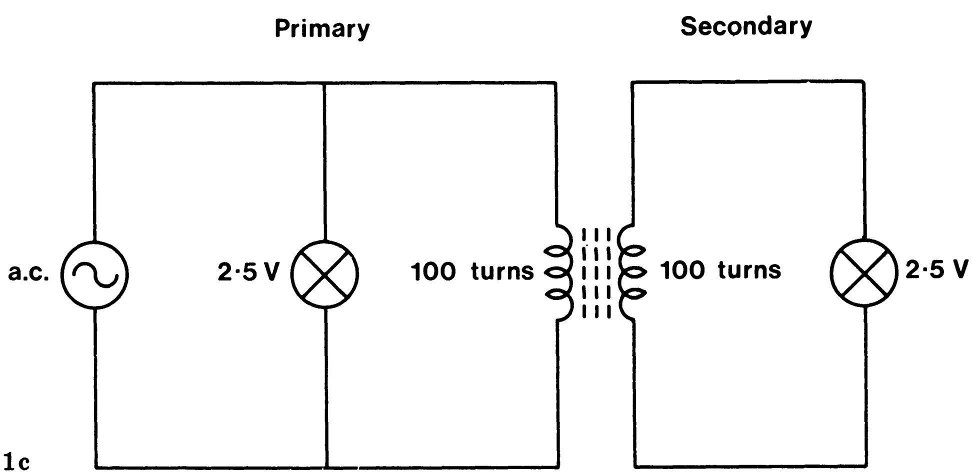


FIG. 1.21c

8. First take out the bulbs and set the signal generator to about 2 kHz (this being the highest frequency at which the avometer will work and the lowest at which the transformer works satisfactorily). Measure the voltage across the primary and across the secondary. They should be roughly equal. Put the bulbs in; they should light up with roughly equal brightness.
9. Take off 50 turns of wire from the secondary and now with only 50 turns on the secondary connect the circuit up again as in Fig. 1.21c. Again with the bulbs removed, check the voltage across the primary and secondary with the avometer. The voltage on the secondary should be roughly half that across the primary. Put the bulbs in and observe that the bulb in the secondary is dimmer than that in the primary. Taking turns *off* the secondary *reduces* the output voltage. Putting turns *on* the secondary *increases* the output voltage. In fact,

$$\frac{V_{out}}{V_{in}} = \frac{\text{turns on secondary}}{\text{turns on primary}}.$$

CIRCUIT 10

Charging and discharging a capacitor

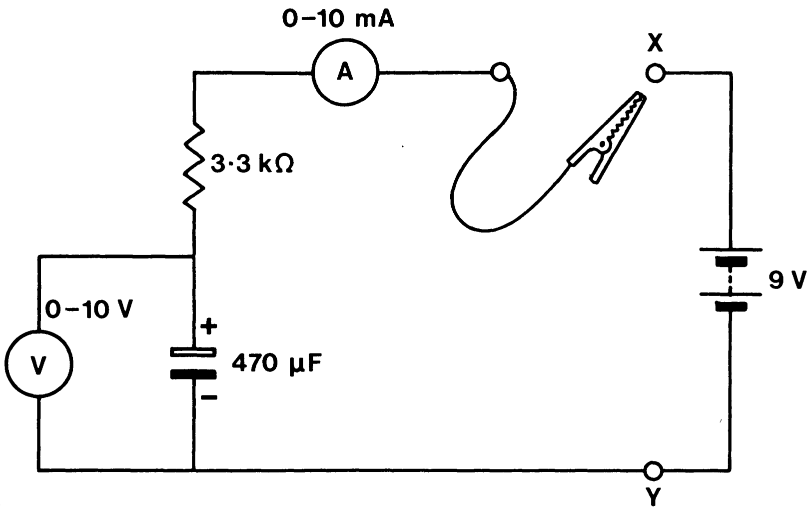
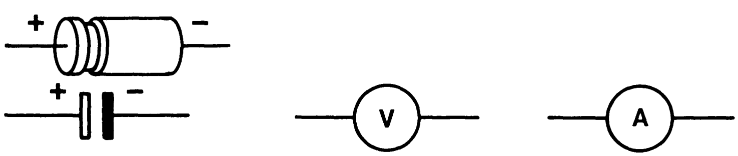


FIG. 1.22a

New symbols



Electrolytic capacitor | Voltmeter | Ammeter

New word

Charge

Guidance

Observe what happens to the voltage and current in the circuit when the capacitor is first charged (with the crocodile clip at X) and discharged (with the crocodile clip at Y).

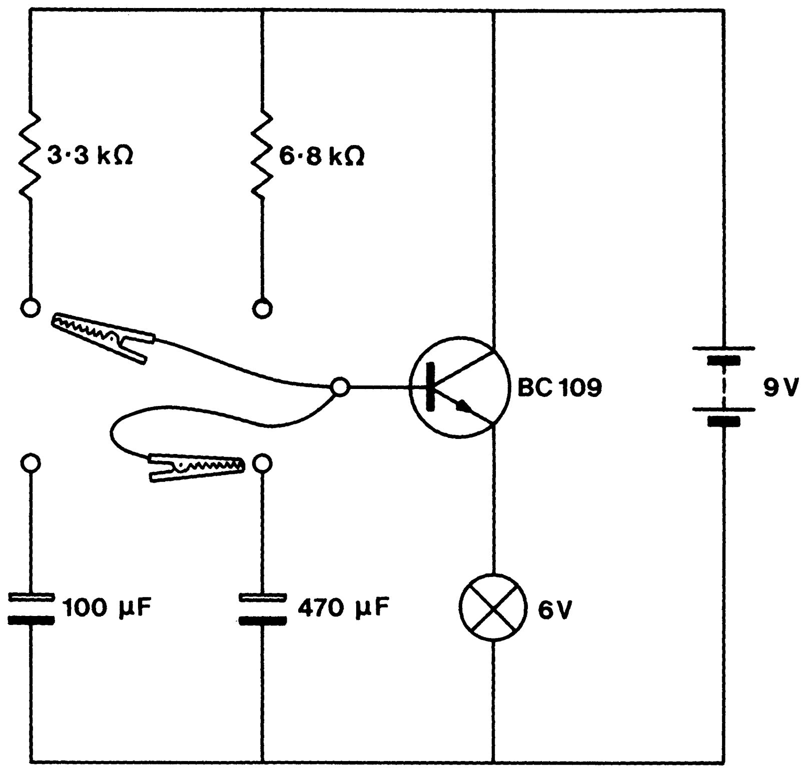


FIG. 1.22b

Guidance

Use the emitter follower circuit shown in Fig. 1.22b to investigate what effects the values of resistance and capacitance have on the charging and discharging times of the capacitor.

Definition of capacitance

$$C = \frac{Q}{V} = \frac{\text{charge}}{\text{voltage}}$$

C in microfarads (1 000 000 μF = 1 farad),
Q in microcoulombs (1 000 000 μC = 1 coulomb),
V in volts.

EXPLANATION 10

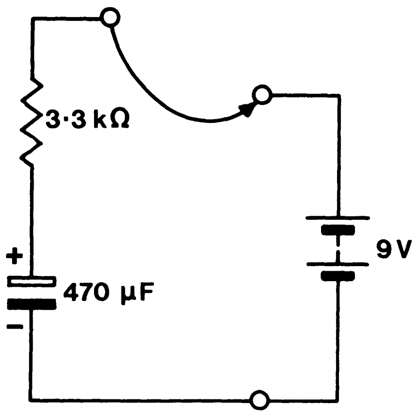


FIG. 1.23a

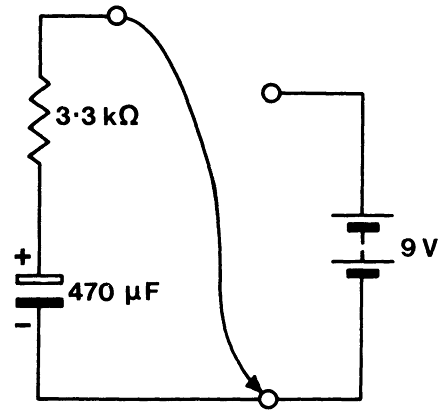


FIG. 1.23b

1. Connect a 470 μF electrolytic capacitor, a 6.8 kΩ resistor and a 9 V battery in series as in Fig. 1.23a. Using a voltmeter, watch what happens to the voltage across the capacitor when the battery is connected in circuit. You will see that the voltage increases, at first quite quickly, then as time passes, more slowly. When the voltage across the capacitor has become steady, disconnect the battery from the circuit and connect the resistor and capacitor together as shown in Fig. 1.23b. You should now find that the voltage across the capacitor drops, quickly at first then gradually more slowly. When the voltage across the capacitor is increasing the capacitor is said to be *charging up* and when it is decreasing it is said to be *discharging*.

2. Now measure the current in the circuit as the capacitor charges up and discharges. You should see that in both cases the current is at first quite large and then falls, first quickly and then more slowly, to zero. Capacitors store electricity and the electricity that is stored is called *charge* (measured in coulombs). Current, in fact, is just charge moving round the circuit (1 amp = 1 coulomb flowing in 1 second). An important property of the capacitor is that the voltage across its terminals depends on how much charge is stored in the capacitor. Thus when a capacitor is charging or discharging, the voltage across its terminals is either increasing or decreasing and, as a result, its stored charge increases or decreases and current flows from the battery round the circuit. When the charging or discharging is complete the charge in the capacitor becomes steady and no more charge flows in the circuit. Current therefore only flows during charging or discharging and is zero at other times. The size of a capacitor is measured in terms of the amount of charge it stores for any value of voltage across its terminals, thus,

$$C = \frac{Q}{V} = \frac{\text{charge}}{\text{voltage}}$$

C in microfarads (1 000 000 μF = 1 F)
Q in microcoulombs (1 000 000 μC = 1 C)
V in volts

3. To find out how the values of capacitor and resistor affect the speed with which the capacitor charges or discharges, build the circuit of Fig. 1.23c. In the circuit the change

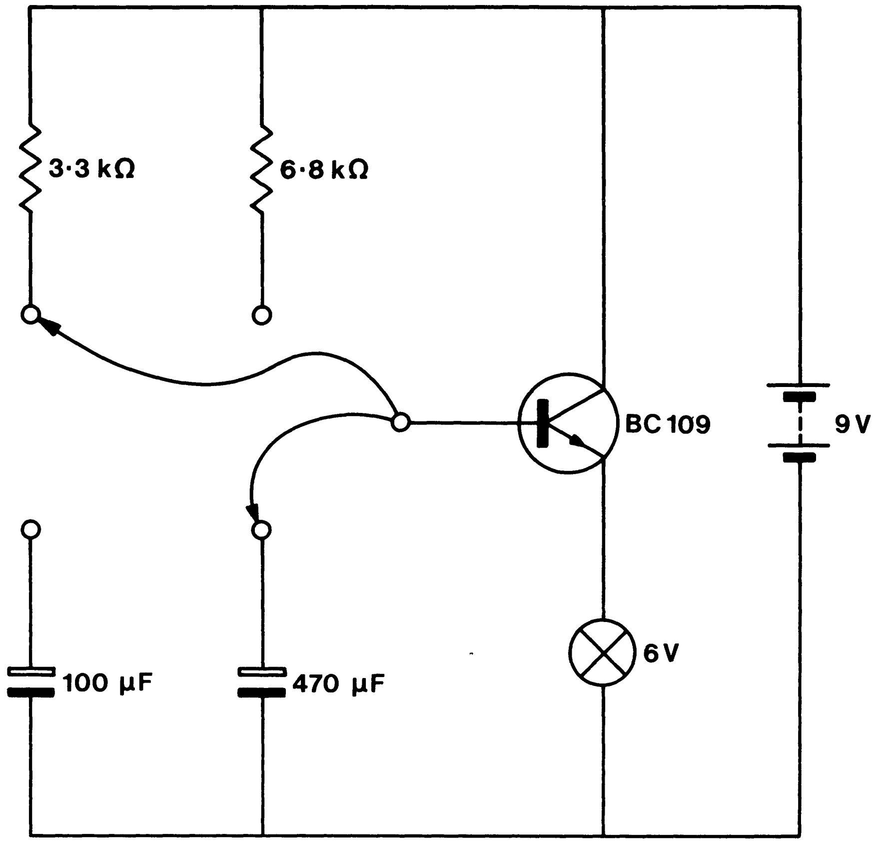


FIG. 1.23c

in brightness of the bulb is used to indicate the change in voltage across the capacitor. The bulb cannot be connected directly in parallel with the capacitor, as we would like, since the resistor does not allow enough current to flow into the bulb to light it. The transistor is used to overcome this difficulty since it allows a large current to flow into the bulb from its emitter while taking only a small current from the resistor through its base. Also, since the base–emitter voltage is always constant at about 0.6 V, the voltage across the bulb is more or less equal to that across the capacitor. This circuit is called an *emitter follower* since the voltage on the emitter follows the changes in the base voltage.

4. With the 470 μF and 6.8 kΩ resistor connected in circuit, find out how long it takes the capacitor to charge up. Next, remove the connection to the resistor and see how long it takes the capacitor to discharge. Repeat these tests using the 3.3 kΩ resistor instead of the 6.8 kΩ resistor and then using the 100 μF with the two resistors in turn. Notice that making the capacitor or resistor smaller decreases the charging time. The explanation for this is that a small resistor allows a larger current to flow, thus charging up the capacitor quicker, while a smaller capacitor stores less charge than a larger one and hence can charge up more rapidly. For the same reason a large capacitor takes longer than a small one to discharge.

CIRCUIT 11

Transistor switch

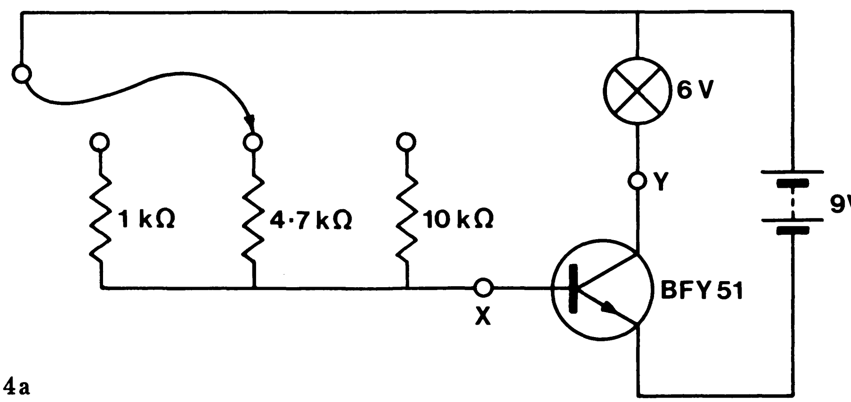


FIG. 1.24a

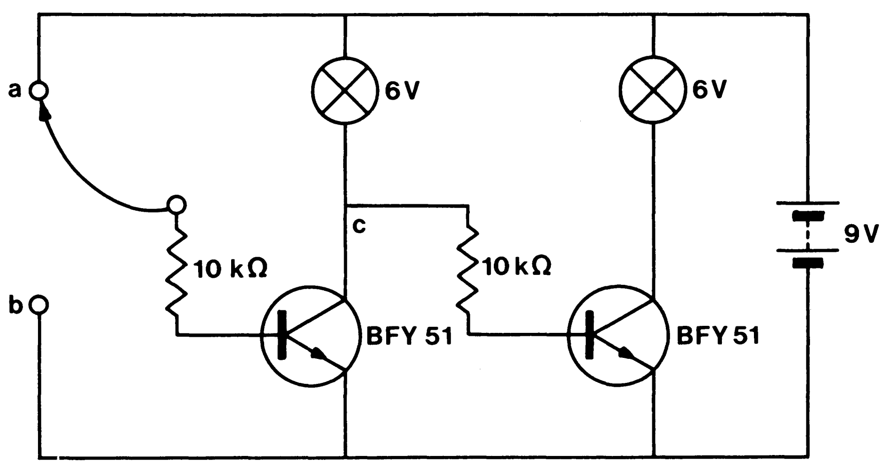


FIG. 1.24b

New words

Saturated transistor

Guidance

1. Measure the currents in the circuit shown in Fig. 1.24a at points X and Y and investigate the effects of different values of base resistor on these.

2. Investigate the use of a saturated transistor as a switch by building the circuit shown in Fig. 1.24b.

EXPLANATION 11

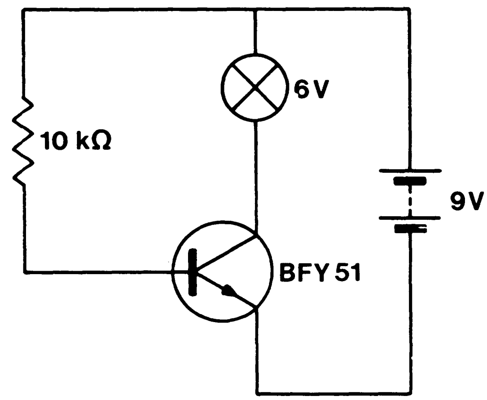


FIG. 1.25

1. The circuit shown in Fig. 1.25 is the same as that used in Circuit 5 for demonstrating the current amplification in a transistor. The effect of all the resistances in the transistor base circuit, i.e. the 22 kΩ variable resistor, the fixed 10 kΩ resistor and the 6 V bulb has been represented by a single resistor. With the variable resistor set to a minimum this is roughly 10 kΩ. Remember that when the variable resistor was set to its minimum, the bulb lit with full brightness. To find out what happens when the base resistance is reduced even more, build the circuit shown in Fig. 1.24a.
2. See what happens when the crocodile clip is connected in turn to the 1, 4.7 and 10 kΩ resistors. Notice that the brightness of the bulb is the same in each case, which means the collector current must be the same for each. Confirm this by measuring the currents at points X and Y for each value of resistor. You should find that although the base current gets larger as the resistance decreases, the collector current stays constant at about 60 mA. Under these conditions, therefore, changes in base current no longer produce proportionally larger changes in collector current and the transistor no longer behaves as an amplifier. In this situation the transistor is said to be *saturated.* A transistor becomes saturated when the voltage between its collector and emitter becomes very small, usually about 0.2 volts. With a meter show that the voltage between the collector and emitter is about 0.2 volts for each resistor and that the transistor must, therefore, always be in saturation.
3. Although saturated transistors cannot be used as amplifiers, they do have another useful property in that they can be used as switches. This is because when the transistor is saturated, nearly all the battery e.m.f. of 9 V appears across the bulb (only 0.2 V is across the collector-emitter of the transistor, so 9 V − 0.2 V = 8.8 V is across the bulb), resulting in the bulb lighting up with full brightness, i.e. being switched on. On the other hand, when no base current is flowing, no collector current can flow either and the bulb is therefore switched off. The transistor therefore acts as a switch for the bulb

such that the switch is off when no base current flows and is on when enough base current flows to saturate the transistor. Since the collector current is about 60 mA and the base current to saturate the transistor less than 1 mA we have a very useful situation in that a small current is being used to switch on and off a larger current. This is not the same as the amplification property, because the actual value of base current used to switch the bulb on does not matter provided that it is large enough to cause saturation.

The circuit in Fig. 1.24b demonstrates the transistor switch. Build this circuit and see what happens as the position of the crocodile clip is changed from point a to point b. Notice that this circuit is just like two transistor switches, as in Fig. 1.24a, connected with the output of the first going into the input of the second (the same battery is used for both transistors). You should find that when the first bulb is switched on, the second is off, and vice versa. What is happening in the circuit is that the crocodile clip allows current to flow into the first transistor, thus switching the first bulb on, only when it is connected to 9 V, i.e. point a. Similarly, the base current can only flow into the second transistor when 9 V is applied to its base resistor at point c. Since the bulb is either on or off, either 0.2 V or 9 V must be at point c at all times and the result is that the second transistor is off or on depending on which condition is present. Thus when bulb 1 is on, 0.2 V is at point c and bulb 2 is off, and when bulb 1 is off, 9 V is at point c and bulb 2 is on. When one bulb is on, therefore, the other is always off.

CIRCUIT 12

Bistable and binary counter

Modify Circuit 11 to obtain the circuit below.

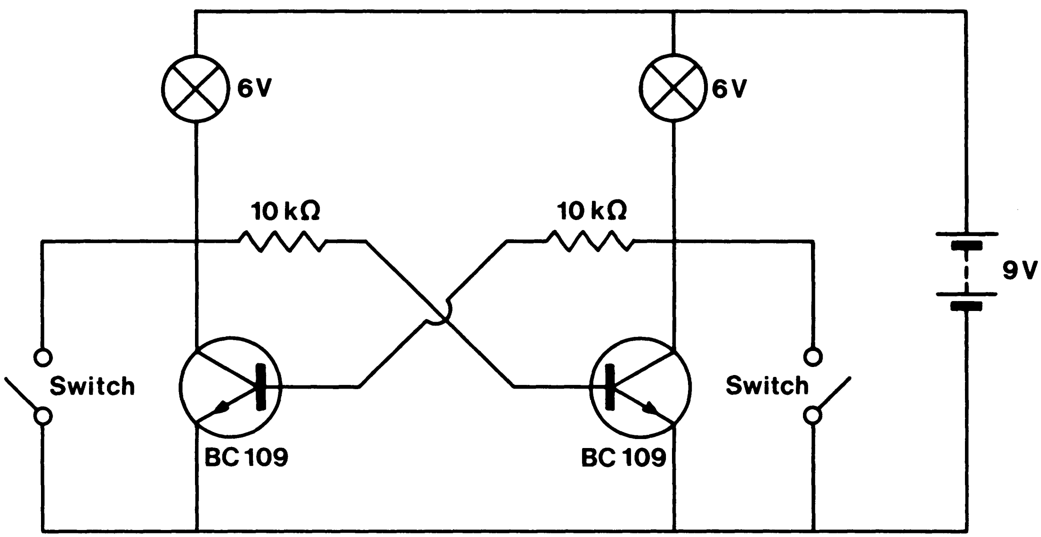


FIG. 1.26

After testing, modify this further to obtain the bistable circuit:

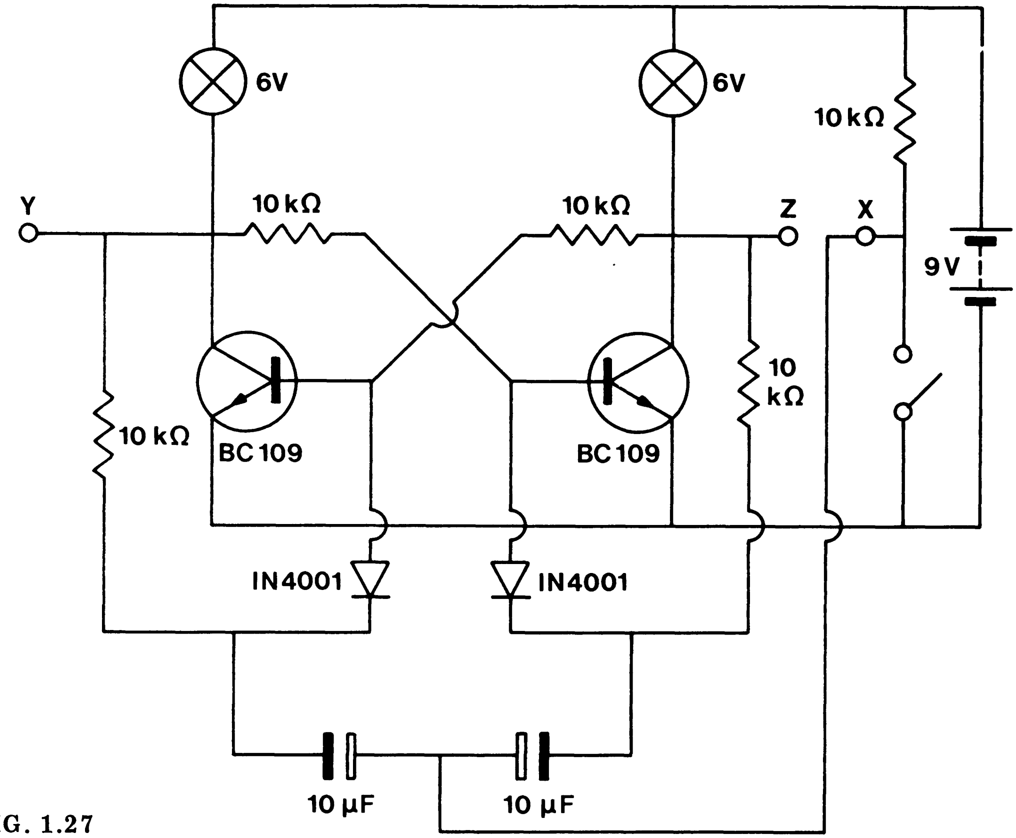


FIG. 1.27

Guidance

Investigate the effects in both circuits of closing the switches.

Connect four bistable circuits together to form a four stage binary counter. Connect the output Y of each stage to the input X of the next stage. Connect the input of the first stage to a switch as before.

New symbol

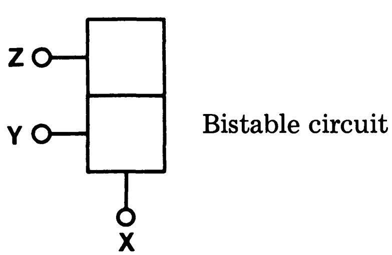


FIG. 1.28

Thus for the four stage counter

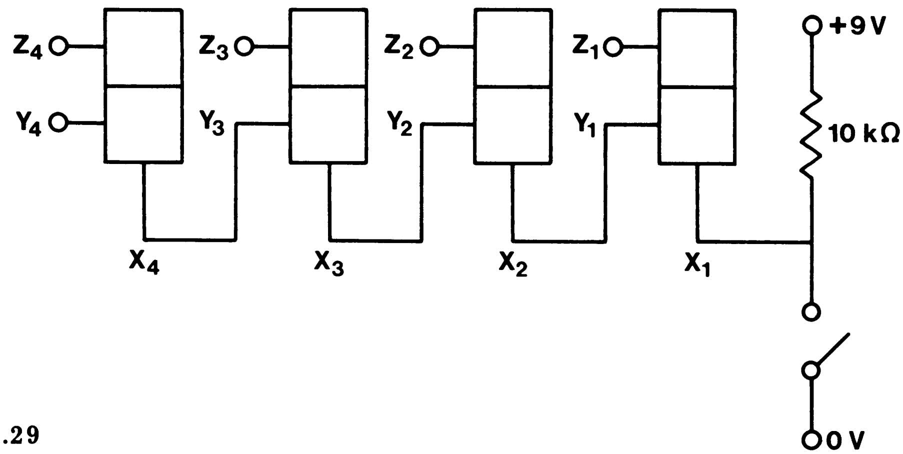


FIG. 1.29

New words

Electrical pulse **Pulse counter**

Guidance

The use of the circuit as a frequency divider and binary counter is outlined in the text.

Note

Because of the relatively large current required by this circuit, a well regulated power supply should be used.

EXPLANATION 12

1. The circuit of Fig. 1.30a is basically the transistor switch circuit introduced in Circuit 11, with the output (collector) of the second transistor connected to the input (base) of the first transistor. Build this circuit, and then connect two pieces of wire as shown below to act as switches such that, when either is closed, the collector and emitter of the appropriate transistor will be shorted together. By joining together the emitter and collector of the first transistor, or those of the second transistor, it should be found that the two bulbs can be made to light up alternately. The reason for this behaviour should be clear from the explanation given in Circuit 11 of the behaviour of a transistor switch. The circuit is called a *bistable* since it is stable with either of the two bulbs lighting up, i.e. it has two stable states. It is widely used in electronics, particularly in digital computers.
2. By removing the two wires and replacing these by the additional resistors, capacitor and diodes shown below in Fig. 1.30b, another important kind of bistable circuit is

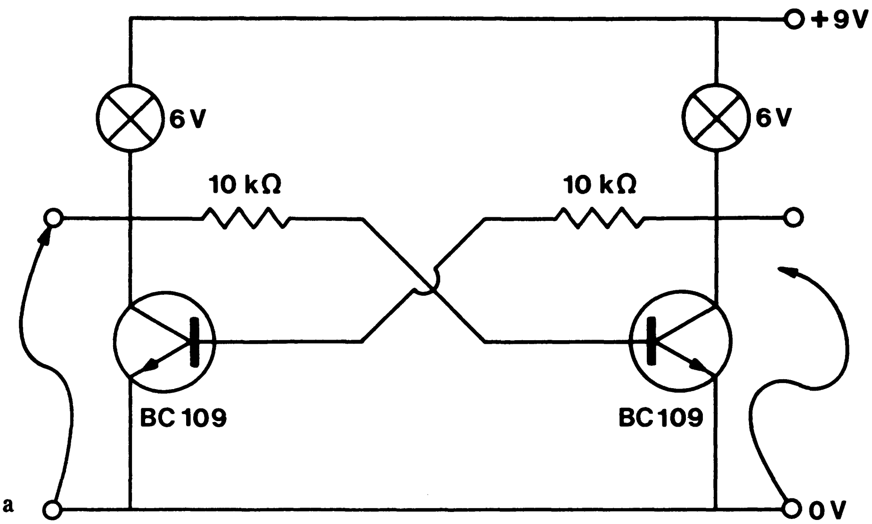


FIG. 1.30a

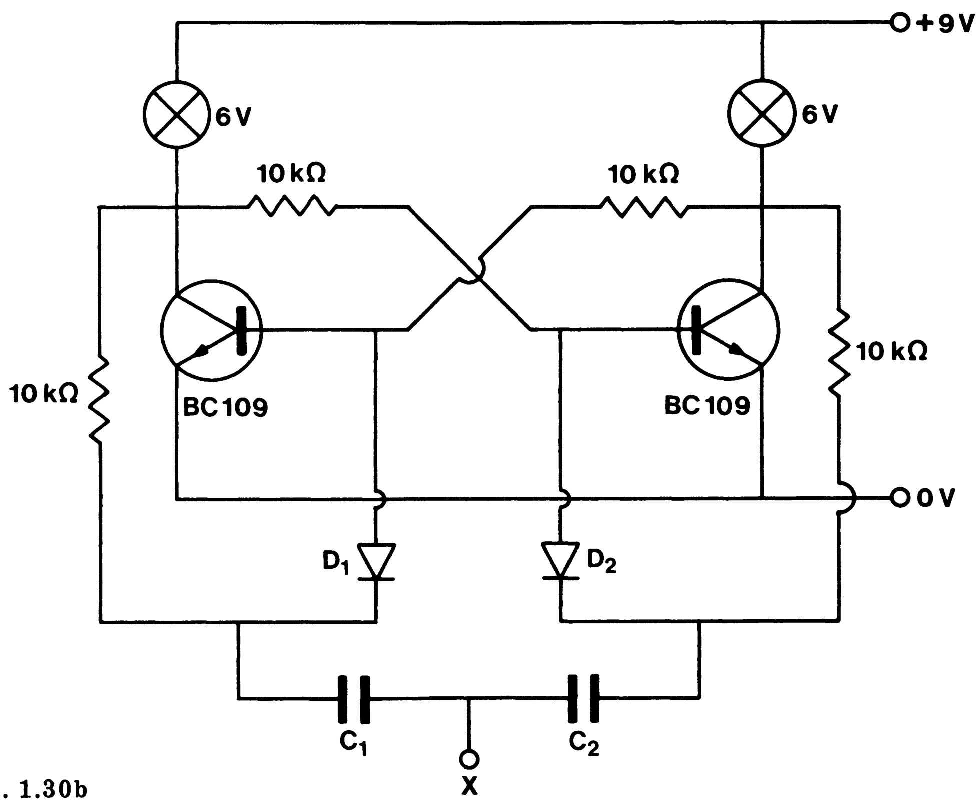


FIG. 1.30b

obtained. With this circuit only one switch is required to make the bulbs light up alternately. Build this circuit and confirm that as point X is connected from 0 V to +9 V and back to 0 V, the bulbs light up alternately, with the bulbs changing over every time X goes from +9 V to 0 V.

The explanation for this is as follows. Consider first the situation in which the first bulb is ON and the second bulb OFF, also point X at +9 V. Capacitor C_1 now charges up to +9 V through the 10 kΩ resistor because one end of C_1 is at +9 V, while the end of the 10 kΩ resistor, which is connected to the collector of the first transistor, is around 0 V. Notice that the diode, D_1, does not conduct since it is reversed biased during the charging period. This is because its positive end is always at the base voltage of the first transistor (about 0.6 V) while its negative end is always at a more positive voltage. D_1, therefore, does not affect the charging of capacitor, C_1. Capacitor C_2, on the other hand, does not charge up as the end of its 10 kΩ charging resistor is connected to the second transistor collector which is at +9 V. Thus, no potential difference exists across the capacitor–resistor combination. Like D_1, D_2 is reversed biased and therefore has no effect in the circuit.

When point X is suddenly switched from +9 V to 0 V, the charge on C_1 instantaneously remains at +9 V and the end of C_1 connected to the diode therefore drops to −9 V. D_1 now conducts since it becomes forward biased and pulls the base voltage of the first transistor negative. The result is that base current stops flowing in the first transistor, the transistor switches OFF thus turning the second transistor ON. D_2 does not conduct during this sequence of events since C_2 is uncharged and hence the voltage on D_2 only falls to 0 V and not negative as with D_1.

When the voltage at point X is now returned to +9 V the situation is reversed since now the second transistor (and hence the second bulb) is ON and the first transistor (and hence the first bulb) is OFF. The result is that this time C_2 charges up while C_1 discharges through the 10 kΩ resistor connecting it to +9 V. Consequently, the next time point X goes from +9 V to 0 V, D_2 conducts, pulling the base of the second transistor negative, switching OFF the transistor and second bulb, thus in turn switching ON the first transistor and bulb. On returning to +9 V at X, the whole cycle starts again.

In order, therefore, to switch the voltage across the first bulb from 0 V to +9 V and then back to 0 V, point X must be switched from 0 V to +9 V, back to 0 V, back to +9 V, then finally back to 0 V. The voltage at point X therefore needs to be switched twice for the voltage across the bulb to switch once. This is a very important property since it enables us to divide frequencies by two. For example, a voltage switching ON and OFF at 100 Hz at point X would give a voltage switching ON and OFF at 50 Hz across the bulbs.

Since the circuit can divide frequencies by 2, two or more of these circuits can be connected together to divide by 2, 4, 8, 16, etc. A combination of such circuits can be used as a counter to count the number of times a voltage switches ON and OFF. A voltage which switches between two voltages is called an *electrical pulse* and the circuit can therefore be referred to as a *pulse counter.*

A combination of four of these *bistables*, connected to form a counter, is shown in Fig. 1.31. Only one bulb is used in each circuit or *stage*, since this is all that is necessary to indicate the state of each circuit. The first bulb has therefore been replaced by a 1 kΩ resistor.

Let us assume initially that the counter has all bulbs switched OFF, i.e. the first transistor in each stage is switched ON. When the switch is now pressed for the first

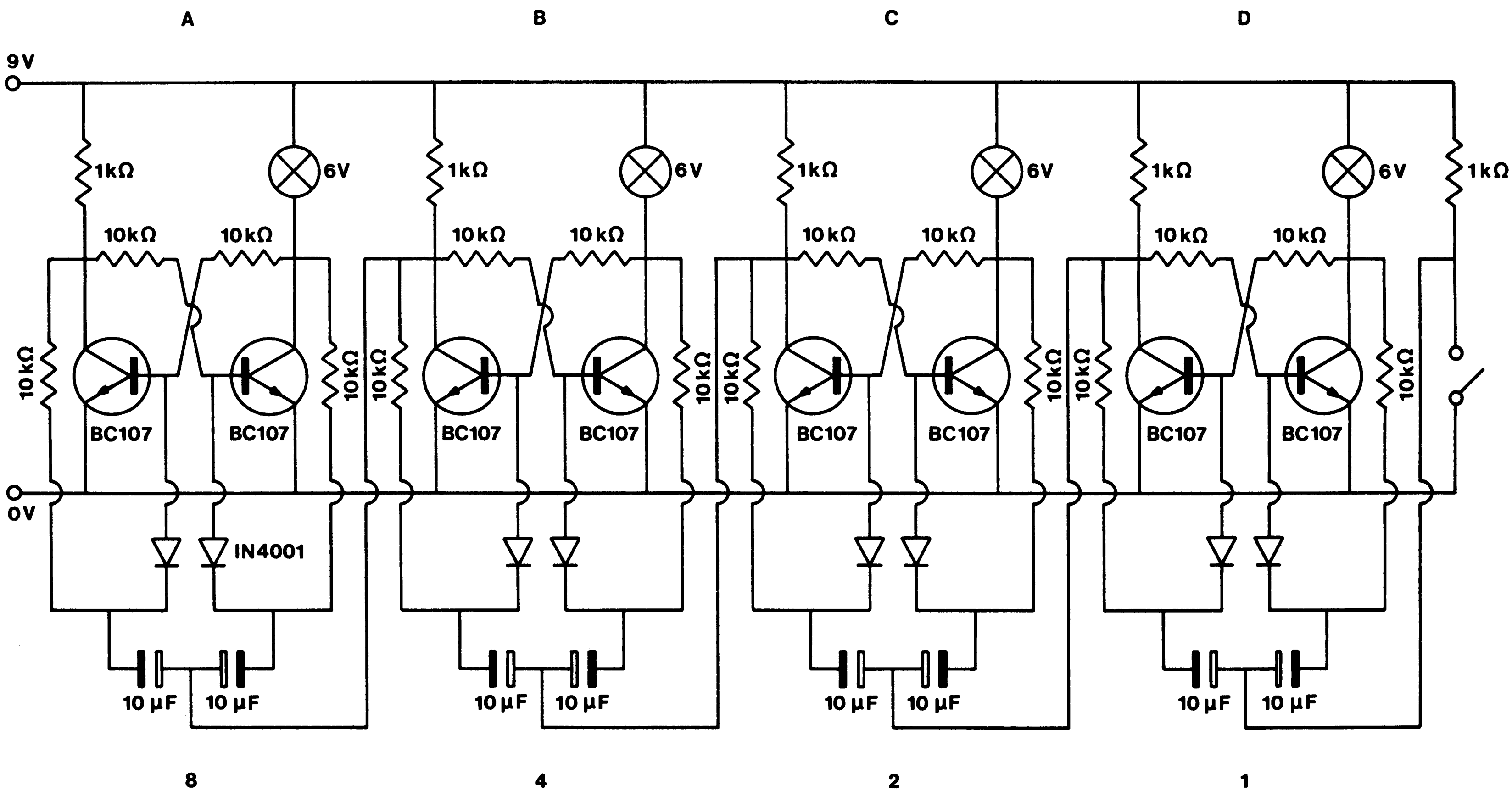


FIG. 1.31 Four bistables connected to form a counter.

time the voltage at the input of the first stage (stage D) goes from +9 V to 0 V with the result that the stage changes state and the bulb in this stage switches ON. The second time the switch is pressed, i.e. when the second pulse is fed into the circuit, the first stage changes state again, the bulb goes OFF, the first transistor in this stage switches ON and the voltage on its collector and hence the voltage at the input to the second stage (stage C) goes from +9 V to 0 V. The changing voltage at the input to the second stage switches the bulb in this stage ON. For the third pulse, the bulb in the first stage comes on again and the voltage at the input to the second stage returns to +9 V, leaving the bulb in the second stage still switched ON. Both bulbs are ON, therefore, after the third pulse. On the arrival of the fourth pulse, the first stage changes state again, its bulb goes off, the second stage changes state, its bulb goes off also, and a negative going voltage is applied to the input of the third stage with the result that it too changes state and the bulb in this stage therefore lights up.

It can be seen, therefore, that the bulb in the first stage comes on after one pulse, the bulb in the second stage after two pulses, and the bulb in the third stage after four pulses. In a similar way the bulb in the fourth stage comes on after eight pulses. By looking which bulbs are on in the circuit and which are off, we can therefore tell how many pulses have been fed into the counter. For example, if the bulbs in the fourth and second stages are on, since it takes eight pulses to light up the fourth stage and two pulses to light up the second, it follows that eight pulses followed by another two pulses, i.e. ten pulses, must have been fed into the counter.

The states the counter goes through are as follows:

Number of pulses	*Stage A*	*Stage B*	*Stage C*	*Stage D*
0	OFF	OFF	OFF	OFF
1	OFF	OFF	OFF	ON
2	OFF	OFF	ON	OFF
3	OFF	OFF	ON	ON
4	OFF	ON	OFF	OFF
5	OFF	ON	OFF	ON
6	OFF	ON	ON	OFF
7	OFF	ON	ON	ON
8	ON	OFF	OFF	OFF
9	ON	OFF	OFF	ON
10	ON	OFF	ON	OFF
11	ON	OFF	ON	ON
12	ON	ON	OFF	OFF
13	ON	ON	OFF	ON
14	ON	ON	ON	OFF
15	ON	ON	ON	ON
16	OFF	OFF	OFF	OFF

If the ON state is represented by writing '1' and the OFF state by writing '0', the following numbers can be used to represent the states of the counter:

Number of pulses	*A*	*B*	*C*	*D*
0	0	0	0	0
1	0	0	0	1
2	0	0	1	0
3	0	0	1	1
4	0	1	0	0
5	0	1	0	1
6	0	1	1	0
7	0	1	1	1
8	1	0	0	0
9	1	0	0	1
10	1	0	1	0
11	1	0	1	1
12	1	1	0	0
13	1	1	0	1
14	1	1	1	0
15	1	1	1	1

These numbers are the binary numbers for 0 to 15 and the counter can therefore be regarded as a *binary counter* with the bulbs ON representing '1' and the bulbs OFF '0'. The binary counter is used a great deal in computers since all digital computers use binary numbers to perform calculations.

CIRCUIT 13

Monostable circuit

Build the following circuit:

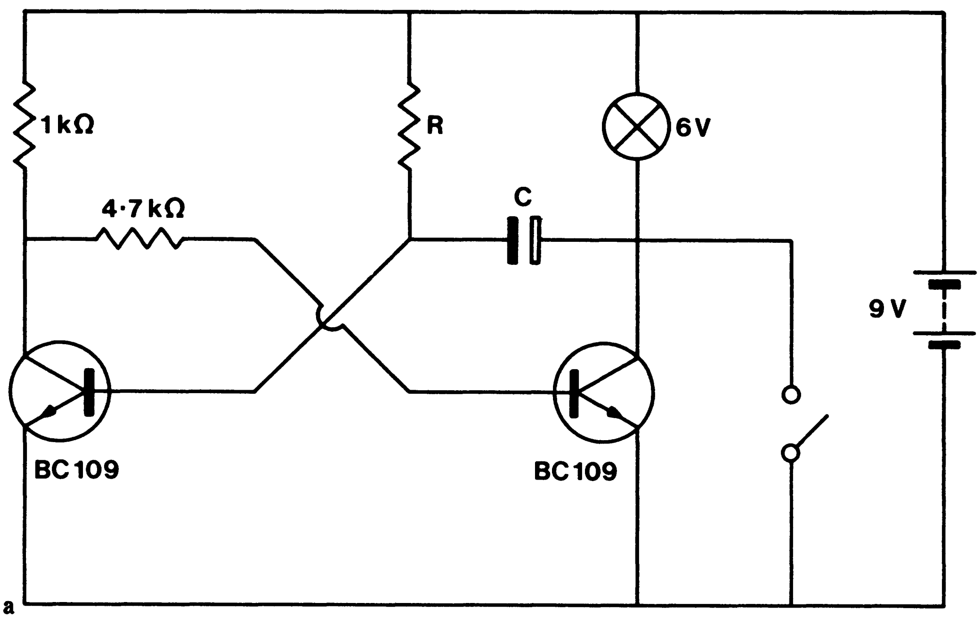


FIG. 1.32a

Guidance

Using values of 10 kΩ and 33 kΩ for the resistor, R, and values of 47 μF (25 V) and 100 μF (25 V) for the capacitor, C; investigate the operation of the circuit for all combinations of R and C.

Modify the circuit to obtain:

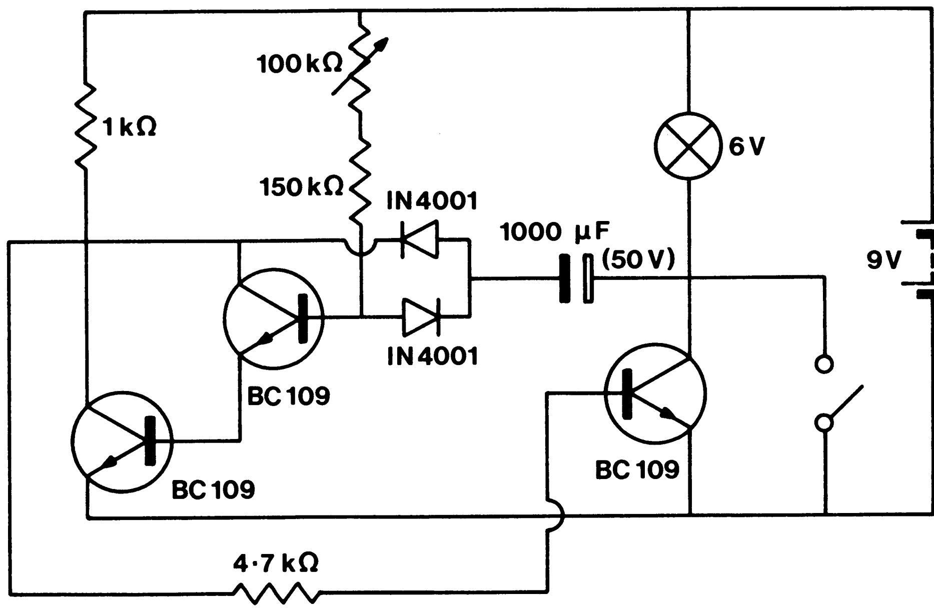


FIG. 1.32b

New words

Time constant **Darlington pair**

Guidance

See what effect changing the setting of the 100 kΩ variable resistor has on the operation of the circuit.

EXPLANATION 13

1. The circuit in Fig. 1.32a above will be recognized as being similar in arrangement to the bistable circuit introduced in Circuit 12. However, one of the base resistors in the bistable circuit has now been replaced by a capacitor, C, and another resistor, R, added. Build this circuit and arrange it so that values of R of 10 kΩ and 33 kΩ can be switched in at will, similarly values of C of 47 µF (25 V) and 100 µF (25 V) can be selected. Now see what happens as the switch, S, is momentarily closed. It should be seen that even though the switch is closed for a very short time the bulb stays ON for several seconds after this, and that the length of time the bulb stays on is determined by the values of R and C used.

To explain the operation of the circuit consider first the conditions present in the circuit before the switch is closed. Resistor R is chosen to be small enough to allow a sufficient base current to flow into the first transistor to ensure it is fully switched on.

In the initial state, therefore, this transistor is switched on and as a result the collector of this transistor is at about 0 V.

Consequently, no potential difference exists across the 4.7 kΩ base resistor of the second transistor, no base current therefore flows and the transistor is thus switched off and the bulb also. About 0.6 V is now at the negative end of capacitor, C, and 9 V at its positive end with the result that it is charged up. If the switch is now closed instantaneously, the collector voltage of the second transistor falls to 0 V and capacitor, C, remaining fully charged therefore drives the base of the first transistor negative. The first transistor then switches off and consequently the second switches on. Thus, the bulb is held on and the voltage on the second transistor collector is maintained at 0 V even though the switch may now have been opened again. This state of affairs is maintained until capacitor, C, has discharged sufficiently through R to allow the base voltage of the first transistor to become positive again and for it to therefore switch on once more. When this occurs the second transistor is again switched off and the bulb extinguished and C charges up again rapidly through the low resistance of the 6 V bulb. As soon as C is charged the process may be repeated. The time taken for C to discharge to 0 V through R is, in fact, given by the formula

$$T = 0.7\,CR,$$

where T is in seconds, C in microfarads and R in megohms.* The product of C and R is called the *time constant* of the resistor–capacitor combination. Because the circuit is only fully stable in one state, that is, with the bulb switched off and the first transistor switched on, it is known as a *monostable.*

2. The monostable can be used as a timer. That is, by choosing the correct values for R and C the bulb can be made to stay on for any length of time required. By making R and C very large the bulb can be made to stay on for several minutes. Making R and C very large can cause certain problems, however. First, if R is too large, not enough current will be able to flow into the first transistor base to switch this on. Large values of C are also very bulky and expensive. The circuit in Fig. 1.32b is a modification of that in Fig. 1.32a which permits much larger values of R to be used. Notice that the first transistor has now been replaced by two transistors. This combination is known as a *Darlington pair*, and allows very small base currents to switch the transistors. The diodes are for protection of the transistors in the Darlington pair during the charging of the capacitor. Build the circuit and use a combination of a 150 kΩ fixed resistor and a 100 kΩ variable for R. The 100 kΩ may be increased to about 330 kΩ if desired.

* T will also be in seconds when C is measured in farads and R in ohms.

CIRCUIT 14

Multivibrator

Modify Circuit 13 to obtain:

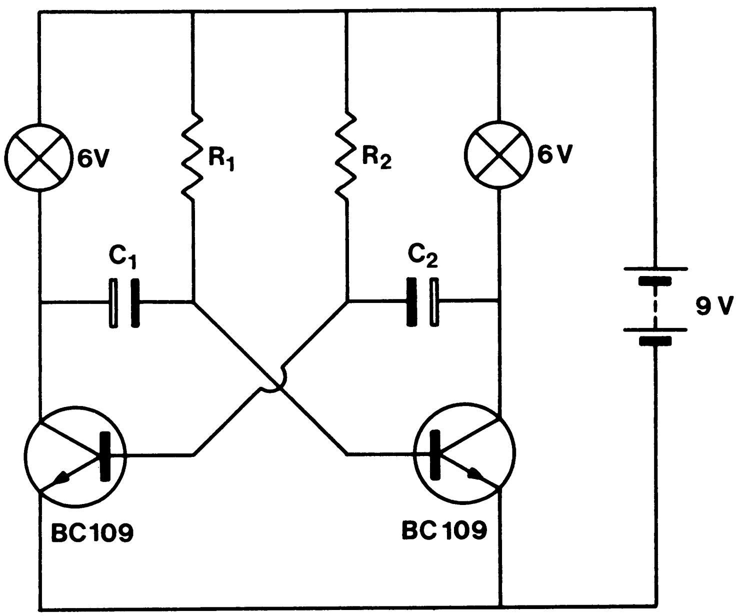


FIG. 1.33

New words

Oscillator circuit **Square wave**

Guidance

1. Observe what happens in the circuit when 1 kΩ resistors are used for R_1 and R_2 and 250 μF (25 V) capacitors for C_1 and C_2. Then, either changing the resistors to 10 kΩ or the capacitors to 50 μF (25 V), observe what happens. Try all combinations of R and C.
2. Connect an earphone between the collector and emitter of one of the transistors and see what happens when R_1 and R_2 are changed from 1 kΩ to 10 kΩ.
3. Connect an oscilloscope to the circuit in the same way and again investigate the effects of changing R_1 and R_2.
4. Investigate the effects of connecting the multivibrator to the input of the binary counter (Circuit 12).

EXPLANATION 14

1. If the bistable circuit of Circuit 12 is modified to include the resistors R_1 and R_2 and capacitors C_1 and C_2 as shown in Fig. 1.33, a very useful circuit is obtained. This is known as the *multivibrator.* Build the multivibrator circuit shown above and design the layout of this in such a way that resistors R_1 and R_2 can be chosen to be either 1 kΩ or 10 kΩ and capacitors C_1 and C_2, 250 μF (25 V) or 50 μF (25 V). When the circuit is working it should be found that the bulbs switch on and off alternately at a regular rate and when the values of R or C are changed the flashing rate also changes.

The operation of the circuit can be explained by considering it to be a combination of two timer circuits. If it is assumed initially that the circuit is in a state with the first transistor and bulb switched on and that immediately prior to the transistor being switched on, capacitor C_1 was fully charged to +9 V, it follows that the voltage on the base of the second transistor will be held negative by C_1, holding this transistor off, for the time it takes C_1 to discharge enough through R_1 to allow the base voltage on the second transistor to become positive and this transistor to switch on. During the period that the second transistor is off, capacitor C_2 charges up to +9 V through the small (~ 100 Ω) resistance of the 6 V bulb. It should be noted that as with the timing circuit, resistors R_1 and R_2 should be chosen such that they can supply enough current to keep the transistors fully switched on. When the second transistor switches on, the second bulb also comes on and the voltage on the transistor collector falls to 0 V. This results in C_2 driving the base of the first transistor negative, and hence the first transistor and bulb switching off. The situation is now reversed and C_1 charges up rapidly to +9 V through the resistance of the first bulb. After C_2 has now discharged sufficiently through R_2, the first transistor and bulb come on again and the second transistor and bulb are thus again switched off. The circuit is now back in the state assumed initially and the whole cycle of events occurs again. Once this switching backwards and forwards between the two states begins, the situation continues indefinitely. In practice, whenever the e.m.f. is applied to the circuit at switch-on, one transistor always switches on slightly faster than the other and this is sufficient to start the circuit flashing. Since the time taken for the capacitors in the circuit to discharge sufficiently to turn the transistors on is given by $0.7\,CR$, the time for which the first transistor is switched off is

$$T_1 = 0.7\,C_2 R_2$$

when T is in seconds, C in farads and R in ohms. The time for which the second transistor is off is similarly

$$T_2 = 0.7\,C_1 R_1.$$

The time for one complete cycle of operations is, therefore,

$$\begin{aligned} T &= 0.7\,(C_1 R_1 + C_2 R_2) \\ &= 1.4\,CR \text{ seconds (where } C_1 = C_2 = C \text{ and } R_1 = R_2 = R). \end{aligned}$$

2. Because the circuit is alternating or oscillating rapidly between its two states it is said to be an *oscillator circuit.* The frequency with which it oscillates is given by dividing the time for one complete cycle into one second, i.e.

$$f = \frac{1}{T} = \frac{1}{1.4\,CR}\ \text{Hz.}$$

An oscillating voltage when fed into an earphone or loudspeaker produces sound vibrations of the same frequency. With the values of C and R as used above these frequencies are too low to be heard. Change C in both cases therefore to 0.1 μF. Connect an earphone between the collector and emitter of either transistor and it should be found that by using either the 1 kΩ or 10 kΩ resistors it is possible to produce two separate tones. Now connect the emitter of either transistor to the negative terminal of an oscilloscope and the collector of either to the positive terminal. Look at the waveforms on the screen for the two different frequencies. It should be possible to see the voltage switching very quickly between +9 V and 0 V. Because of the rectangular shape of the waveform this is called a *square wave*. It should be found that at the higher frequency, the positive going edge of the waveforms are not so steep. This is caused by the time taken for the capacitors to charge up to +9 V through the resistances of the two bulbs. Now set the controls of the oscilloscope to calibrate and measure the two frequencies. Compare these with the frequencies calculated from the formula given above.

3. Because the circuit produces a voltage switching rapidly between two levels it can be regarded as a generator of electrical pulses. To demonstrate this, connect the multivibrator to the same power supply as the binary counter circuit (Circuit 12) and connect the collector of one of the transistors in the multivibrator to the input of the first stage of the counter. It should be found that for every cycle of the multivibrator one pulse is counted by the binary counter. The counter, therefore, should go through one complete cycle every 16 cycles of the multivibrator.

PART 2
Circuit components

Introduction

A component is something which makes up part of a circuit and contributes to the way in which it functions. Every material tends to inhibit the flow of electrons in a circuit (if only to a very small degree in some cases). That property is referred to as *resistance.* Resistors are components with specific values of resistance. Capacitors and inductors are components which will store electrical energy. They can therefore generate wave forms and can be used in tuning and filtering. Finally, there are a wide variety of semiconductor components which will conduct well under certain conditions and not so well otherwise, which are used in amplification, rectification and switching and which we deal with under *diodes* and *transistors.*

We have deliberately confined this section to a discussion of the three most commonly encountered classes of component, resistor, capacitor and semiconductor, in order to emphasize that some understanding of these basic components will improve your understanding of all the circuits dealt within this book.

Resistors

The current flowing in a circuit is defined as the average number of electrons passing a fixed point per second. Since the number of free electrons available is constant, the current which actually flows is controlled by the speed at which the electrons are flowing in the circuit. The job of a resistor is to control this speed.

Resistors are of two main types, those that consist of a length of wire of known properties, and those which are composed of carbon granules. Each granule has a fairly high resistance, in the same way that an ordinary carbon electrode has, but when several thousand of them are compressed to form a small rod the main source of the resistance is when an electron passes from one granule to another. The two granules are only in contact over a fairly small area and the electrons are all forced to pass through this narrow passage and are therefore slowed down considerably. The value of any particular resistor is determined by just how narrow the passage is and so how much the electrons are slowed down.

The other form of simple resistor is made from a piece of wire which is manufactured so as to have exactly the same resistance per unit length all along its length. It is usually wound in the form of coil (for instance a laboratory rheostat) but this is purely for convenience. The source of the resistance in this case is the vibration of the atoms in the wire; the electrons collide with the atoms and are slowed down.

The energy of the electrons which are slowed down in a resistor is converted to heat. The power in watts released as heat is:

W (watts) = p.d. (volts) $\times$ I (amps).

There are a number of different types of resistor. Their use depends upon cost, reliability, values required and the amount of heat being dissipated.

Carbon composition resistors are the most common and the cheapest. They are available in values ranging from 2.2 Ω to 22 MΩ. They are manufactured by pressing a mixture of carbon, ceramic dust and resin at high temperature into a rod which is then cut up and fitted with metal caps to hold the end wires. This rod can be sold as it is or insulated with a coating of plastic. When they are made a large number are produced aiming at a particular value. The greatest number are within 20% of the value, less are between 5 and 10% and the least within 1% which are of course more expensive to buy in the shops. They can be obtained with a heat dissipation of 0.04 W to 3 W, the latter again being more expensive.

Wire-wound resistors are expensive because even using wire of a high resistivity alloy requires a considerable length of wire (nickel–chrome alloy would use about 3 metres (~ 10 ft) for 9 kΩ resistor) and it must be wound into a ceramic former. They are used for very low resistances (2 ohms and below) and in industrial equipment where several hundreds of watts needs to be dissipated. The wire can heat up and not melt at temperatures of 300° C or more. Wire-wound resistors are usually coated with a cermic insulating material and the value and power dissipation are printed on. Any colour coding could fade and change colour with the heat.

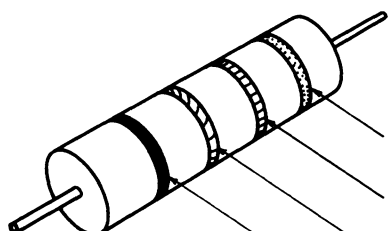


FIG. 2.1 Resistor colour code

Bands 1, 2 and 3	*Number*	*Band 4*	*Error (%)*
Black	0	Salmon	20
Brown	1	Silver	10
Red	2	Gold	5
Orange	3		
Yellow	4		
Green	5		
Blue	6		
Purple/violet	7		
Grey	8		
White	9		

Examples

Band 1	*Band 2*	*Band 3*	*Band 4*	*Value*	*Error*
Brown	Black	Black	Silver	10 Ω	10%
Brown	Green	Yellow	Gold	150 Ω	5%
Brown	Green	Black	Silver	15 Ω	10%
Yellow	Purple	Black	Gold	?	?
Grey	Red	Black	Gold	?	?
Brown	Green	Brown	Silver	?	?
Orange	Orange	Brown	Salmon	?	?

Film resistors are less expensive than wire-wound but cost more than composition resistors. They can be made to a greater accuracy and are therefore more reliable for designers of electronic equipment. They change resistance very little with changes of temperature.

Most resistors are marked with three or four colour bands which show the value and tolerance of the resistor.

The values of resistors that you can buy have been agreed by the manufacturers so that they do not need to make a huge variety of different values. These are called 'preferred' values. The preferred values are:

1.0, 1.1, 1.2, 1.3, 1.5, 1.6, 1.8, 2.0, 2.2, 2.4, 2.7, 3.0, 3.3, 3.6, 3.9, 4.3, 4.7, 5.6, 6.2, 6.8, 7.5, 8.2, 9.1.

A typical carbon resistor might be available therefore at: 22, 220, 2.2, 22, 220 and 2.2 M ohms.

A designer would use Ohm's law to decide what resistor he would need given the voltage and current used. He would then use the closest preferred value available. Rather than buy a resistor, he might use resistors he had and wire them in series or parallel.

Capacitors

There are many different types of capacitor and each sort is used where its particular properties are most useful. For instance:

Air capacitors

These consist of a fixed set of metal plates between which a second set of plates is mounted. By altering the amount by which the two sets of plates overlap the capacitance of the system can be altered. This sort of capacitor is most commonly used in radio work where variable capacitances are vital. If you look carefully inside any radio you should be able to find one quite easily.

Paper capacitors

This form of capacitor is used where space is limited, it consists of two sheets of metal foil between which is placed a piece of waxed paper. The whole thing can be rolled up very compactly.

Mica and ceramic capacitors

Both of these forms of capacitor are made by depositing a thin coating of metal directly on to both sides of a plate, the plate being made of either mica or ceramic.

The mica capacitor is quite expensive to make but minimizes losses so that it is used mainly in high frequency circuits. The ceramic capacitor is little affected by changes in temperature over quite a wide range and is used in place of mica in circuits where this is an important factor.

Electrolytic capacitors

This form of capacitor is made up of two sheets of aluminium foil, one with an oxide film deposited on it; between these two is placed a sheet of paper which has been saturated in an electrolyte (i.e. ammonium borate). This 'sandwich' is then rolled up and fitted into a container (usually aluminium) which is then sealed so as to be airtight.

The main advantage of this type of capacitor is that a very large capacitance is available from a small container. The main disadvantage is that this sort of capacitor can only be used where the voltage never changes its direction. This means that it is ideal for use in smoothing out the voltage obtained from a rectifier. (Several improvements have been made to this design; notably, the wet paper is replaced by dry manganese dioxide.)

As can be seen from the descriptions of the various types of capacitors, they all have basically the same design: two parallel plates made of a conducting material (i.e. metal) separated by a non-conducting layer, which is called the dielectric.

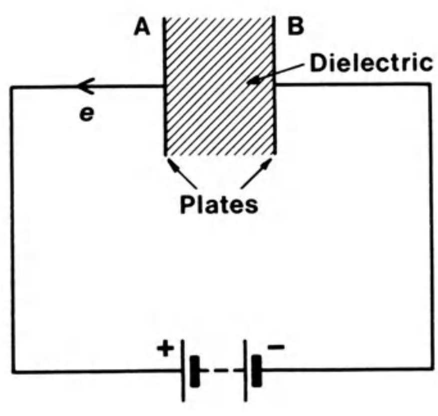


FIG. 2.2

When a capacitor is connected to a battery (as shown) electrons are taken from plate A, through the battery and deposited on plate B. They cannot cross the dielectric and so a charge is built up on each plate, positive on A, negative on B, until the p.d. between A and B is equal to that of the battery.

The battery has to do work in order to separate the charges and the energy used can be released by by-passing the dielectric so that the electrons can flow back. *Thus the capacitor is a device for storing energy in the form of separated charges.*

Capacitance is the measure of the amount of charge stored by the capacitor per volt across it. It is controlled by the area of the parallel plates which overlap the distance between the plates and the properties of the dielectric.

Semiconductors

An atom of a material is made up of a nucleus containing a positive charge surrounded by electrons moving around the nucleus. Those electrons which are close to the nucleus are tightly bound to it by the attraction of their opposite charge, but the electrons that are further away are acted on by a much smaller force and the electrons in the outer orbit are easily detached. When thinking about semiconductors, the materials that are important are germanium and silicon. In these materials the atoms are arranged in an orderly way. In both germanium and silicon each atom has four outer electrons, these are known as valency electrons and germanium and silicon are said to have a valency of four. If we could isolate a single atom of either of these we could represent it as shown in Fig. 2.3.

When atoms are as tightly packed as they are in a germanium or silicon crystal the four valency electrons are shared with the four neighbouring atoms; this is shown diagrammatically in Fig. 2.4. Thus each nucleus has eight electrons (in four electron pairs) orbiting it. Each electron pair is known as a covalent bond. A two-dimensional cross-section through a germanium crystal is shown diagramatically in Fig. 2.5.

The covalent bonds hold the crystal together; they are so strong that at absolute zero there are no free electrons and the crystal is a perfect insulator. At room temperature a few bonds are broken but the crystal may still be regarded as a very good insulator. Semiconductor properties arise when traces of impurities are added to the crystals. There are two types of semiconductor and we will look at each separately.

n-type semiconductors

Certain elements such as phosphorus, arsenic and antimony have a valency of five, i.e. each atom has five outer electrons. When a small trace (i.e. 1 part in 10^8) of such an element is added to pure germanium or silicon, the conductivity of the crystal is greatly increased.

When an atom of valency five is introduced to the crystal it enters the lattice structure by replacing one of the original atoms, but only four of its five valency electrons can join in covalent bonding. Thus the crystal has an extra free electron for every atom of impurity (see Fig. 2.6). It is known as an n-type semiconductor because the free charge is negative. The spare electrons move randomly about the crystal but in such a way that the density of free electrons is constant; there is no build-up of negative charge anywhere. The greater the amount of impurity in the semiconductor the greater is the number of free electrons per unit volume and therefore the greater the conductivity of the semiconductor.

All we have said so far has assumed that there is no p.d. across the semiconductor; if there is, the nett flow of electrons will be towards the higher potential. However, an equal number of electrons will enter the semiconductor as are leaving it.

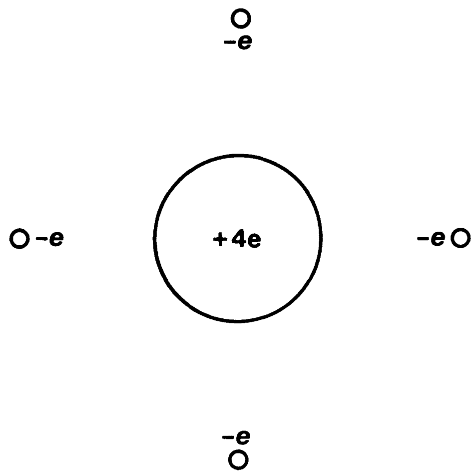


FIG. 2.3 An isolated atom which has four valency electrons may be represented as a central portion containing the nucleus and the inner, more tightly bound, electrons, surrounded by its four valency electrons. The original atom was neutral so that when four negative charges are removed the remaining region has a resultant charge of +4e. Such a charged central portion is known as an ion.

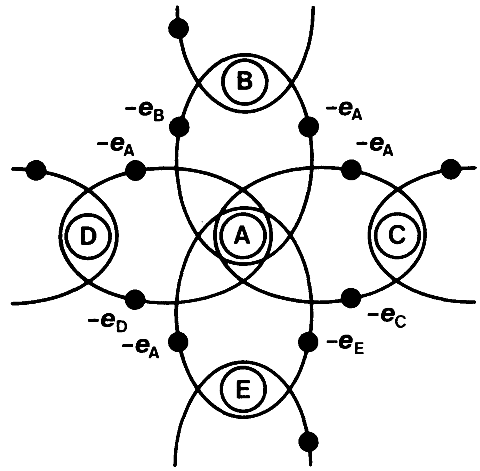


FIG. 2.4 *Covalent electron bonds.* A shares its four valency electrons with atoms B, C, D and E - in other words one of A's valency electrons links with A and B, another with A and C etc. Similarly one valency electron from each atom B, C, D and E links with atom A.

The paths shown are not intended to indicate the actual paths taken by the electrons, they merely show which atoms are linked, and how.

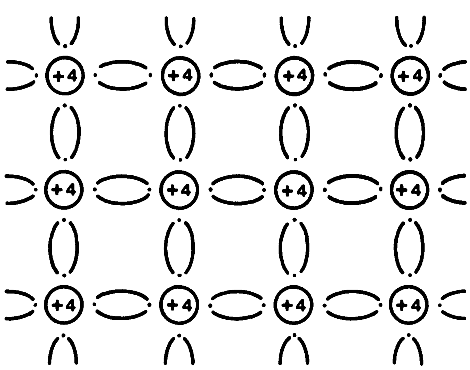


FIG. 2.5 A diagrammatic representation of the lattice structure of atoms with four valency electrons. The small dots represent electrons and the brackets represent covalent bonds.

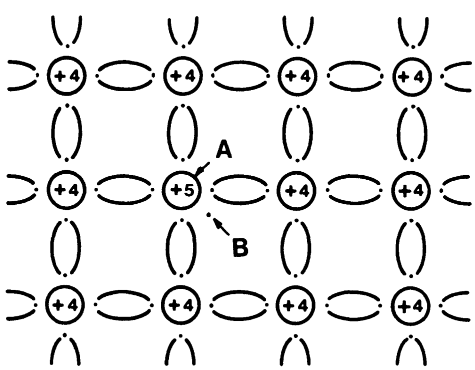


FIG. 2.6 *An n-type semiconductor.* An atom with 5 valency electrons has been introduced into the lattice (A). After forming the four covalent bonds with its neighbours it has one electron (B) left over. This is the free electron which may move about the crystal and which gives it its semiconductor properties.

p-type semiconductors

Some elements have only three valency electrons, examples are gallium, boron and aluminium. When a trace of one of these is introduced into a pure germanium or silicon crystal the atoms take up places in the lattice, but they are only able to complete three covalent bonds. This means that for every atom of impurity there is an incomplete valency bond, this vacancy is known as a 'hole' (this term is peculiar to semiconductors).

The incomplete bond can attract a valency electron from a near-by complete bond and thus the vacancy, or hole, can move around the crystal. If there is no p.d. across the crystal the holes move randomly at about half the speed of the free electrons in the n-type. As before the overall density remains constant.

When a p.d. is applied the holes will tend to flow towards the lower potential. Electrons will be lost at the higher potential and thus new holes created. The rate of loss of holes is equal to the rate of creation of new ones.

Diodes

There are two main types of diode: those containing an anode and cathode, and those which are made from semiconductors. We will look at the valve diode first. If you are not familiar with semiconductors, you should read that section before looking at the notes on semiconductor diodes.

The valve diode

The diode valve consists of a heated cathode and an anode, often in the form of a cylinder, contained within an airtight container. Inside the container there is usually a vacuum but in some cases a small amount of inert gas may be introduced.

The cathode is heated either by passing a current through it or by placing a heater near by. The heat energy given to it is used to increase the energy of the free electrons that exist in the metal cathode. In many cases the electrons will have enough energy to free themselves from the main body of the cathode. In the absence of any anode, the electrons will be attracted back, as the cathode now has a positive charge on it. A state of equilibrium will be reached when equal numbers of electrons are leaving and re-entering the cathode at any time.

However, when an anode is brought near, the positive charge on it is much greater than that on the cathode and the electrons are pulled across to the anode. If this is in the form of a cylinder the electrons will pass through it to the battery connection (as shown in the diagram). In this way a current will flow through the diode. It is very important to note that this will only happen if the cylinder is positively charged with respect to the cathode. If the battery is reversed so that the cylinder is negative, it will actually repel the free electrons. Thus a diode is a means of passing current in one direction only. If an alternating current is put through it, only the part of the cycle in which the cylinder is positive will be passed (see Fig. 2.7).

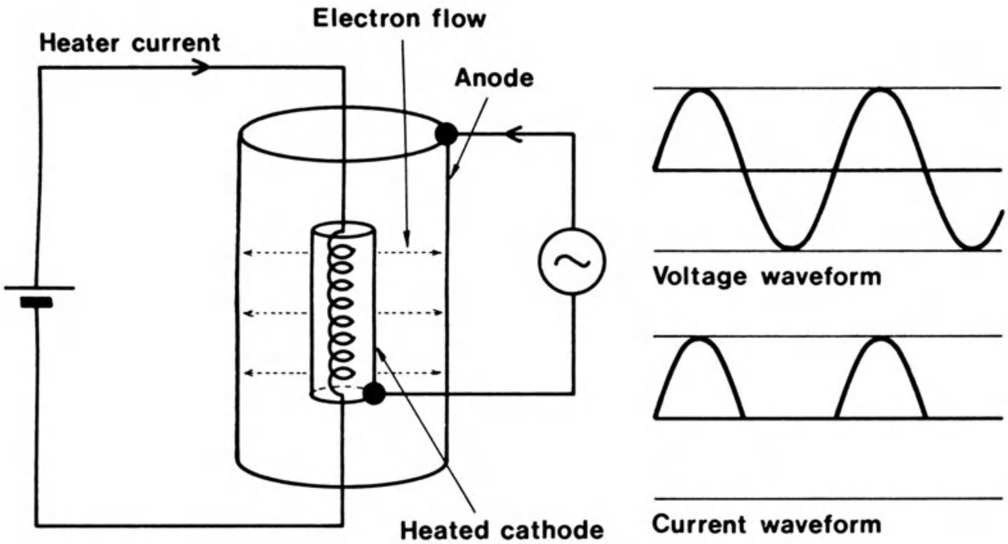


FIG. 2.7

Semiconductor (junction) diodes

Unless you are already familiar with semiconductors you should read that section before trying to understand this one.

A semiconductor diode consists of a crystal, one half of which is n-type, the other p-type; we will try to see how it works. Initially the p-type semiconductor has mobile holes and an equal number of negative ions and is therefore neutral. Similarly the n-type semiconductor has free electrons and an equal number of positive ions and is also neutral (see Fig. 2.8). Owing to their random motion, a few of the holes will diffuse over into the n-type and a few of the electrons into the p-type (Fig. 2.9). This means that the area A has a net negative charge which repels any more electrons trying to enter it, similarly B has a net positive charge and so repels any further holes. Both charges are concentrated near the boundary and thus form a potential barrier between the two regions.

We will now look at what happens when we apply a potential across the crystal between G and H. First consider G being positive with respect to H (Fig. 2.10); this is known as the forward bias. The direction of the electric field in the semiconductor produces a drift of holes towards the right in the p-type and of free electrons to the left in the n-type. In the region around the junction, free electrons and holes combine, i.e. free electrons fill the vacancies represented by the hole. For each combination an electron is liberated from a covalent bond in the region of the positive plate and enters that plate, thus producing a new hole which moves through the p-type material towards the junction. Simultaneously an electron enters the n-region from the negative plate and moves through the n-type semiconductor towards the junction. Thus the current flow in the diode is due to the hole flow in the p-type region, electron flow in

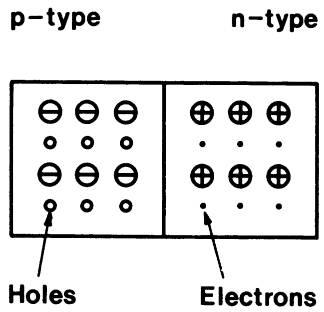


FIG. 2.8 Each half of the crystal is neutral, each containing free charges plus an equal number of oppositely charged ions.

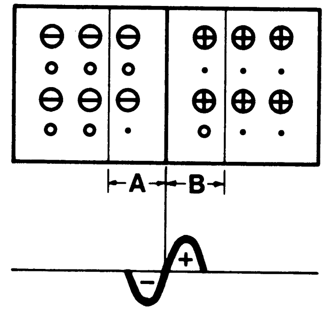


FIG. 2.9 At the boundary layer some of the free charges move across the boundary into the other side. This builds up a charged area and hence a potential barrier.

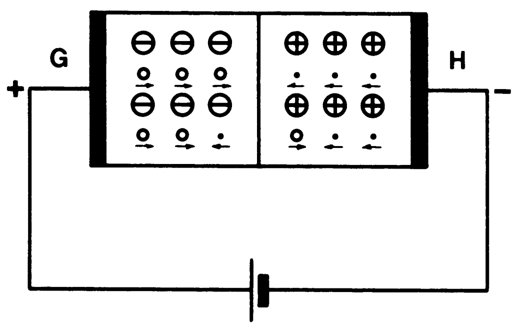


FIG. 2.10 When a forward bias voltage is applied the holes flow towards H and the electrons towards G. They will meet in the central region and combine.

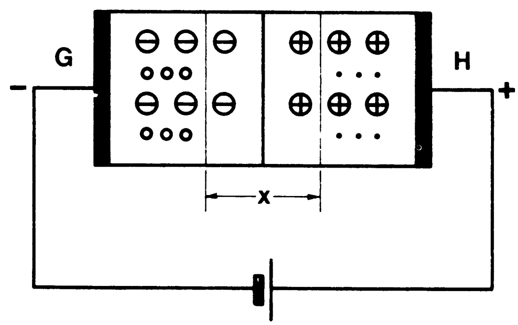


FIG. 2.11 When a reverse bias voltage is applied the holes flow towards G and the electrons to H and no current can pass. x is the depletion layer where there is no free charge.

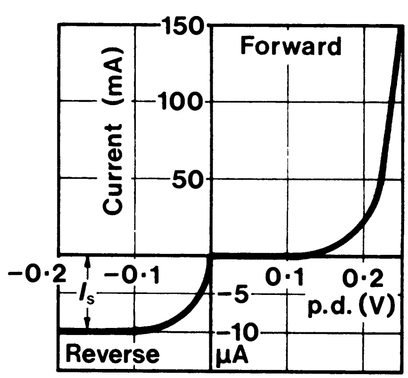


FIG. 2.12 Note the change of scale on the current axis. The current flow when a forward bias is applied is much greater than that with reverse bias. I_s is the saturation current, obtained when all the thermally released electrons are being used.

the n-type region and a combination in the junction region. Fig. 2.12 shows the relationship of current to p.d.

If the applied voltage is reversed so that H is now positive with respect to G (Fig. 2.11, this is known as reverse bias) the holes are attracted to the negative end and the electrons to the positive. This leaves the central region with no free changes, it is therefore called the depletion layer. This means that the junction acts as an insulator.

In practice, there is a small current owing to the fact that at room temperature the atoms are vibrating in the crystal and some valency electrons acquire sufficient energy to break away from their atoms. Fig. 2.12 shows the relationship between the current and the p.d.

Fig. 2.13 shows an example of the actual construction of a junction diode.

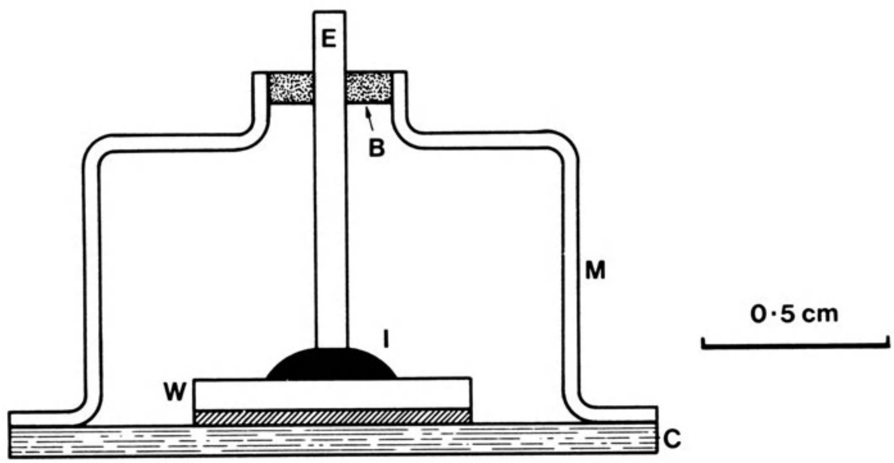


FIG. 2.13

A thin wafer W is cut from an n-type germanium crystal, the area of the wafer being proportional to the current rating of the diode. The lower surface of the wafer is soldered to a copper plate C and a bead of indium I is placed centrally on the upper surface. The unit is then heat-treated so that the indium forms a p-type alloy with the germanium. A copper electrode E is soldered to the bead during the heat-treatment and the whole element is sealed in a metal or other opaque container M to protect it from light and moisture. The electrode E is insulated from the container by a brush B.

Junction transistors

Before trying to understand junction transistors you should be familiar with the section on semiconductors and junction diodes.

The term transistor is derived from the words ‘transfer-resistor’, namely a device for the transfer of current from a low-resistance circuit to approximately the same current in a high-resistance circuit.

A junction transistor is a combination of two junction diodes and consists of either a thin layer of p-type semiconductor sandwiched between two n-type semiconductors (as in Fig. 2.14) and referred to as a n–p–n transistor, or a thin layer of an n-type semiconductor sandwiched between two p-type semiconductors (as in Fig. 2.15) and referred to as a p–n–p transistor. The thickness of the central layer, known as the base, is about 25 μm.

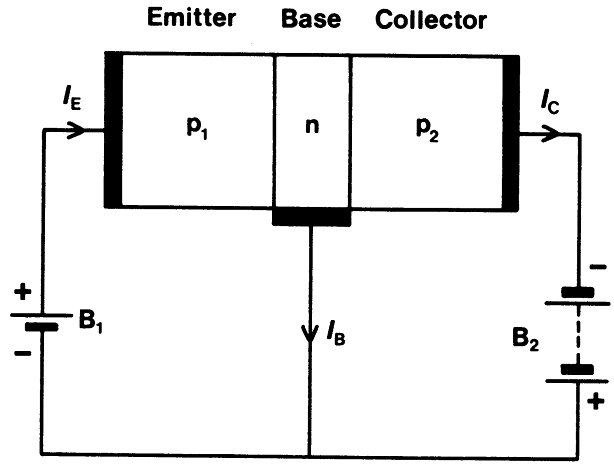


FIG. 2.14 n–p–n transistor.

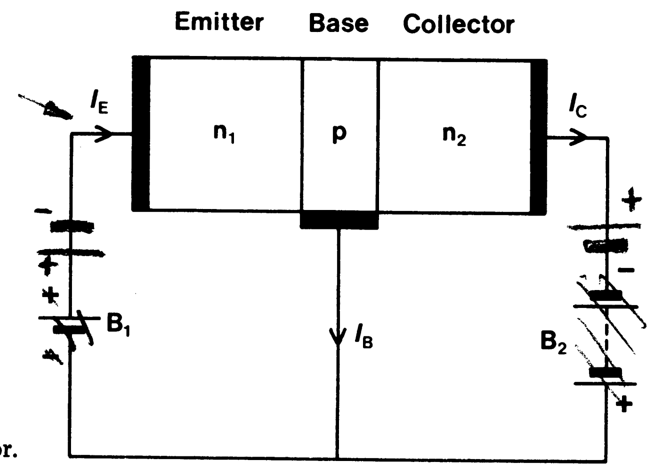


FIG. 2.15 p–n–p transistor.

The junction diode formed by n_1–p in Fig. 2.14 is biased in the forward direction by a battery B_1 so that free electrons are urged from n_1 towards p. Hence n_1 is termed an 'emitter'. On the other hand, the junction diode formed by n_2–p in Fig. 2.14 is biased in the reverse direction by battery B_2 so that if battery B_1 were disconnected, i.e. with zero emitter current, no current would flow between n_2 and p apart from that thermally generated. However, with B_1 connected as shown in Fig. 2.14, the electrons from emitter n_1 enter p and diffuse through the base until they come under the influence of n_2, which is connected to the positive terminal of battery B_2. Consequently, the electrons which reach n_2 are collected by the metal electrode attached to n_2; hence n_2 is termed a 'collector'.

Some of the electrons, in passing through the base, combine with holes; others reach the base terminal. The electrons that do not reach the collector n_2 are responsible for the current at the base terminal, and the distribution of electron flow in an n–p–n transistor can be represented diagrammatically as in Fig. 2.16. The conventional current flows are represented by the arrows I_E, I_B, and I_C.

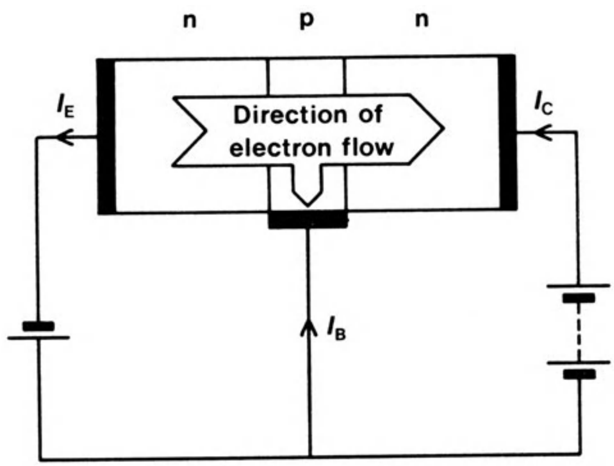


FIG. 2.16 Electron flow in an n–p–n transistor.

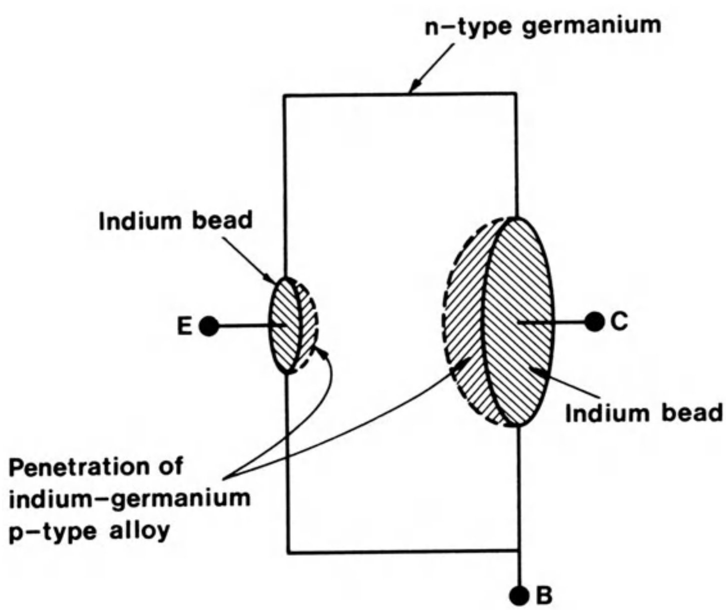


FIG. 2.17

By making the thickness of the base very small and the impurity concentration in the base much less than in the emitter and collector, the free electrons emerging from the emitter have little opportunity of combining with holes in the base, with the result that about 98% of the electrons reach the collector.

In the above explanation we have dealt with the n–p–n transistor, but exactly the same explanation applies to the p–n–p transistor of Fig. 2.15 except that the movement of electrons is replaced by the movement of holes.

The diagram of Fig. 2.17 shows one of the common forms of construction of a p–n–p transistor.

The first step is to purify the germanium or silicon so that any impurities do not exceed about 1 part in 10^{10}. In one form the purified material is grown as a single crystal, and while the material is in a molten state, an n-type impurity (e.g. antimony in the case of germanium) is added in the proportion of about 1 part in 10^8. The solidified crystal is sawn into slices about 0.1 mm thick. Each slice is used to form the base region of a transistor. In the case of n-type germanium, a pellet of p-type impurity, such as indium, is placed on each side of the slice, the one which is to form the collector being about three times the size of the emitter. The assembly is heated in a hydrogen atmosphere until the pellets melt and dissolve some of the germanium from the slice. Leads for the emitter and collector are soldered to the excess material and a nickel tab is soldered to make a connection to the base. The assembly is then sealed so as to be airtight in a metal container to protect it from heat and light.

PART 3

Questions

The questions collected below are from a variety of internal courses in schools, technical colleges and universities, professional examinations, external boards at C.S.E., 'O' level and 'A' level, and degree examinations. The object of giving them here is to give the reader an idea of the range of questions asked in modern examination papers. They have been picked to supplement the text* and provide an additional teaching resource which the reader may need to use in conjunction with a teacher or lecturer on the subject. The questions are interesting in that they demonstrate the extent to which the approach to the subject has changed in the last ten years. Marks awarded are shown at the right hand side where given on the appropriate examination papers.

1. Three lamps, X, Y, Z are lit using the circuit shown. Lamp Z suddenly goes out, lamps X and Y remain alight. If the following laboratory procedures were tried in order to get all three lamps to light, which one might be successful?

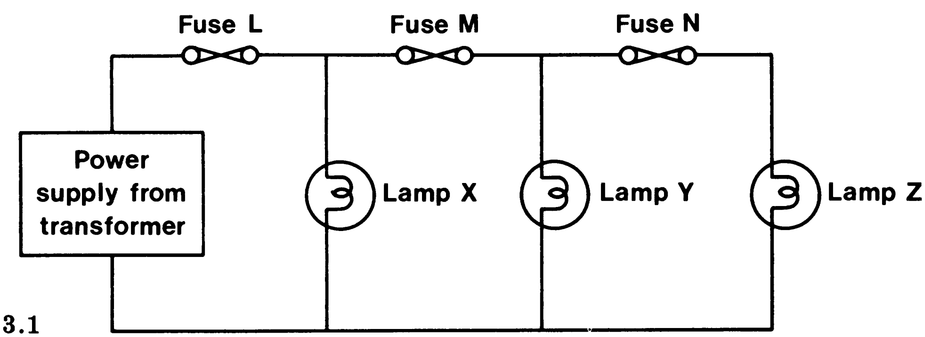


FIG. 3.1

A. replacing the transformer with one giving a higher voltage
B. changing X and Y for lower wattage lamps
C. interchanging lamps X and Z
D. replacing fuse L
E. replacing fuse N

2. The circuit shown in Fig. 3.2 is set up. What will happen to the lamps when the switch S is closed?

A. The 100 W lamp will be bright, the 24 W lamp very dim.
B. The 100 W lamp will be very dim, the 24 W lamp bright.
C. The 100 W lamp will be bright, the 24 W lamp will blow.

* The questions follow the topics dealt with in Circuits 1 to 14 in order.

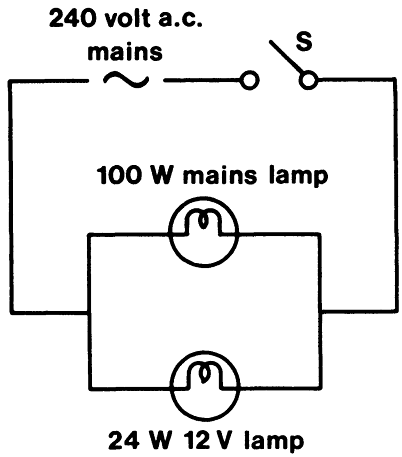


FIG. 3.2

D. The 100 W lamp will be bright and the 24 W lamp will be bright.
E. The 100 W lamp will go out, the 24 W lamp will blow.

3. You are given a single dry cell and three similar lamps, each of which could be lit fully from that cell. Sketch at (a), (b) and (c) the circuit which will give you the result written below each space.

(a) all the three lamps glow dimly and at the same low intensity,

(b) all the three lamps glow brightly and at the same intensity.

(c) two lamps glow equally dimly and one brightly.

(d) In case (a) say what will happen to the brightness of the remaining lamps if one lamp is removed.

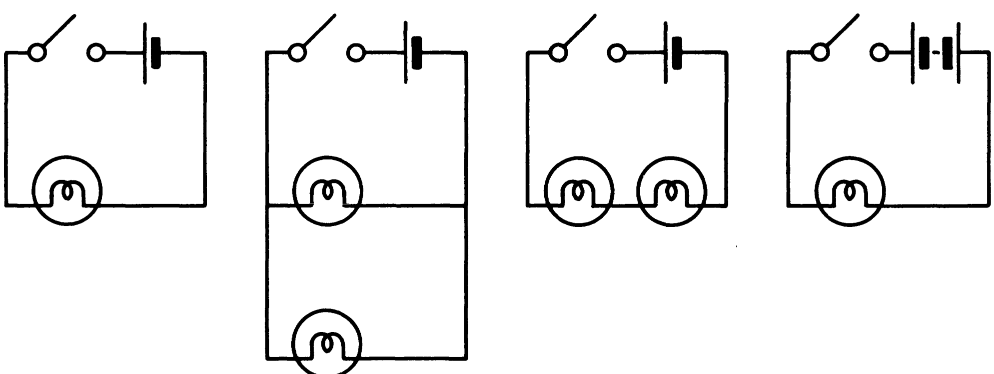
(e) In case (b) say what will happen to the brightness of the remaining lamps if one lamp is removed.

(f) What will happen in case (c) if one of the two dimly lit lamps is removed?

What would happen if you were to connect many of these lamps (say, 100) in parallel with the single cell?

Why is this?

4. (a) The electric cells shown in the diagram are rated at 1·5 V and the bulbs are marked 1·5 V, 0·3 A.



(i) (ii) (iii) (iv)

FIG. 3.3

State whether the bulbs will light up
- (i) normally (as bright as the manufacturer intended),
- (ii) brighter than normal,
- (iii) dimmer than normal, or
- (iv) not at all,

when the switch is closed in each of the circuits (i), (ii), (iii) and (iv).

(b) A battery, consisting of two 2 V cells wired in *parallel*, is connected to a 10 ohm resistor and a 6 ohm resistor connected in series to form a circuit.
- (i) Draw a circuit diagram of the arrangement.
- (ii) What is the voltage of the battery?
- (iii) What is the effective resistance of the resistors in the circuit?
- (iv) Calculate the current flowing through the 10 ohm resistor.

(c) The resistance between the ends of a specimen of wire 5 metres long and with a cross-sectional area of 1 mm^2 is 2 ohms. What will be the resistance of a length of wire of the same material but having a length of 15 metres and a cross-sectional area of 0·5 mm^2?

(South East Regional Examinations Board)

5. *Equations you may require:*
Quantity of electricity = $I\,t$
Electrical energy = $I\,V\,t$
Gravitational potential energy = mgh
Earth's gravitational field strength = 10 newton per kilogramme

(a) Fig. 3.4 shows a one-cell battery connected to a lamp. The lamp is normally bright. Similar lamps and batteries are used in the following circuits. Write one of the following in the spaces provided:

brighter than normal
normal
dim
not lit.

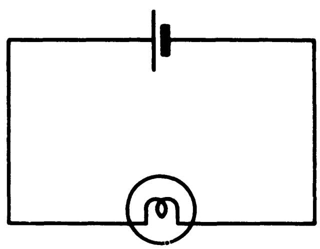


FIG. 3.4

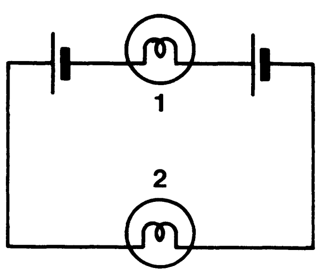


FIG. 3.5

Lamp 1 is
Lamp 2 is

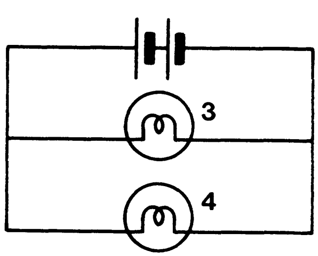


FIG. 3.6

Lamp 3 is
Lamp 4 is

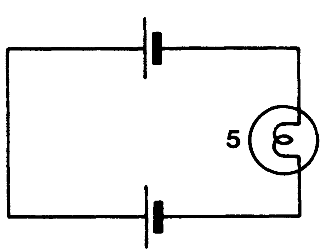
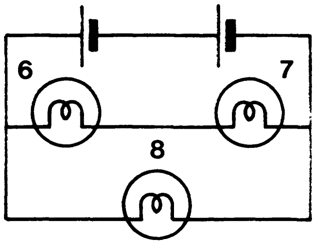


FIG. 3.7

Lamp 5 is



Lamp 6 is
Lamp 7 is
Lamp 8 is

FIG. 3.8

(b) You are given a 20 volt electrical supply, ammeter, voltmeter, variable resistor and a 12 volt electric motor.

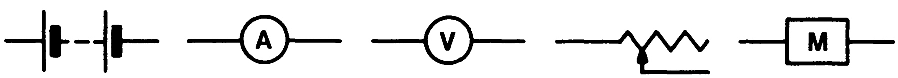


FIG. 3.9

(i) Draw a diagram of the circuit you would set up to measure the current through the motor when the potential difference across it is 12 V.

(ii) If the voltmeter reading were 14 volt what adjustment would you make?

(c) In an experiment with this apparatus it was found that the motor would raise a load of 4 kg through a height of 2 m in 8 s. The voltmeter reading was 12 V and the ammeter reading 1.5 A.

(i) How many coulombs of electricity have passed through the motor?

(ii) How much energy was used in lifting the 4 kg load?

(iii) How much electrical energy is used when the load is lifted 2 m?

6. Fig. 3.10 shows the current in a network of resistors connected to a d.c. supply. Which resistor has the smallest resistance?

A. R_1
B. R_2
C. R_3
D. R_4
E. R_5

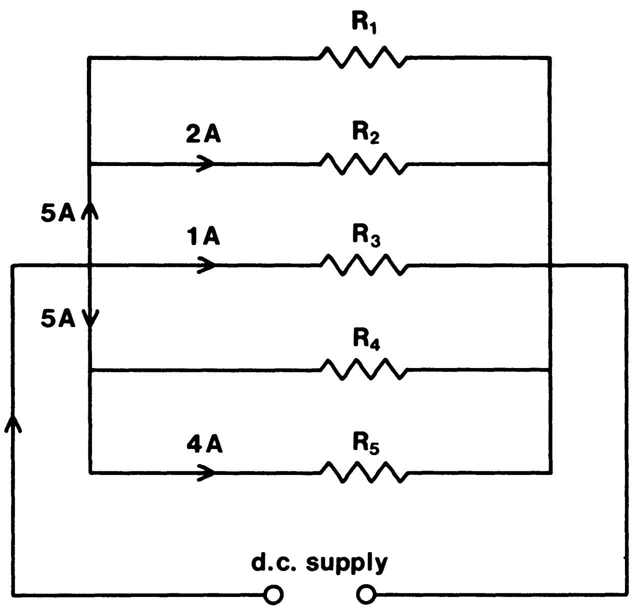


FIG. 3.10

7. In the circuit shown in Fig. 3.11 ammeter A_2 reads 4 A.

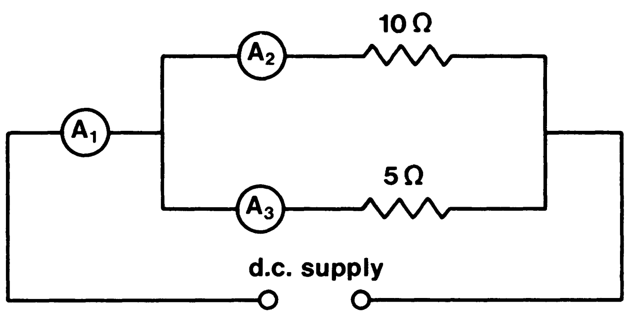


FIG. 3.11

What is the reading on ammeter A_1?

A. 2 A
B. 4 A
C. 6 A
D. 8 A
E. 12 A

8. In the circuit shown in Fig. 3.12, V is a voltmeter connected across the rheostat and A is an ammeter in series with the rheostat.

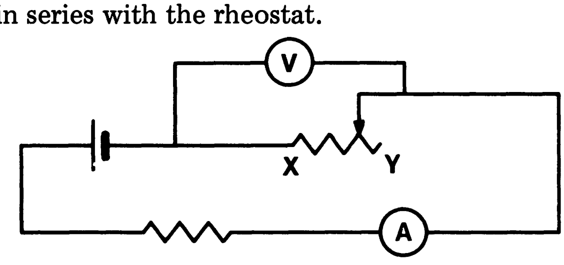


FIG. 3.12

What happens to the reading on A and V when the sliding contact of the rheostat is moved from X to Y?

	Ammeter reading	*Voltmeter reading*
A.	increases	decreases
B.	decreases	increases
C.	remains constant	increases
D.	increases	remains constant
E.	decreases	remains constant

9. Calculate the effective resistance between the points A and B in the diagrams shown in Fig. 3.13.

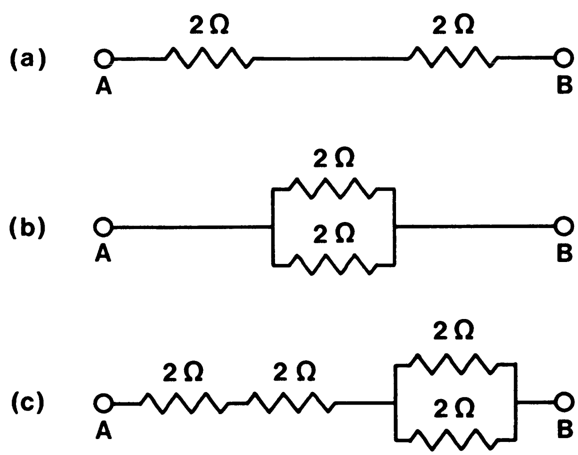


FIG. 3.13

(*East Midland Regional Examinations Board*)

10. In the circuit shown below, the potential difference between A and B is 6 V.

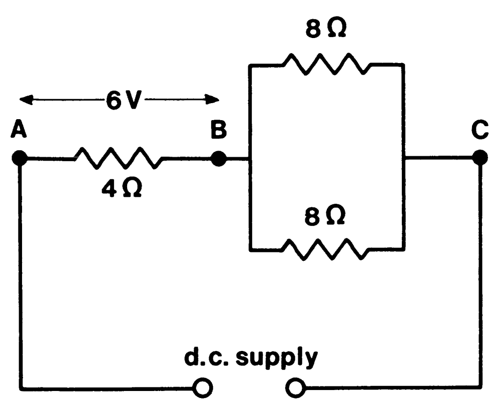


FIG. 3.14

The potential difference between B and C is

A. 3 V
B. 6 V
C. 12 V
D. 20 V
E. 24 V

11. Fig. 3.15 shows two resistors connected in parallel.

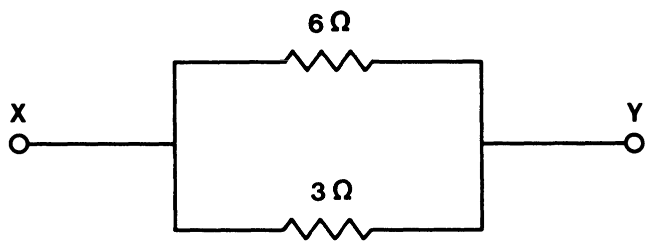


FIG. 3.15

The resistance between X and Y is

A. 0·5 ohm
B. 2 ohms
C. 3 ohms
D. 4·5 ohms
E. 9 ohms

12. In the circuit shown in Fig. 3.16, when S is closed, the reading on the ammeter is 3 A. When S is open, the reading on the ammeter is 2 A.

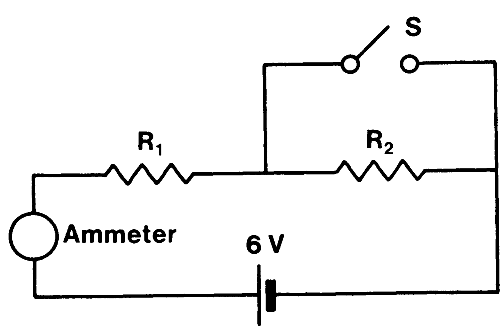


FIG. 3.16

What are the values of R_1 and R_2?

	R_1	R_2
A.	2 Ω	1 Ω
B.	3 Ω	1 Ω
C.	3 Ω	2 Ω
D.	2 Ω	2 Ω
E.	4 Ω	2 Ω

13. A moving coil galvanometer G has an internal resistance of 99 Ω and a range of 0 to 1 mA. To adapt this meter to measure currents up to 100 mA, the best arrangement would be

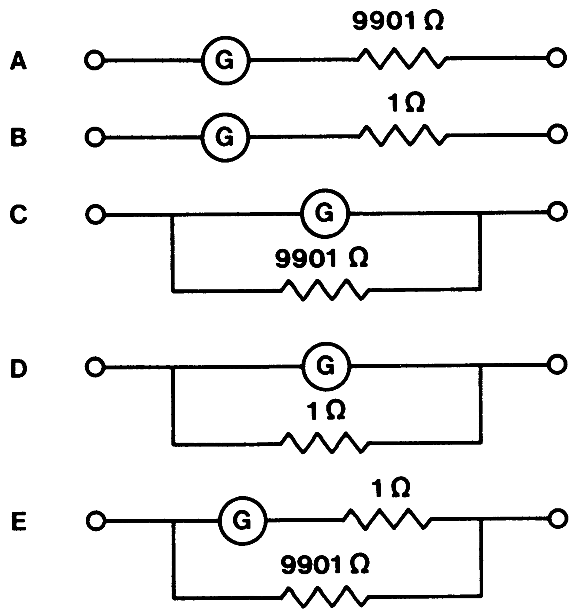


FIG. 3.17

14. Which of the arrangements shown in Fig. 3.18 would be used to convert a galvanometer into a voltmeter reading very high voltages?

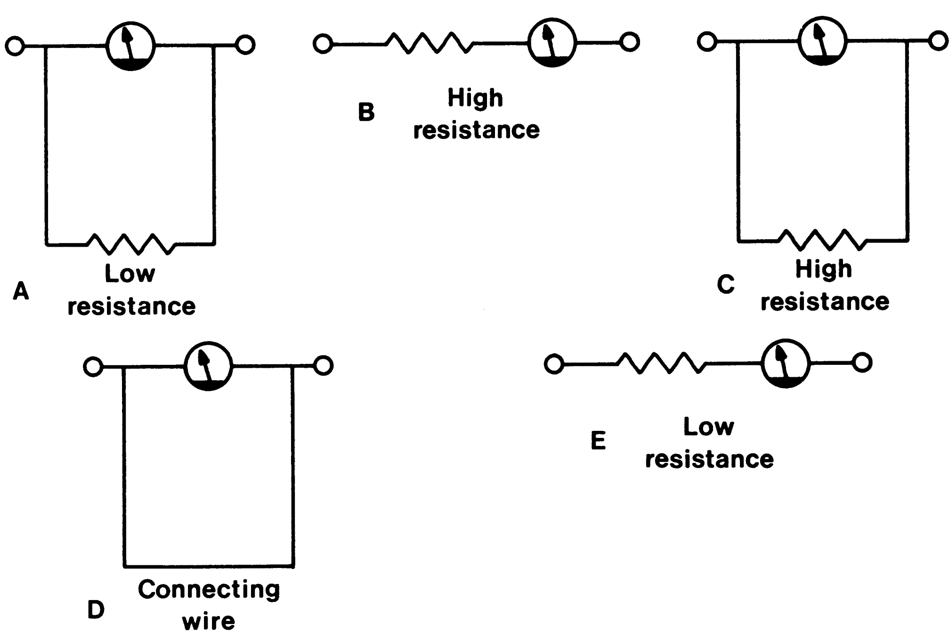


FIG. 3.18

15. In the circuit of Fig. 3.19 a low voltage supply is connected to the terminals PQ and a voltmeter is connected across the 12 ohm resistor.

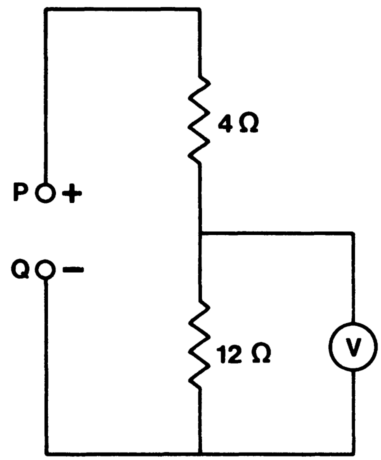


FIG. 3.19

If the voltmeter indicates 9 V, the supply voltage is

A. 6 V
B. 9 V
C. 12 V
D. 16 V
E. 18 V.

16. In the circuit of Fig. 3.20 point X is to be kept at a steady potential of +1 V by the resistances R_1 and R_2 connected across the low resistance 6 V power supply. R_2 is a 10 kΩ resistor.

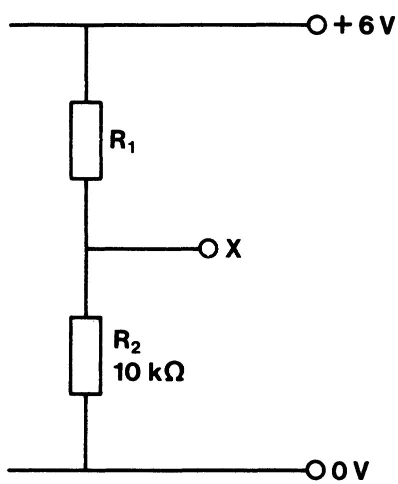


FIG. 3.20

(a) The value of R_1 should be

A. 1·6 kΩ
B. 2 kΩ
C. 10 kΩ
D. 50 kΩ
E. 60 kΩ

(b) The current flowing through R_2 is

A. 0.10 mA
B. 0.12 mA
C. 0.25 mA
D. 0.30 mA
E. 0.50 mA

17. Fig. 3.21 shows a circuit made up of two similar cells, each of e.m.f. 2 V and negligible internal resistance, and two lamps each rated at 2 V, 2 W. What current flows in the wire PQ?

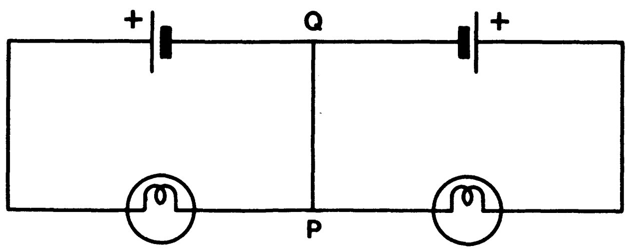


FIG. 3.21

A. zero
B. 1 A from P to Q
C. 1 A from Q to P
D. 2 A from P to Q
E. 2 A from Q to P

18.

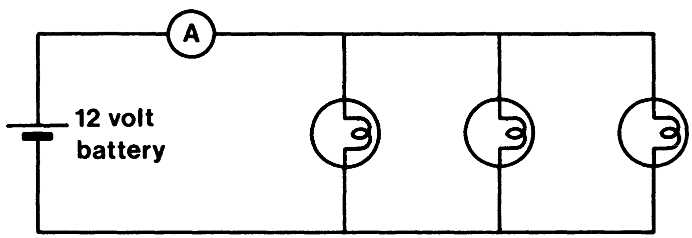


FIG. 3.22

Three 24 W 12 V lamps are connected in parallel to a 12 V battery which has no internal resistance. The current, in amperes, flowing through the ammeter A is

A. 0 B. 2 C. 4 D. 6 E. 8

19. A four-terminal box is connected as shown in Fig. 3.23 to a battery and two milliammeters. The currents in the two meters are identical.

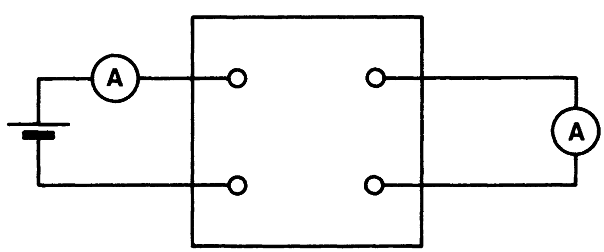


FIG. 3.23

Which of the circuits A to E below, within the box, is the only one which will give this result?

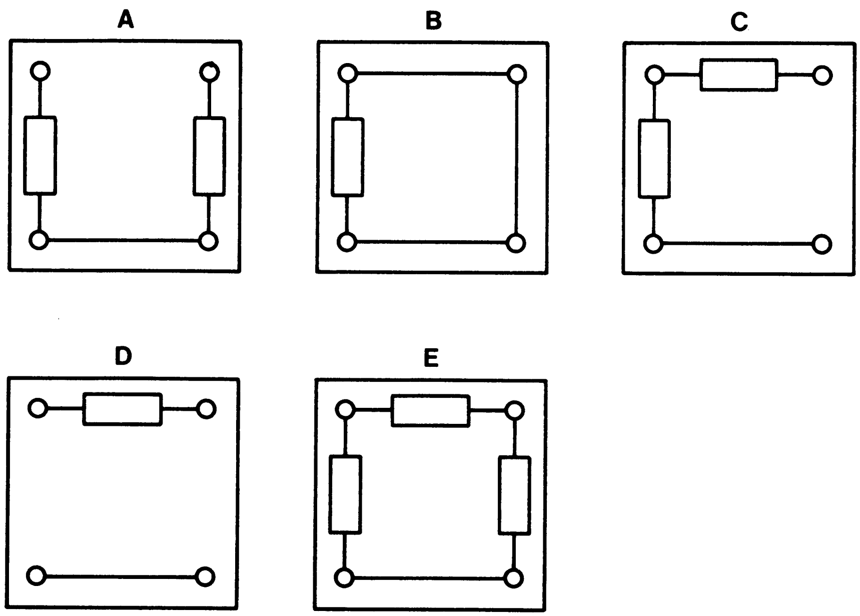


FIG. 3.24

20.

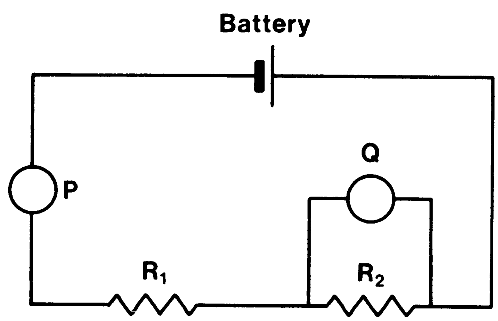


FIG. 3.25

Readings of the meters P and Q in the circuit shown in Fig. 3.25 enable us to determine the value of

A. the resistance of R_1 if P is an ammeter and Q a voltmeter.
B. the resistance of R_2 if P is an ammeter and Q a voltmeter.
C. the resistances of both R_1 and R_2 if P is a voltmeter and Q an ammeter.
D. the resistance of R_1 if P is a voltmeter and Q an ammeter.
E. the energy converted per second in R_2 if P is a voltmeter and Q is an ammeter.

21. In each of the circuits 1 and 2 shown in Fig. 3.26 the position (S) of the slide on the potentiometer (P) is varied between positions 1 and 2 and the readings of the voltmeter (V) are plotted as a function of the position of S. The e.m.f. of the

battery is 4 volt and it has very low internal resistance; the total resistance of P is equal to the resistance of R and the internal resistance of V is much greater than R.

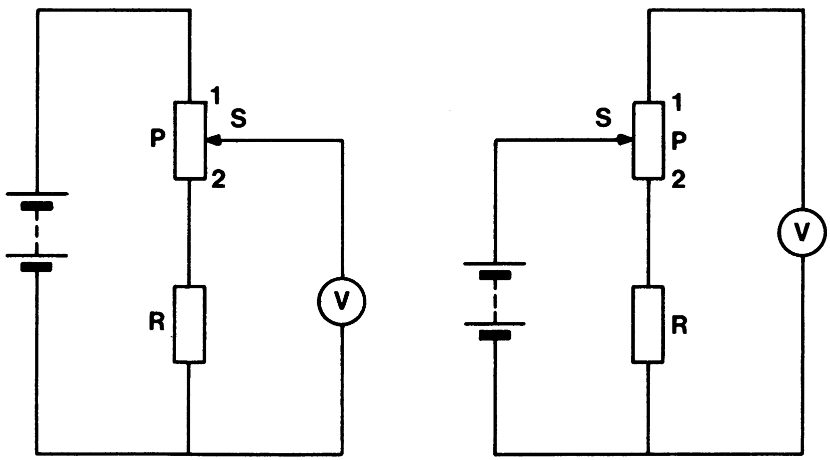


FIG. 3.26 Circuit 1 Circuit 2

(a) Which one of the graphs A–E represents the voltage variation for circuit 1?

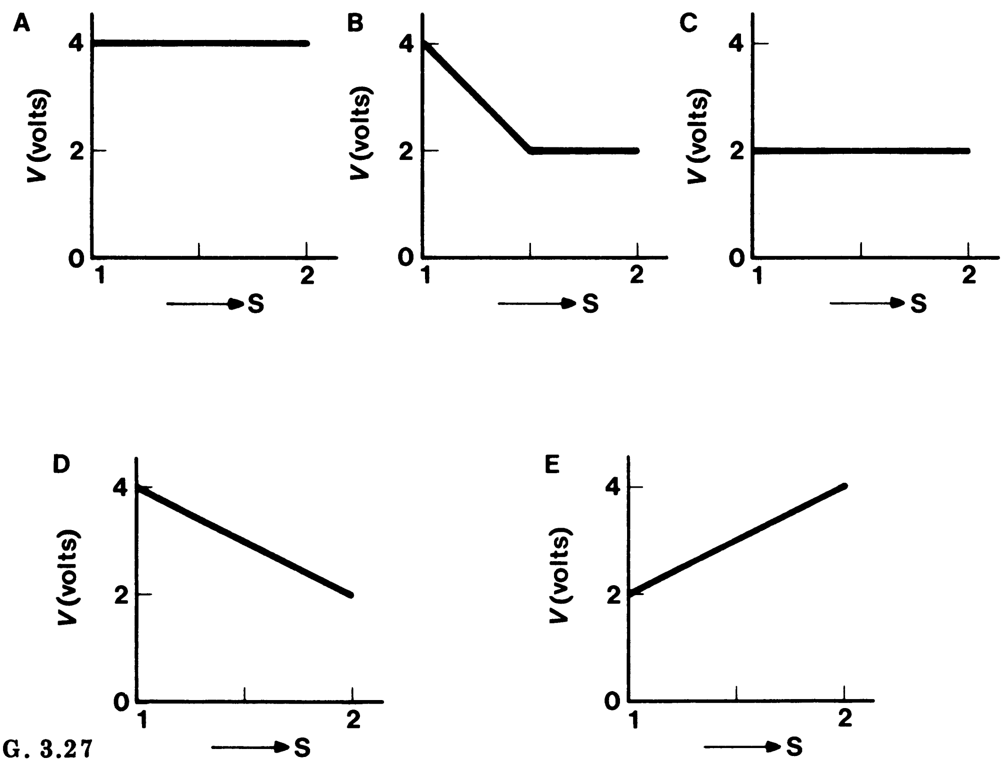


FIG. 3.27

(b) Which one of the graphs A–E above represents the voltage variation for circuit 2?

22. In the circuits shown in Fig. 3.28, similar lamps, ammeters, and cells of negligible internal resistance are used. When one cell is connected in series with a lamp and an ammeter, the reading on the ammeter is 0.2 A.
(a) Estimate possible readings of the ammeters numbered 1–7 in each of the following circuits.

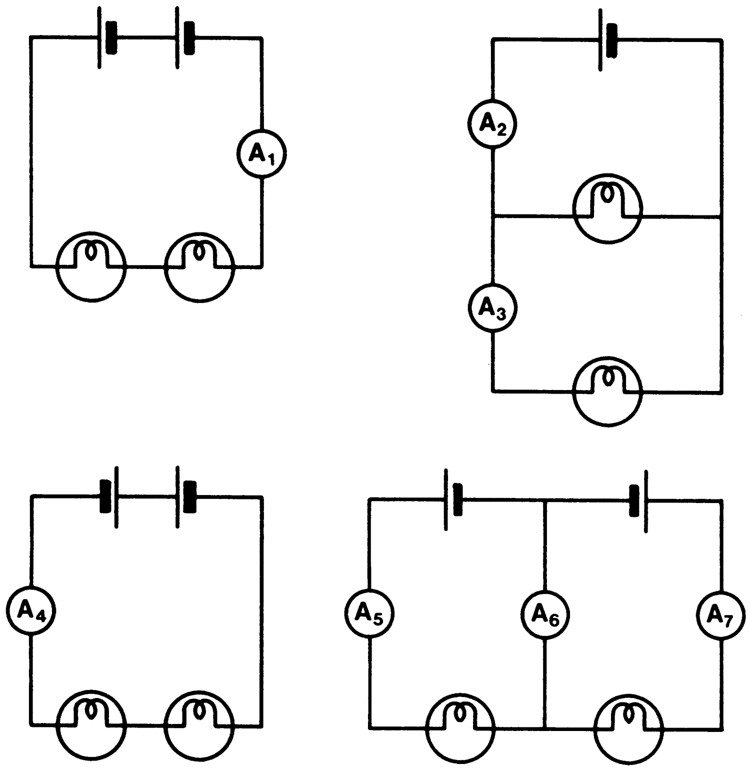


FIG. 3.28

(b) (i) Comment on the brightness of the lamps in the circuit shown in Fig. 3.29.
(ii) Assuming the lamps and the cells are similar to those in (a), what would be your estimate of the ammeter reading in this circuit? Give a reason for your answer. (2)
(c) Batteries have *two* terminals, one marked positive, one negative. Why are there usually *three* pins on an electric cable used to connect an electric fire to the mains? (3)
(d) What is the purpose of a fuse in an electric circuit? How does it work? (3)
(e) Sometimes two or even three electrical appliances are connected by means of an adaptor into one 13 A a.c. mains socket. The following three appliances were used at the same time with an adaptor fitted with a 13 A fuse:
Electric fire rated at 2.5 kW 250 V; ~~Electric iron rated at 0.5 kW 250 V~~

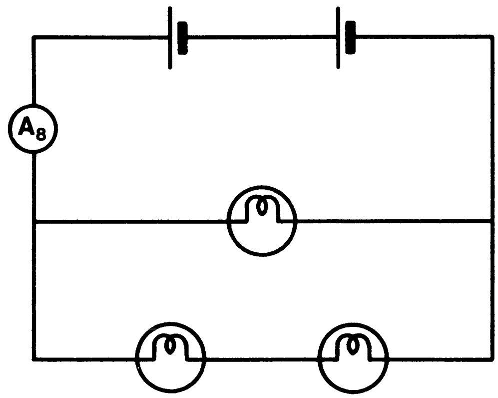


FIG. 3.29

Electric iron rated at 0.5 kW 250 V;
Electric hair dryer rated at 0.75 kW 250 V.

Explain, with relevant calculations, what you would expect to happen. (4)

(f) How would you connect a battery, bell and two bell-pushes so that the bell could be rung at the front door of the house or at the back door?

(g) How would you connect two switches and one light socket to the mains supply so that the light can be switched on or off at either switch (for example, one switch upstairs and one switch downstairs)? (3)

23. What is the highest power that should be taken from a plug with a 5 ampere fuse connected to a 240 volt supply?

A. $\frac{5}{240}$ W

B. $\frac{240}{5}$ W

C. 5×240 W

D. $5 \times 5 \times 240$ W

E. $\frac{240 \times 240}{5}$ W

24. An electric heater is marked 250 V, 750 W. Which of the following fuses would be the most suitable to use with it?

A. 2 A

B. 5 A

C. 10 A

D. 13 A

E. 30 A

25. The circuit shown below (Fig. 3.30) has a thermistor (a resistor whose resistance changes with temperature) in series with a fixed resistor of 200 Ω. The circuit is designed to *switch on* the lamp indicator at *low* temperatures. The lamp indicator is fully lit when the potential difference across it is 6 V.
The graph below (Fig. 3.31) gives the output–input characteristics of the basic unit.

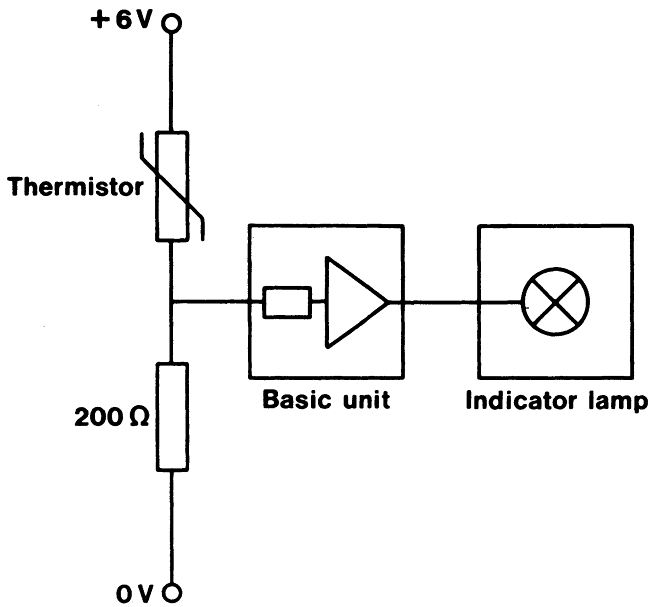


FIG. 3.30

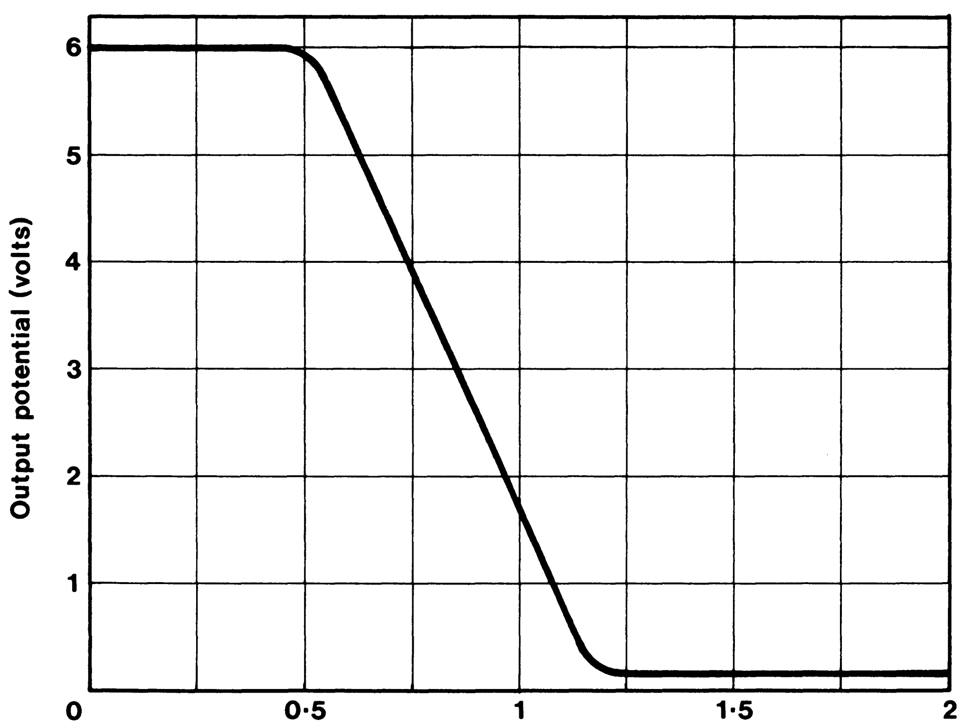


FIG. 3.31

In each of the following questions you should *explain how you arrived at your answer.*

(a) (i) What maximum input potential to the basic unit is needed in order that the output potential is just at its *maximum* value?

(ii) What minimum input potential is needed in order that the output potential is just at its *minimum* value?

(b) Assuming that the basic unit draws negligible current from the resistor–thermistor chain, calculate the resistance of the thermistor which would produce

(i) the input potential calculated in (a) (i) above.

(ii) the input potential calculated in (a) (ii) above.

(c) The graph in Fig. 3.32 shows how the resistance of the thermistor varies with temperature. From the graph deduce the temperature (i) at which the output

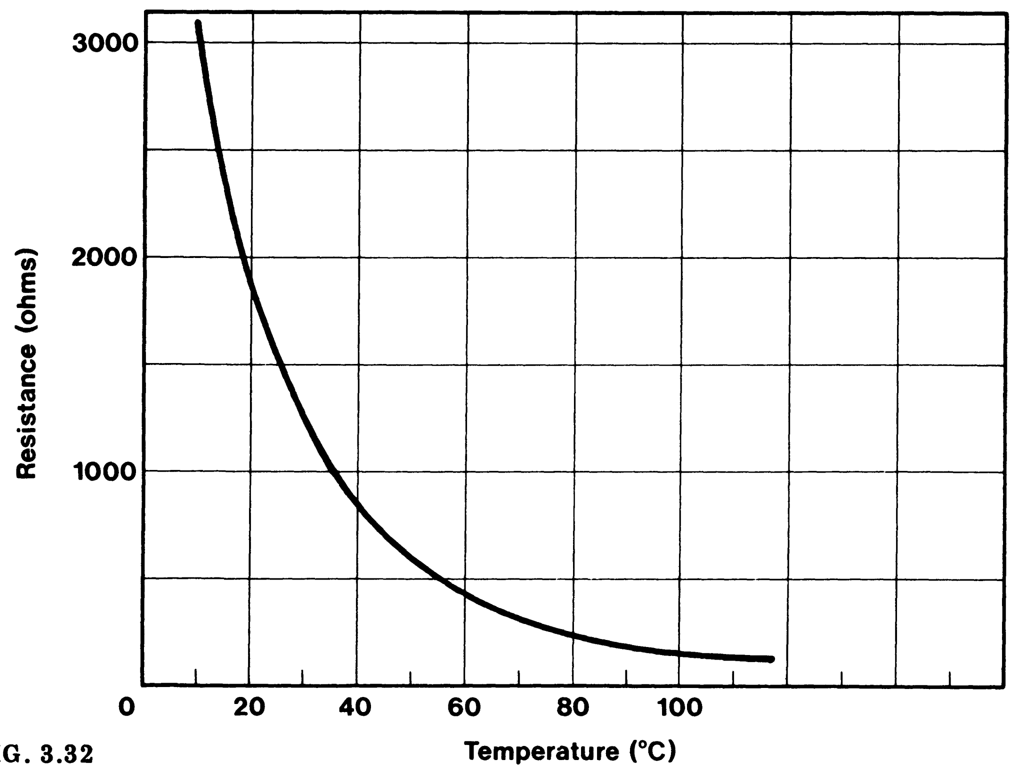


FIG. 3.32

potential of the basic unit is just at its maximum value, and (ii) at which the output potential of the basic unit is just at its minimum value.

(i)

(ii)

(d) In practice the lamp appears to switch on and off over a smaller temperature range than the one calculated above.
Suggest a reason for this.

26. A circuit contains lamps and diodes connected as shown in Fig. 3.33.

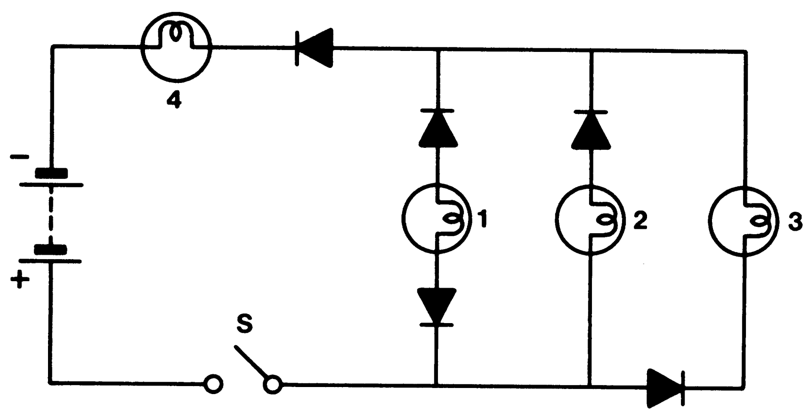


FIG. 3.33

When the switch S is closed, lamp 4 lights. Which other lamp(s) will light as well?

A. 1 only
B. 1 and 2
C. 1 and 3
D. 2 and 3
E. 1, 2 and 3

27. The diagrams A–E in Fig. 3.34 are traces seen on the screen of an oscilloscope.

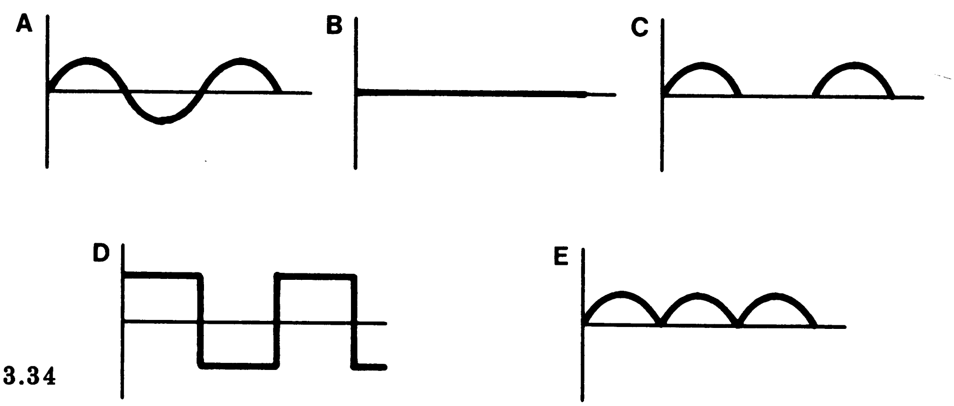


FIG. 3.34

Which one of A–E above would you expect to see on the screen when an a.c. voltage (as in A) is applied in the circuit shown in Fig. 3.35?

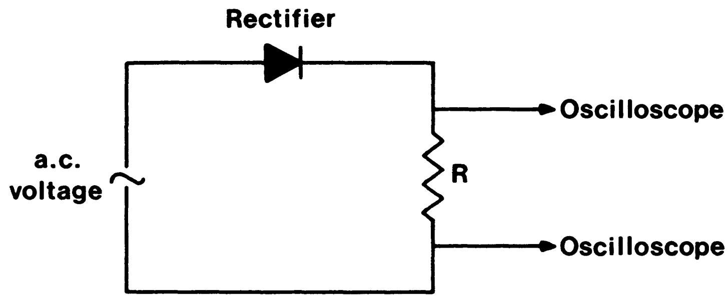


FIG. 3.35

28. Consider the circuit in Fig. 3.36:

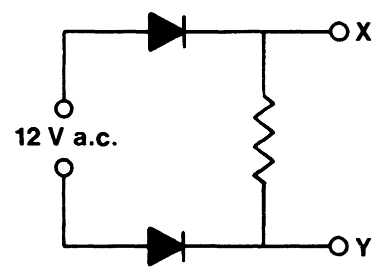


FIG. 3.36

What trace appears on an oscilloscope connected across XY?

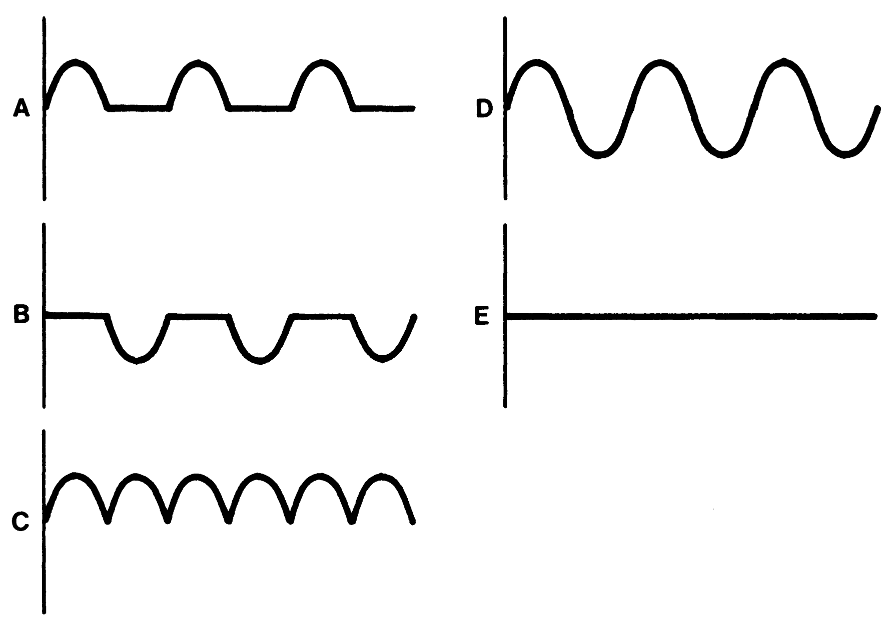


FIG. 3.37

29. A student designs a circuit to convert an alternating voltage to a lower direct voltage. His circuit is shown in Fig. 3.38.

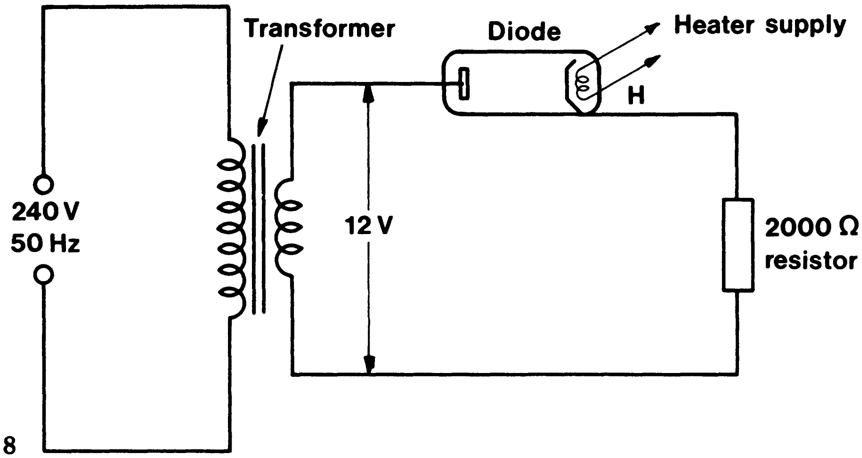


FIG. 3.38

(a) The input to the transformer is 240 V 50 Hz and the output is 12 V. How does the number of turns on the output coil compare with the number of turns on the input coil? (3)

(b) The output of the transformer varies with time as shown in Fig. 3.39. Is the maximum voltage greater than, equal to, or less than 12 V? Explain your answer. (4)

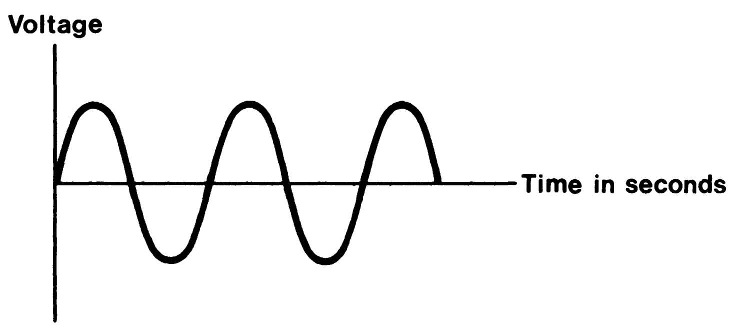


FIG. 3.39

(c) Explain the part played by the diode in the circuit (Fig. 3.38). (5)

(d) Sketch a graph of the voltage across the resistor plotted against time. (3)

(e) The student could use an oscilloscope to find the maximum current in the diode circuit.

(i) Where would he connect the oscilloscope in the circuit? (2)

(ii) What reading would he take and how would he calculate the current from the reading? (5)

(f) Explain what effect reducing the current through the heater H would have on the maximum current in the diode circuit. (3)

30. Fig. 3.40 shows a signal generator being used to apply an alternating voltage to the Y-plates of an oscilloscope.

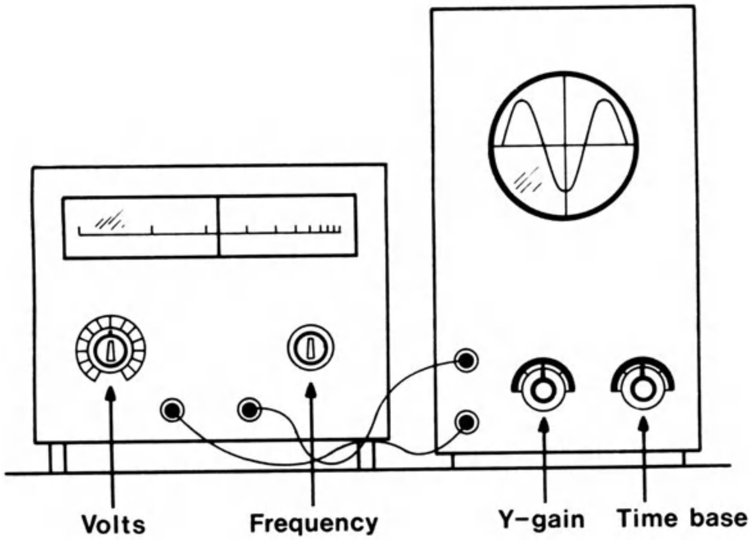


FIG. 3.40

Which two controls both alter the number of cycles seen on the screen?

A. volts and frequency
B. frequency and Y-gain
C. Y-gain and time base
D. volts and time base
E. frequency and time base

31.

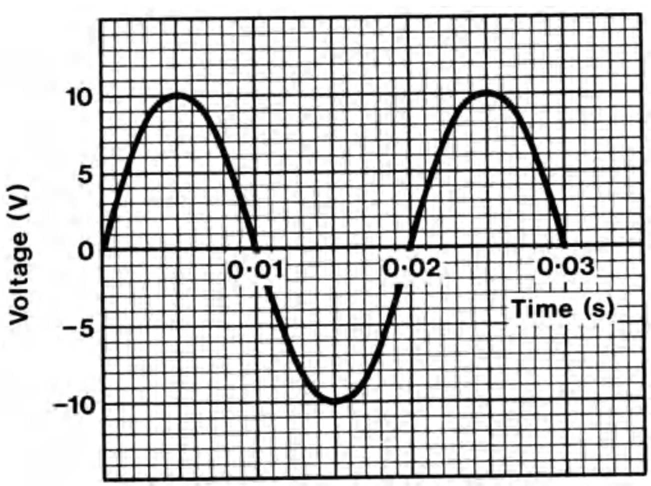


FIG. 3.41

Calculate the r.m.s. voltage and frequency of the signal shown above.

32. Fig. 3.42 shows the trace obtained on the screen of an oscilloscope when an a.c. source of frequency 50 Hz is applied to the Y-plates.

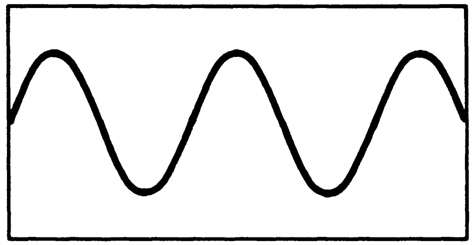


FIG. 3.42

The time taken for the spot to sweep across the screen is

A. 4 milliseconds
B. 8 milliseconds
C. 50 milliseconds
D. 100 milliseconds
E. 125 milliseconds

33. When a 9 V battery is connected across the Y-plates of an oscilloscope the spot is deflected 3 cm. When the Y-plates are connected across a bulb in a lighting circuit the spot is deflected 1.5 cm. This means that

A. the current in the bulb is 1.5 A
B. the resistance of the bulb is 1.5 Ω
C. the p.d. across the bulb is 18 V
D. the p.d. across the bulb is 1.5 V
E. the p.d. across the bulb is 4.5 V

34. *Equations you may require:*
Potential difference, current and resistance $V = IR$
Electrical power $= IV$

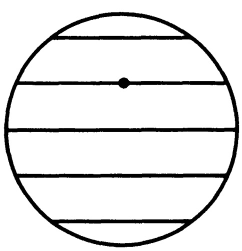


FIG. 3.43

Fig. 3.43 shows an oscilloscope adjusted so that there is a deflection of 1 cm when a 2.0 V d.c. supply is connected across the input terminals.

(The grid on the tube represents 1 cm spacings.)

(a) The time base is switched off.
Mark on the appropriate diagram, what you would see on the screen when:
(i) the terminals of the 2.0 V d.c. supply are reversed.
(ii) a 4.0 V d.c. supply is connected.
(iii) an a.c. supply of 4.0 V peak value is connected.

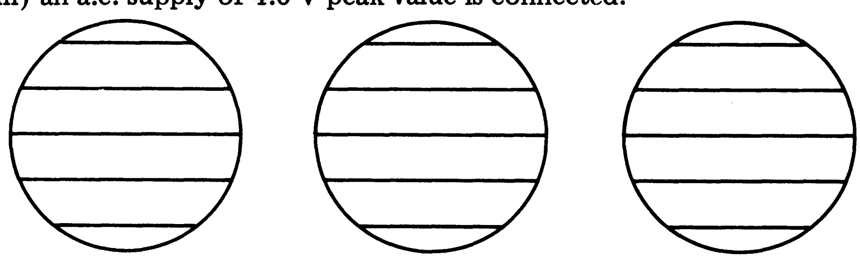


FIG. 3.44 (i) (ii) (iii)

The time base is switched on and adjusted so that the spot sweeps across the screen in 0.02 (a fiftieth) second.
Mark on the appropriate diagram, what you would seen on the screen when the following are connected across the input terminals?

(iv) a 4.0 V d.c. supply.
(v) an a.c. supply of 4.0 V peak value at 50 hertz.
(vi) an a.c. supply of the same value but at 100 hertz.
(vii) a rectifier is placed between the output terminals of the 100 hertz a.c. supply and one of the input terminals of the oscilloscope.

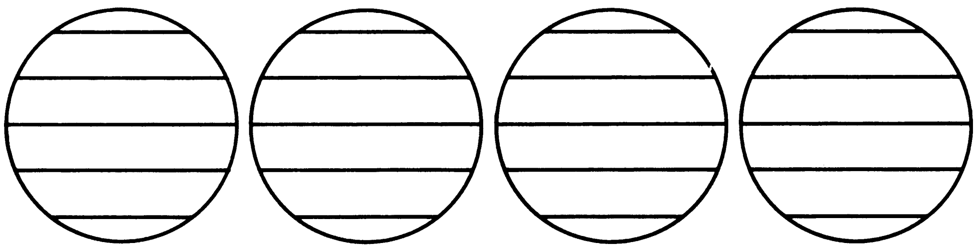


FIG. 3.45 (iv) (v) (vi) (vii)

(b) A battery is connected in series with a lamp and an ammeter.
When the input terminals of the oscilloscope are connected across the bulb there is a deflection of the spot 2 cm upwards.
(i) What is the potential difference across the lamp?

The reading on the ammeter is 2 A.
(ii) What is the resistance of the lamp?

(iii) What is the power of the lamp?

35. A microphone M is placed on top of a small metal plate P which can be tapped to produce a very sharp sound pulse. The sound pulse is picked up by the microphone and produces a pulse X on the screen of a cathode ray oscilloscope (CRO). There is also a second pulse Y produced by the first echo from a flat wall W. The distance between the CRO pulses, XY, is 6 cm when the CRO time-base is set at 10 millisecon centimetre. If the speed of sound in air is 300 m/s, the distance MW, in metres, from the microphone to the wall is

A. 1.5
B. 9
C. 18
D. 900
E. 9000

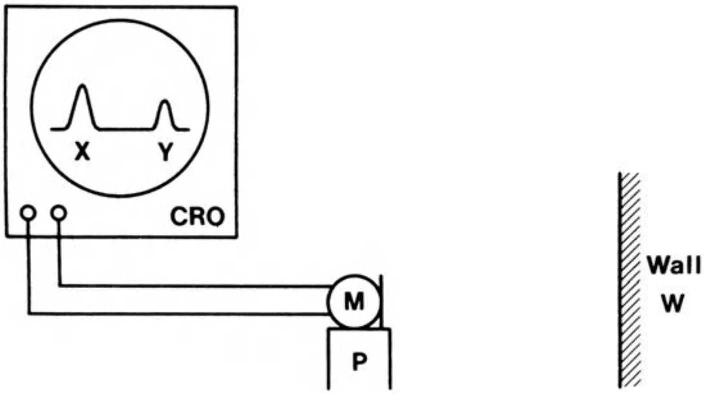


FIG. 3.46

36. Diagrams A, B and C in Fig. 3.47 show alternating voltages applied to a resistor, a diode and a capacitor.

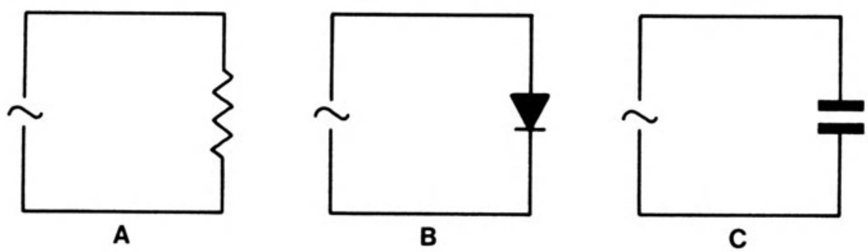


FIG. 3.47

(a) Draw a graph of the applied voltage against time.
(b) Draw graphs to show the current flowing in each of the *three* circuits with time, giving reasons why the device behaves in that way.
(c) If the a.c. supply were replaced by d.c. what difference would this make to the current flowing in (i) the resistor, (ii) the diode and (iii) the capacitor?
(d) What do you understand by a 'choke' and what can it be used for?

37. The readings in the table were taken when variable frequency alternating current was passed through the circuit in the Box X in the circuit shown in Fig. 3.48.

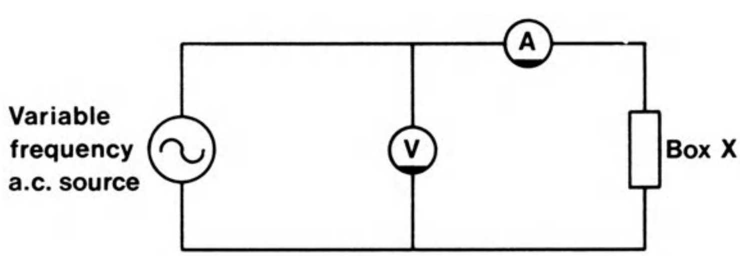


FIG. 3.48

Reading on meter A in mA (r.m.s)	5 mA	2 mA	3 mA
Reading on meter V in V (r.m.s.)	5 V	5 V	5 V
Frequency of supply in Hz	100 Hz	500 Hz	1000 Hz

Of which of the following could the circuit in box X consist?

A. a capacitor and inductor in parallel
B. a resistor and inductor in parallel
C. a capacitor and resistor in series
D. a capacitor and inductor in series
E. a capacitor and resistor in parallel

38.

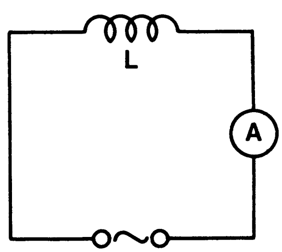


FIG. 3.49

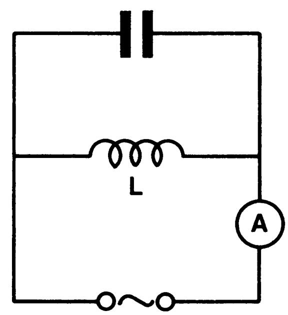


FIG. 3.50

An inductor L is connected across an alternating supply, as in Fig. 3.49. When a capacitor is added in parallel, the current in the alternating current ammeter A *decreases.*

Which one of the following is a valid reason for this effect?

A. The currents in the inductor and capacitor are out of phase.
B. The capacitor stores an appreciable part of the current.
C. There is in Fig. 3.50 no induced voltage across the inductor.
D. The capacitor short-circuits the supply.
E. The inductor in Fig. 3.50 carries no current.

39. Study the oscilloscope trace shown in Fig. 3.51.

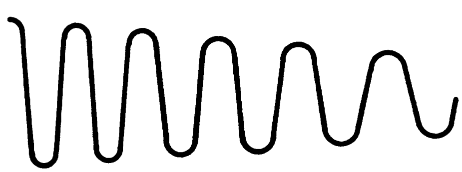


FIG. 3.51

It is obtained from one of the circuits shown below by closing switch S_1 for a few seconds, then opening it and then, a few seconds later, closing switch S_2. Which circuit produces the trace?

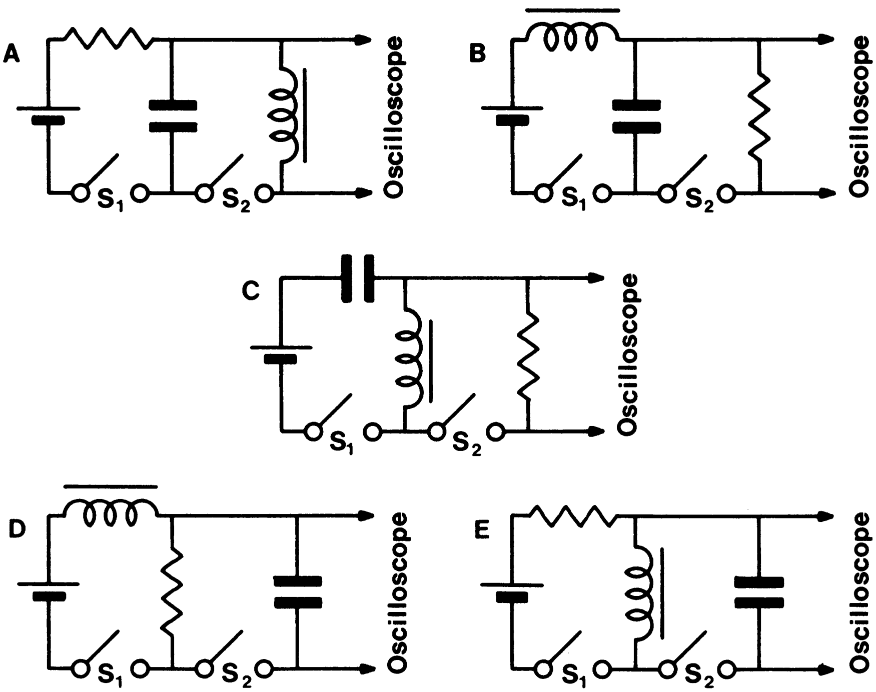


FIG. 3.52

40. Jack and Jill passed 'O' level last year and are now taking Physics in the sixth form. One exercise set them is to construct a new form of ripple-tank vibrator from laboratory materials, not using an electric motor. Jack thinks of several designs that are dismissed as too complicated, but finally produces the plan shown in Fig. 3.53. He proposes to connect a small low-voltage mains (50 cycles per second) transformer at 'source of a.c.'.
    (a) Explain how this apparatus might work, i.e. produce the ripples desired.
    (b) Why use a.c. rather than d.c.? What happens if d.c. is used?
    (c) Actually the vibrator does not work even with a.c., and Jill says she thinks the frequency is wrong; they must use a frequency less than 50 per sec. They obtain a variable-frequency power source and find that there is one suitable frequency, less than 50 per second, which produces powerful vibrations for only a small current. How do you explain this?
    (d) They want to get a faster rate of vibration; suggest two ways in which this could be done (they still have the variable-frequency a.c. generator).
    (e) How could they demonstrate a 'pulse' of ripples?
    (f) To show the ripples, they place a small filament lamp above the tank and white paper on the floor beneath. They can see the bright and dark ripple pattern quite clearly: 'Why is it so clear?' asks Jill. 'Shadows', said Jack. 'Nonsense' said Jill; 'clear water cannot cast shadows; besides, some parts of the paper are actually brighter than when no ripples are made in the tank'. How do you explain the brightness of the ripple pattern on the paper? A diagram will assist your explanation.

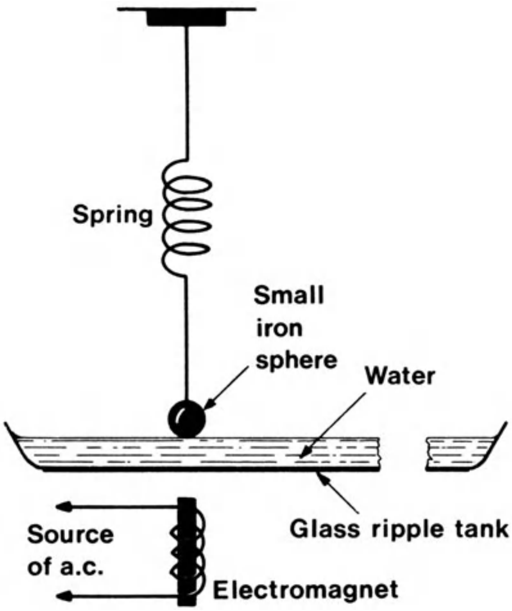


FIG. 3.53

41. In the circuit shown in Fig. 3.54, the switch (S) is used to charge the parallel plate capacitor (C) from the battery (V) and also to discharge it through the micro-ammeter (M) and resistor (R).

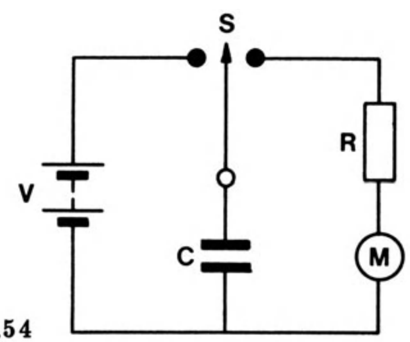


FIG. 3.54

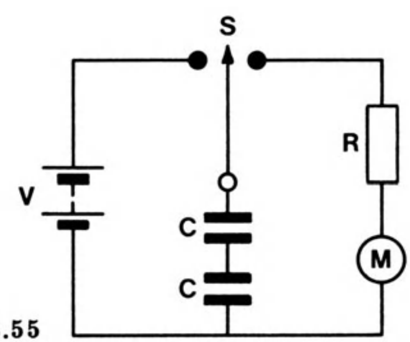


FIG. 3.55

Here are three statements about the effect of changes on the deflection of the micro-ammeter (M):

1. an increase in the e.m.f. of the battery V with the circuit as in Fig. 3.54 would increase the deflection of M.
2. an increase in the separation of the plates of the capacitor C with the circuit as in Fig. 3.54 would increase the deflection of M.
3. connecting a second capacitor, identical to C, in series with C as in Fig. 3.55 would increase the deflection of M.

Which of these statements is/are correct?

A. 1 only
B. 3 only
C. 1 and 3 only
D. 2 and 3 only
E. 1, 2 and 3

42. (a) To study the charging of a capacitor the circuit of Fig. 3.56 is used.

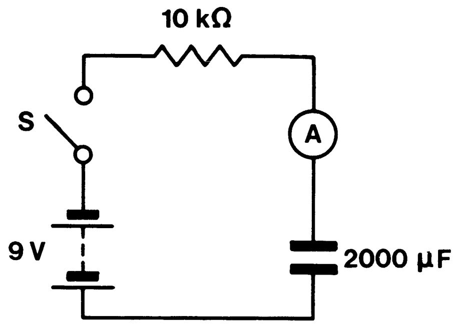


FIG. 3.56

(i) Describe the response of the ammeter after switch S is closed. (2)
(ii) How would you know when the potential difference across the capacitor capacitor is at its maximum? (1)
(iii) Suggest a suitable range for the ammeter. (1)
(iv) If the 10 kΩ resistor is replaced by one of larger resistance, what will be the effect on the maximum potential difference across the capacitor? (1)

(b) In the circuit of Fig. 3.57, the neon lamp flashes at regular intervals.

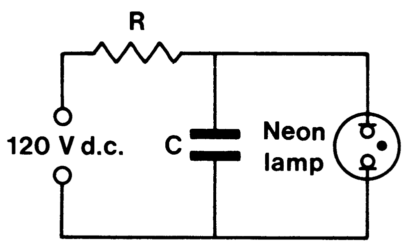


FIG. 3.57

The neon lamp requires a potential difference of 100 V across it before it will conduct and flash. It continues to glow until the potential difference across it drops to 80 V. While it is lit, its resistance is very small compared with R.

(i) Explain why the neon lamp flashes regularly. (3)
(ii) Suggest two methods of decreasing the flash rate. (2)

43. Fig. 3.58 shows approximately how the current through a silicon diode varies as the p.d. across the diode is altered over a range of −50 V to +1.0 V.

(a) Use the graph to estimate the resistance of the silicon diode at the p.d.'s shown below, and record your estimates in the spaces provided.

p.d./V	−50	+0.5	+0.7	+0.9
resistance/Ω				

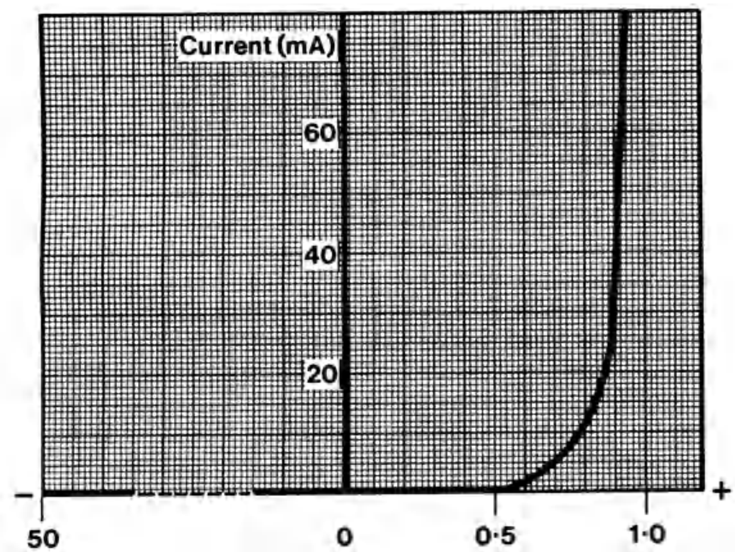


FIG. 3.58 **Potential difference (V)**

(b) Two such diodes connected as shown in Fig. 3.59 may be used to protect a sensitive galvonometer against electrical overload.

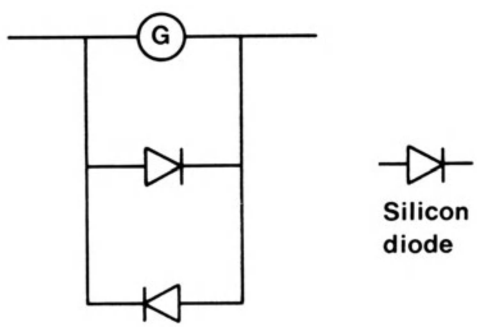


FIG. 3.59

Explain qualitatively how this arrangement provides protection.

(c) Suppose that a galvanometer of resistance 25 Ω, protected in this way, is used in a circuit as shown in Fig. 3.60.
S is a reed switch which operates to charge the capacitor C, of capacitance 10^{-9} F, to 50 V and discharge it through the galvanometer 100 times in each second.

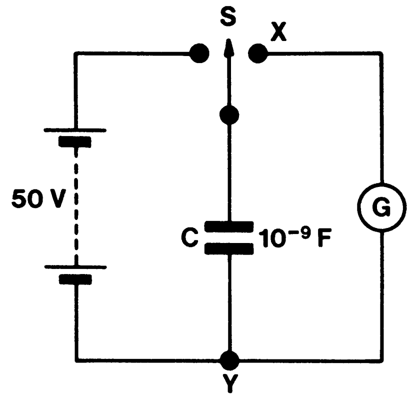


FIG. 3.60

Calculate the average value of the current through branch XY of the circuit.

(d) In fact, the average value of the current indicated by G would be considerably below the value calculated in (c). How do you account for this?

(e) Connecting a 10 kΩ resistor in series with the galvanometer restores the reading of G to the value calculated in (c). Why is this?

44.

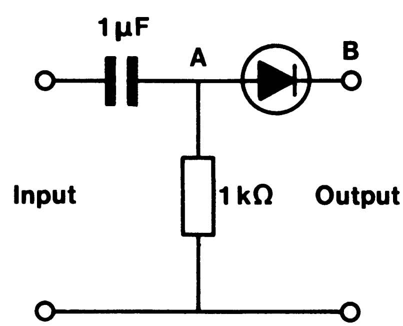


FIG. 3.61

Using sketch graphs, explain the voltage waveforms you would expect to see at A and B in the circuit shown in Fig. 3.61 with the following input signal:

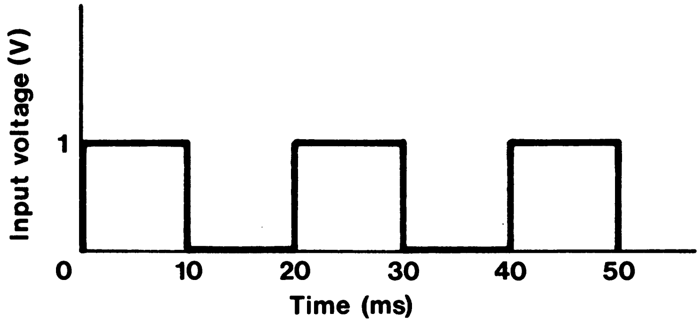


FIG. 3.62 (6)

45. The circuit shown in Fig. 3.63 is called a *differentiating circuit.* When a square wave pulse is applied across AB, a pair of 'spiky' pulses appear across XY.

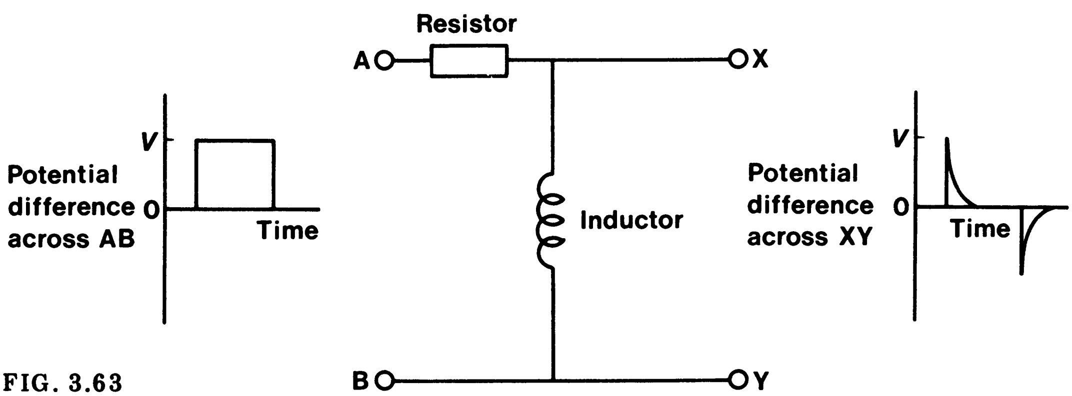


FIG. 3.63

(a) Give a physical reason why the potential difference across XY is zero when the potential difference across AB is at the constant value V (that is, it is not changing).

(b) Give a physical reason why the potential difference across XY does not fall immediately to zero after the potential difference across AB has reached V.

(c) Describe **one** change you would make to the circuit to make the potential difference across XY fall more quickly to zero when the potential difference across AB has reached *V*. Give a reason for your answer.

46.

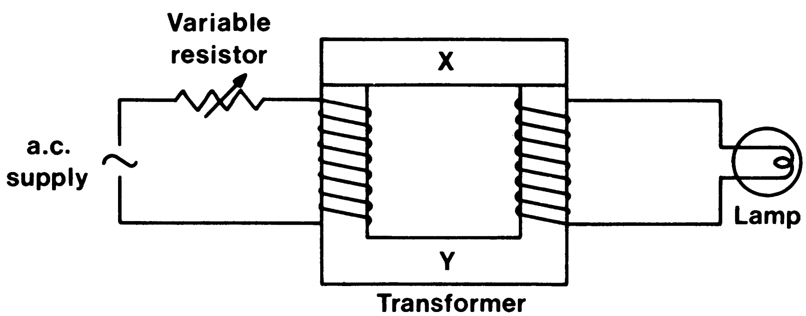


FIG. 3.64

The circuit above is set up (Fig. 3.64). The lamp is excessively bright. Which of the following procedures could be used to reduce its brightness?

(i) Increase the resistance in the primary.
(ii) Decrease the number of turns in the secondary.
(iii) Move the part X of the transformer so that it does not touch Y.

A. (i), (ii) and (iii)
B. (i) and (ii) only
C. (i) and (iii) only
D. (iii) only
E. some other response

47. When 24 V is applied across the primary of a transformer, the current in the primary is 1 A. The output voltage is 12 V and a current of 2 A flows in the secondary. The ratio of the power in the secondary to the power in the primary is

A. 1 : 4
B. 1 : 2
C. 1 : 1
D. 2 : 1
E. 4 : 1

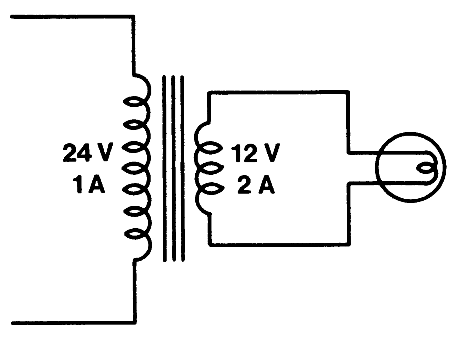


FIG. 3.65

48. A transformer in which losses can be neglected has 200 primary turns and 5 secondary turns. If a current of 10 mA flows in the primary circuit, the current in the secondary will be

A. 10 A
B. 400 mA
C. 100 mA
D. 40 mA
E. 4 mA

49. In the circuit shown below (Fig. 3.66), which switches must be closed for the lamp L to light up brightly?

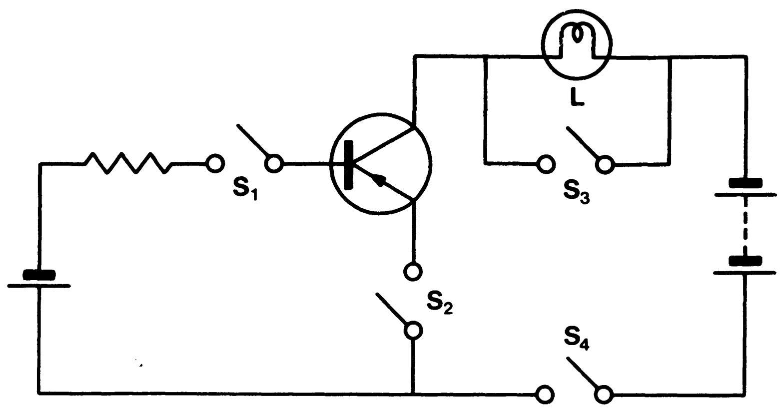


FIG. 3.66

A. S_1, S_2, S_3
B. S_1, S_2, S_4
C. S_1, S_3, S_4
D. S_2, S_3, S_4
E. S_2, S_4

50. Study the simple circuit shown in Fig. 3.67.

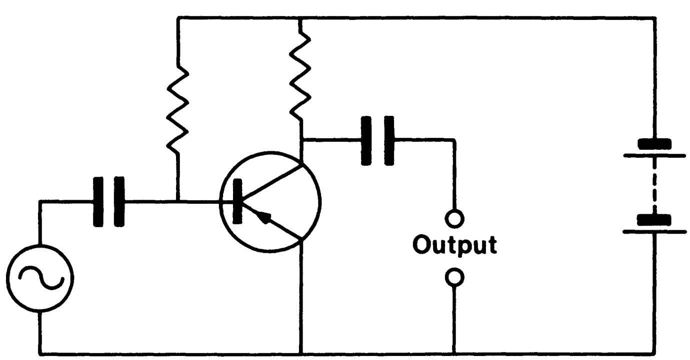


FIG. 3.67

This transistor circuit is normally used
A. to convert a.c. into d.c.
B. to convert d.c. into a.c.
C. as a simple radio set
D. as a simple amplifier
E. as a simple oscillator.

51. Calculate the p.d. developed across the 8-Ω load of the amplifier shown in Fig. 3.68 if the signal source voltage, V_s, is 10 mV and its resistance, R_s, is 250 Ω.
(Amplifier characteristics: Voltage gain = 400
Input impedance = 750 Ω
Output impedance = 8 Ω)

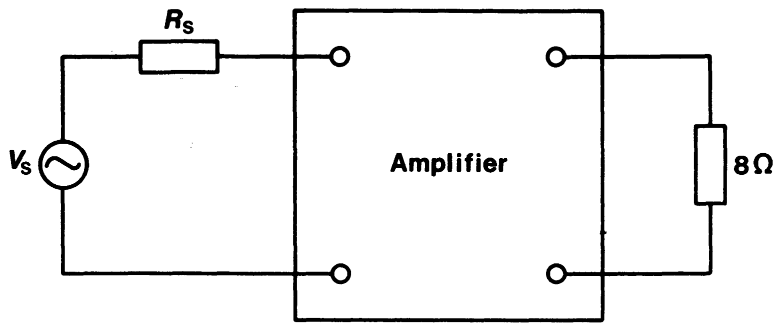
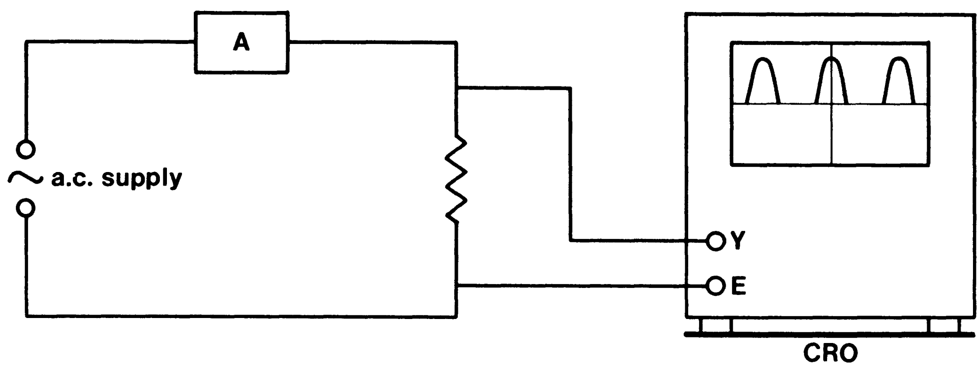
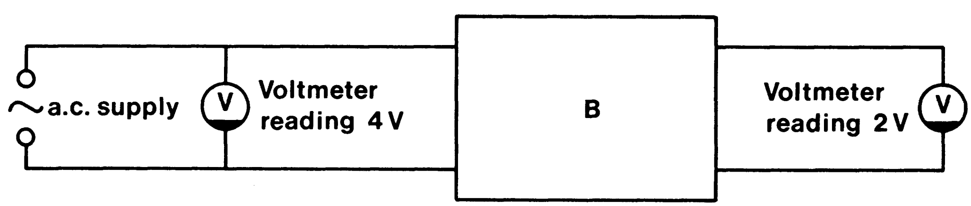


FIG. 3.68 (5)

52. Fig. 3.69 shows experiments in which important components have been omitted, and are indicated by capital letters.
State what each of the items A, B, C, D and E is, and **briefly** describe its purpose in its circuit.





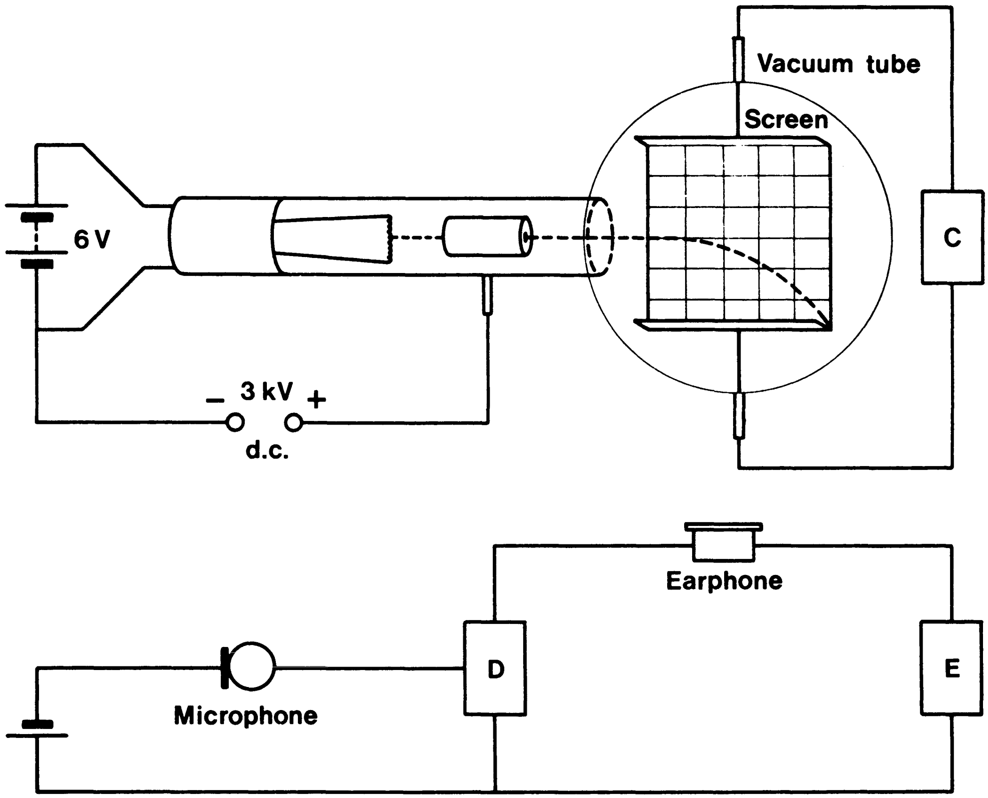


FIG. 3.69 (continued) (10)

53. There exists a two-terminal device, the Zener diode, which has the following properties:

When the p.d. across it is below a certain value, called the breakdown voltage, the device does not conduct.

When the p.d. across it reaches the breakdown voltage the device begins to conduct. The p.d. across the device then remains constant at the breakdown voltage irrespective of the current through it.

The idealized current-p.d. characteristic for a Zener diode is shown in Fig. 3.70.

(a) The Zener diode Z in Fig. 3.71 has a breakdown voltage, V_z, of 4 V. Calculate the current in Z.

Explain, giving values, the effect on the current in Z of

(i) a rise in supply voltage to 12 V,

(ii) connecting a load of 100 Ω across AB (with a supply voltage of 10 V).

If the circuit of Fig. 3.71 is used to provide a stable voltage supply what is the minimum resistance which may be connected across AB?

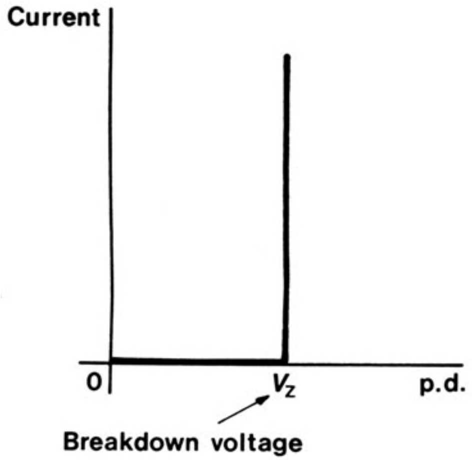


FIG. 3.70

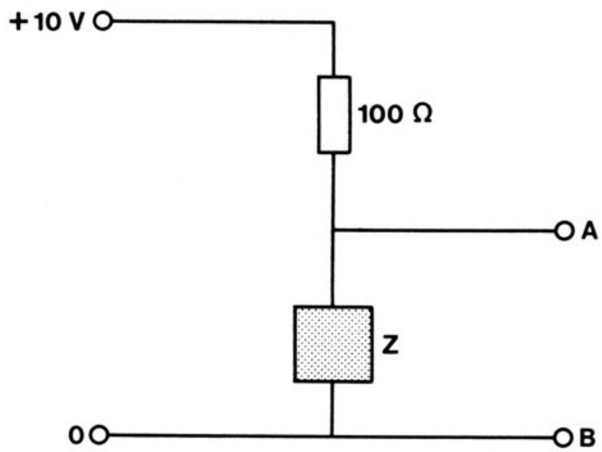


FIG. 3.71

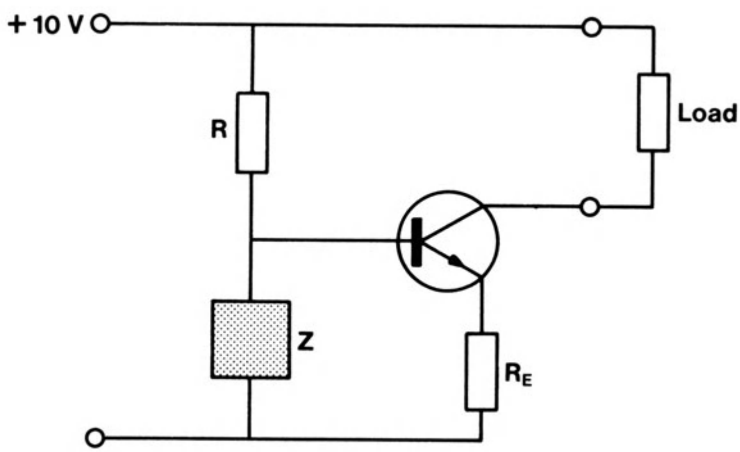


FIG. 3.72

The circuit of Fig. 3.72 provides a stabilised *current* source. Explain
(i) why a rise in supply voltage does not lead to a rise in current through the load, and
(ii) how the circuit responds to a change in the resistance of the load.
Discuss briefly what would happen if
(iii) the load were reduced to zero resistance, and
(iv) the load were removed (i.e. increased to infinite resistance).

54. Suggest a circuit to switch on a warning light when the air temperature exceeds a certain value, using a thermistor, transistor, relay and any other components you need. Explain how your circuit works. Give approximate component values.

55. Draw a circuit diagram of an astable (free running) multivibrator. Explain, with the aid of sketch graphs of collector and base voltages, how the multivibrator works. State, giving reasons, which components you would change to alter the frequency of the multivibrator.
How would a multivibrator giving a symmetrical wave (mark to space ratio 1 : 1) differ from one giving a non-symmetrical wave?
State and explain the effects of changing the supply voltage.

56. Read the following passage carefully and then answer the questions at the end.

The Digital Voltmeter (*DVM*). A digital voltmeter gives a reading on a numerical display, whereas conventional moving coil meters give a reading which has to be interpreted from the position of a pointer on a scale. The digital meter thus gives an illusion of accuracy because the person reading it does not have to make any contribution to the estimation of the value or take precautions to avoid errors such as parallax.

FIG. 3.73

The digital meter compares the voltage to be measured with an internal reference voltage which is a repetitive ramp waveform similar to the timebase of a CRO The voltage to be measured is, after being amplified, fed in as one input to a

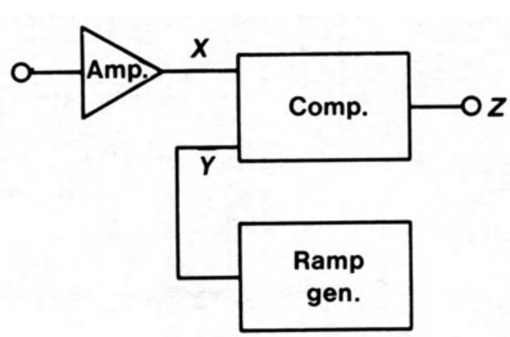


FIG. 3.74

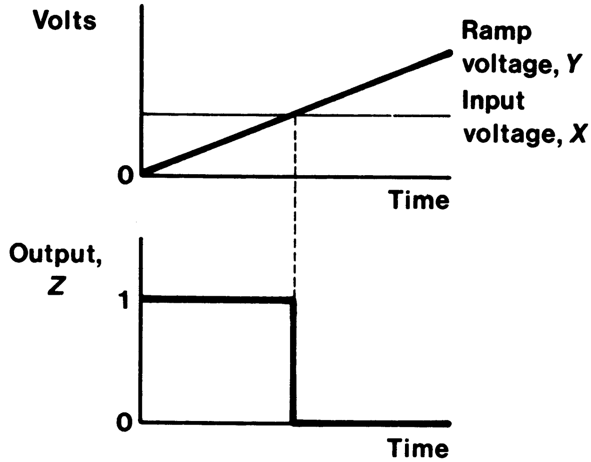


FIG. 3.75

comparator circuit as shown above. The reference voltage is fed into the other input. When the input, X, from the voltage to be measured is greater than the reference voltage, Y, the output is 1. When Y exceeds X the output is 0.
The output from the comparator, Z, is one input of the AND gate in the circuit shown in Fig. 3.76. The other input is a regular pulse train.

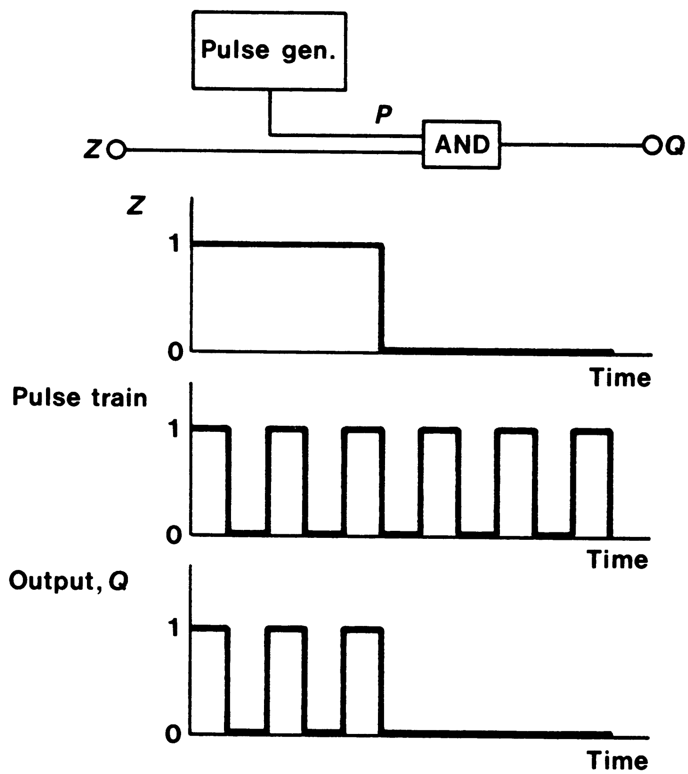


FIG. 3.76

As long as the comparator output, Z, is 1 the pulse train is allowed through the AND gate. As soon as $Z = 0$ the pulse train is cut off by the gate.

These pulses are fed into a counting circuit (register). A decoding circuit converts the information from binary to decimal form and it is then shown on a digital display. The complete system is thus as shown below in block diagram form in Fig. 3.77.

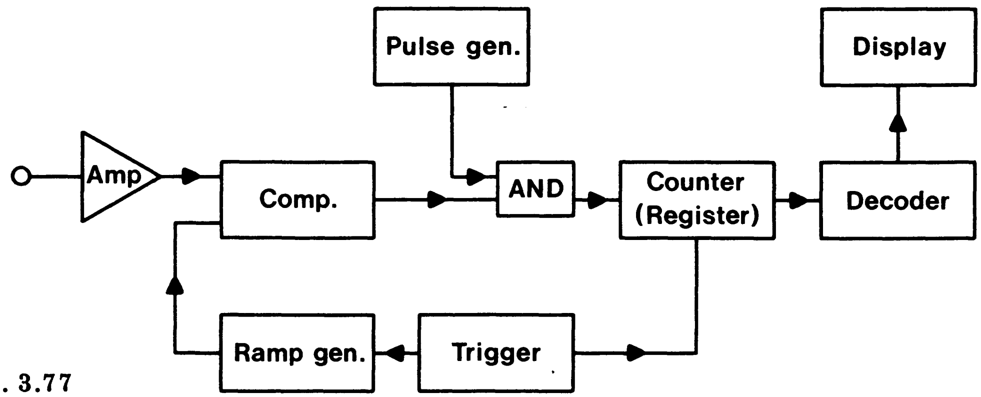


FIG. 3.77

The cycle of operation is thus:

(a) A trigger starts the ramp and clears the register.
(b) The comparator gives a 1 output until the ramp voltage is equal to the voltage to be measured, X.
(c) When the ramp voltage reaches the value X the comparator output falls to 0.
(d) The AND gate admits a series of pulses, the number of which measures the time the ramp voltage takes to reach X. If the ramp is linear this time is proportional to X.
(e) The number of pulses is recorded in the register.
(f) The decoder converts the information into a decimal reading and passes it to the display.
(g) Whilst the operation of measurement is taking place the display holds the previous reading.

It will be seen that the DVM is sampling the voltage to be measured at regular intervals (Fig. 3.78).

Digital voltmeters, because the input is into an electronic amplifier, can have a very high impedance - up to 10 MΩ in some cases. They can also measure very low voltages, of the order of millivolts, as the signal to be measured is amplified before being processed.

Questions

(a) Comment on the statement 'Instruments with digital displays are better because they are more accurate'. (3)
(b) What factors affect the voltage range of a DVM? (4)
(c) Explain what would happen if an alternating voltage were applied to the input of the DVM. (3)

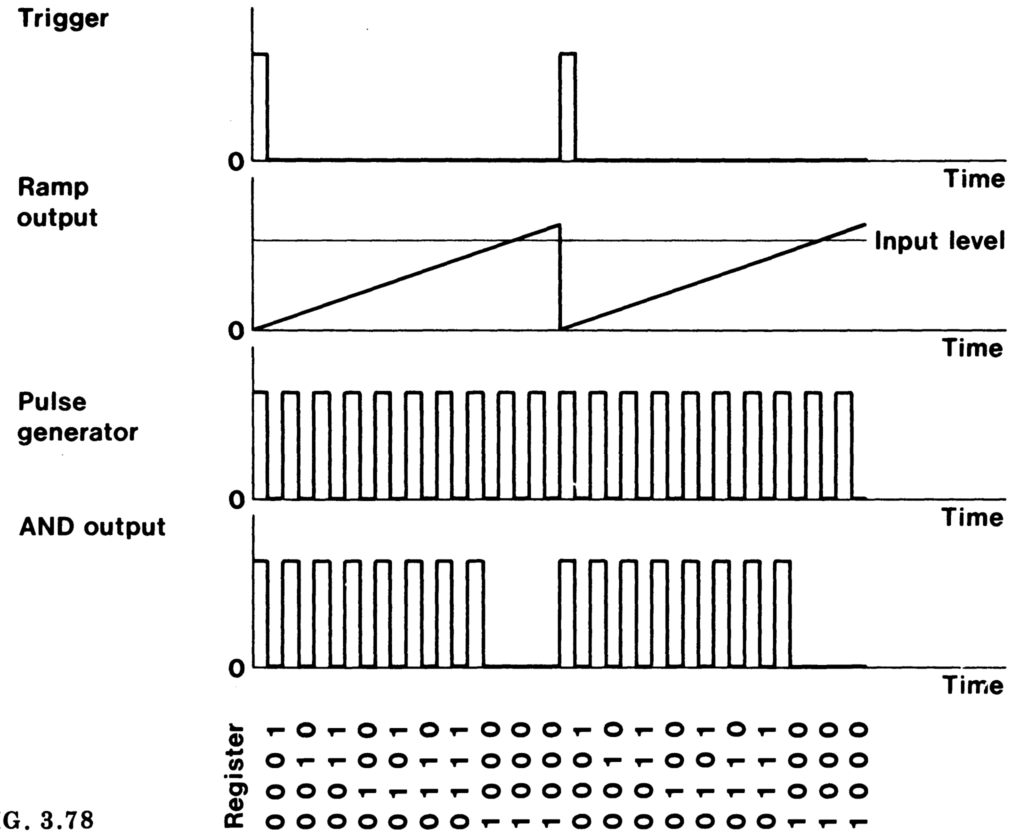


FIG. 3.78

(d) What factors determine whether a DVM with a four-digit display can distinguish between a voltage of 1.001 V and one of 1.002 V? (4)

(e) If a DVM has a three-digit readout reading up to 999 what is the minimum number of bistable circuits that would be needed in the register? (3)

(f) Is the high impedance of a DVM a good or bad thing? Explain your answer. (3)

PART 4
Answers

1. Replacing fuse N would probably be successful providing the bulb itself has not blown.

2. On closing switch S the 24 W 12 V bulb will blow since 240 V would have been applied across it. The 100 W mains lamp will continue to work at normal brightness since the two lamps are wired in parallel.

3.

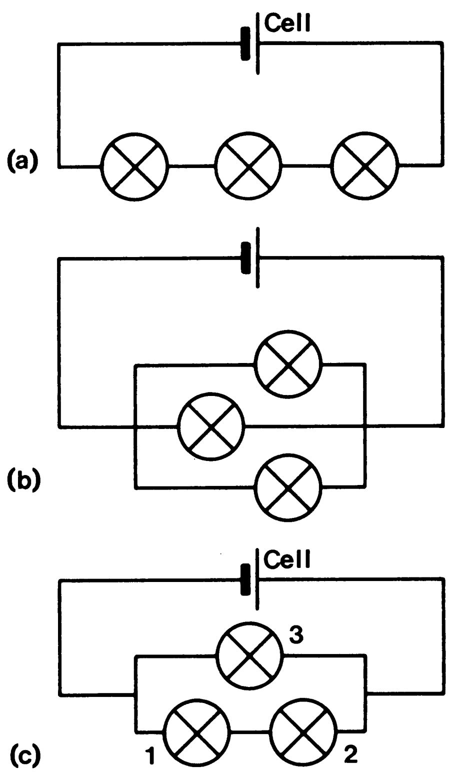


FIG. 4.1

(a) In this case the p.d. across each bulb is $\frac{1}{3}$ the e.m.f. of the battery, hence the bulbs glow dimly.

(b) Here the p.d. across each bulb is the full e.m.f. of the battery, and therefore the bulbs glow brightly.

(c) The p.d. across bulbs 1 and 2 in series is $\frac{1}{2}$ the e.m.f. of the battery, and hence they glow dimly. The p.d. across bulb 1 is the e.m.f. of the battery and it glows brightly.

(d) Removing any one of the lamps will cause a break in the circuit and the other two bulbs will go out.
(e) In this case the lamps will continue to glow brightly since they are connected in parallel.
(f) Lamps 2 will go out as it is connected in series with the removed lamp. Lamp 1 will continue to glow brightly since it is connected in parallel with the lamp that was removed.

None of the lamps would light up since the battery would not be able to supply even enough current for the lamps to glow dimly.

4. (a) Each bulb has a resistance $R = \frac{\text{volts}}{\text{amps}} = \frac{1.5\text{ V}}{0.3\text{ A}} = 5\,\Omega$.

(i) Normally
(ii) Normally
(iii) Dimmer than normal since the resistance is double, $10\,\Omega$
(iv) Not at all since the e.m.f.s of the batteries are opposed

(b) (i)

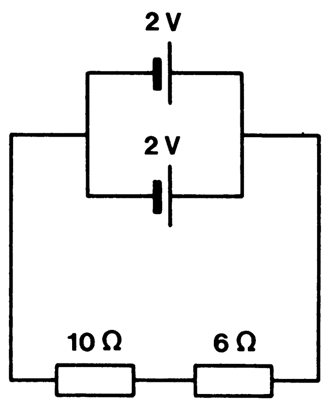


FIG. 4.2

(ii) 2 volts
(iii) The effective resistance $= 10\,\Omega + 6\,\Omega$
$= 16\,\Omega$.

(iv) The current in the circuit $I = V/R = 2\text{ V}/16\,\Omega = 1/8\text{ A}$.

This is also the current flowing through the $10\,\Omega$ resistor.

(c) The resistance of a wire $R = k \times l/a\,\Omega$, where k is a constant, l the length of the wire in m and a the cross-sectional area of the wire in m^2. Therefore if the length increases the resistance increases. If the cross-sectional area decreases the resistance increases. Hence the new length of wire will have a resistance 6 times (3 times for the length, 2 times for the cross-sectional area) that of the original wire, i.e. $12\,\Omega$.

5. (a)

Lamp 1	Normal	Lamp 5	Not lit
Lamp 2	Normal	Lamp 6	Normal
Lamp 3	Brighter than normal	Lamp 7	Normal
Lamp 4	Brighter than normal	Lamp 8	Brighter.

If you are not sure of any of these answers then calculate the total e.m.f. in the circuit and use Ohm's law to calculate the various currents through the bulbs.

For example, for a normally lit circuit the current $I = V/R = 2/2 = 1$ A.

If your calculations for the other circuits result in values of I either higher or lower than that for the normally lit bulb, then the bulb will be either brighter or dimmer respectively.

(b) (i)

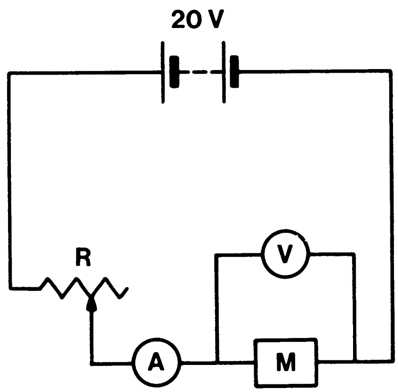


FIG. 4.3

Adjust the variable resistor R until the voltmeter V reads 12 V. The ammeter A will then show the current through the motor when the p.d. across it is 12 V. (The current taken by the voltmeter is usually negligible.)

(ii) Adjust the variable resistor so as to ‘drop’ more volts across it.

(c) (i) Quantity of electricity used in coulombs, $C = I \times t$, where I is the current in amps and t the time in seconds.

$$Q = 1.5\,\text{A} \times 8\,\text{s}$$
$$= 12\,\text{C}.$$

(ii) Energy used in joules, $J = m \times g \times h$, where m is the mass of the load, h the height in metres through which the load is moved and g the earth's gravitational field strength (~10 N/kg).

$$J = 4\,\text{kg} \times 10\,\text{N/kg} \times 2\,\text{m}$$
$$= 80 \text{ joules}.$$

(iii) Electrical energy used by the motor in joules, $J_e = I \times V \times t$ where I is the current, V the voltage and t the time in seconds.

$$J_e = 1.5\,\text{A} \times 12\,\text{V} \times 8\,\text{s}$$
$$= 144 \text{ joules}.$$

Notice that the energy used by the motor is more than the energy strictly necessary to lift the load. This extra energy required by the motor is because it is not 100% efficient. It does not change all the electrical energy into mechanical energy but wastes some of it in heating. You may have noticed that an electrical motor becomes hot when it is being used.

6. R_1 since it has the largest current passing through it (3 A).

7. The voltage across the 10 Ω resistor V = current × resistance

$$= 4\,\text{A} \times 10\,\Omega$$
$$= 40\,\text{V}.$$

This is also the voltage across the parallel resistance network whose total resistance R is given by:

$$\frac{1}{R} = \frac{1}{10} + \frac{1}{5}\,\Omega^{-1}$$

$$R = 3\tfrac{1}{3}\,\Omega \text{ (the resistance of the ammeter is negligible).}$$

The current through A_1, I = p.d./resistance

$$= \frac{40\text{ V}}{3\frac{1}{3}\,\Omega}$$

$$= 12\text{ A.}$$

This question can also be answered by considering that the current going through the $5\,\Omega$ resistor will be twice that through the $10\,\Omega$ resistor. Then since A_1 is the sum of A_2 and A_3, the current will be $4\text{ A} + 8\text{ A} = 12\text{ A}$.

8. As the take-off on the rheostat is moved from X to Y the resistance of the circuit increases, consequently the current decreases. As the current decreases the p.d. across the fixed resistor decreases. The p.d. across the rheostat must increase since the p.d. across both the rheostat and the resistor remains constant (and equal to the e.m.f. of the battery).

9. (a) $4\,\Omega$. (b) $1\,\Omega$. (c) $4\,\Omega + 1\,\Omega = 5\,\Omega$.

10. The resistance R between B and C is given by:

$$\frac{1}{R} = \frac{1}{8} + \frac{1}{8}$$

$$R = 4\,\Omega.$$

The p.d. between B and C must therefore be 6 V, the same as the p.d. across the other $4\,\Omega$ resistor.

11. The resistance R between X and Y is given by:

$$\frac{1}{R} = \frac{1}{6} + \frac{1}{3}$$

$$= \frac{1}{2}$$

$$R = 2\,\Omega.$$

12. With S closed the value of the only resistance in the circuit R_1 (since R_2 is shorted out) is given by:

$$R_1 = \frac{\text{p.d.}}{\text{current}}$$

$$= \frac{6\text{ V}}{3\text{ A}}$$

$$= 2\,\Omega.$$

With S open the total resistance of the circuit $R_1 + R_2 = \frac{\text{p.d.}}{\text{current}} = \frac{6\ \text{V}}{2\ \text{A}}$

$$2\ \Omega + R_2 = \frac{6\ \text{V}}{2\ \text{A}} = 3\ \Omega$$

$$\therefore \quad R_2 = 1\ \Omega.$$

13.

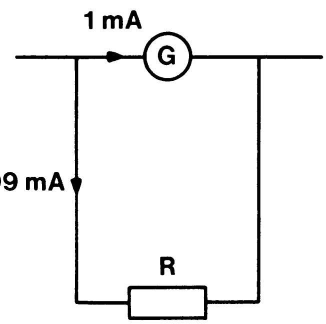


FIG. 4.4

The meter can only accept up to 1 mA of current. Therefore if it is to measure 100 mA (when suitably calibrated), 99 mA must be 'shunted' around the meter using a suitable resistor wired in parallel. Now the voltage across the galvanometer when 1 mA is flowing is given by:

$$\begin{aligned} V &= \text{current} \times \text{resistance} \\ &= 1\ \text{mA} \times 99\ \Omega \\ &= 99\ \text{mV}. \end{aligned}$$

This is also the p.d across the shunt since they are wired in parallel. Hence the value of the shunt resistor $R = \frac{\text{p.d.}}{\text{current}}$

$$= \frac{99\ \text{mV}}{99\ \text{mA}} = 1\ \Omega.$$

14. If a high resistance is placed in series with the galvanometer then it can be used to measure high voltages. The high resistance limits the current flowing into the galvanometer by 'dropping' most of the voltage across itself and thereby leaving the galvanometer to measure only a few volts (which is what it is designed to do). When this is done the galvanometer needs to be calibrated.

15. The current through the 12 Ω resistor $I = \frac{\text{p.d.}}{\text{resistance}} = \frac{9\ \text{V}}{12\ \Omega}$

$$= \tfrac{3}{4}\ \text{A}.$$

Hence the voltage across the 4 Ω resistor $V = \text{current} \times \text{resistance}$

$$\begin{aligned} &= \tfrac{3}{4}\ \text{A} \times 4\ \Omega \\ &= 3\ \text{V}. \end{aligned}$$

The voltage of the power supply is the sum of the voltages across the two resistors, i.e. 12 V.

Another method of doing this question is to say that since the p.d. across a resistor is proportional to the value of the resistor, then the p.d. across the 4 Ω resistor will be $\frac{1}{3}$ that across the 12 Ω resistor. Hence the total p.d. is

$$3\text{ V} + 9\text{ V} = 12\text{ V}.$$

16. If point X is at a potential of 1 V the voltage drop across R_2 will be 1 V, and across R_1 5 V.

Therefore current through R_2, $I = \dfrac{1\text{ V}}{10\text{ k}\Omega}$

$= 0.1\text{ mA}.$

This is also the value of the current through R_1, hence its resistance

$$R = \frac{5\text{ V}}{10\text{ mA}} = 50\text{ k}\Omega.$$

Another way of looking at the problem is by using the idea of proportions. Since the 10 kΩ resistor drops 1 volt across it, then for a 5 volt drop R_1 must have a value equal to 5 × 10 k = 50 kΩ.

The current through R_1 is then given by: $I = \dfrac{5\text{ V}}{50\text{ k}\Omega} = 0.1\text{ mA}.$

17. The current flowing in the left-hand circuit $I = \dfrac{\text{power}}{\text{p.d.}}$

$$= \frac{2\text{ W}}{2\text{ V}} = 1\text{ A}.$$

Similarly the current in the right-hand circuit is 1 A. The current in the wire PQ therefore is 2 A and it flows from P to Q.

18. The resistance of the lamp $R_1 = V^2/W$, where V is the voltage across the lamp and W is the power of the lamp in watts.

$$R_1 = \frac{144}{24} = 6\ \Omega.$$

The total resistance of the circuit R_t is given by:

$$\frac{1}{R_t} = \frac{1}{R_1} + \frac{1}{R_1} + \frac{1}{R_1} = \frac{1}{2}\Omega$$

$$R_t = 2\ \Omega.$$

The current $I = \dfrac{V}{R_t} = \dfrac{12\text{ V}}{2\ \Omega} = 6\text{ A}.$

19. Circuit D is the only circuit which will give identical currents in the two milli-ammeters since it is the only circuit where the various components are in series. This means that the current passing through one meter must pass through the other one.

20. If P is an ammeter and Q a voltmeter then R_2 can be found since we will know the voltage across it and the current going through it. If no more information is given then this is all we can find. If we assume that the e.m.f. of the battery is known then we can also find the value of R_1. The p.d. across R_1 is the e.m.f. of the battery minus the p.d. across R_2. Then since we know the current through R_1 from meter P, we can find the value of R_1.

21. In circuit 1 when the slide of the potentiometer is in position 1, the voltmeter measures the full p.d. across P and R - 4 volts. When the slide is in position 2 the voltmeter only measures the p.d. across R - 2 volts (half the e.m.f. of the battery since P and R are equal). Between positions 1 and 2 of the slide the voltage drops linearly. Hence graph D represents the voltage variation in circuit 1. It may be appreciated that in this circuit the current remains constant.

In circuit 2 with the slide in position 1 the voltmeter measures the p.d. across P and R - 4 volts. In position 2 the voltmeter measures only the p.d. across R. This will also be 4 volts (although the resistance is halved compared to position 1 the current will be double, resulting in the same p.d. being measured). In between these two positions the measured p.d. does not change. Hence graph A represents the measured voltage variation of circuit 2.

22. (a) A_1 will read 0.2 A. Although the resistance of the circuit has been doubled by having two lamps, the number of cells has also been doubled.

The total resistance of circuit 2 is half that due to one lamp in series because the two lamps are in parallel. Hence A_2 will read 0.4 A and since this current is equally divided between the two branches of the parallel network, A_3 will read 0.2 A.

A_4 will show no reading since the two cells in the circuit are opposed and the net e.m.f. generated will be zero.

A_5 and A_7 can be considered to be in two separate circuits consisting of a cell in series with one lamp, hence they will each read 0.2 A. Both these currents flow through A_6, hence it will read 0.4 A.

(b) (i) and (ii) Lamp P can be considered to be in a series circuit with two cells hence it will be brighter than normal and the current flowing in this branch of the parallel network will be 0.4 A. Lamps R and Q can also be considered to be in a series circuit with two cells hence they will glow with normal brightness. The current in this branch of the parallel network will be 0.2 A.

A_8 will therefore read the sum of the two currents in the two branches of the parallel network, i.e.

$$0.2\text{ A} + 0.4\text{ A} = 0.6\text{ A}.$$

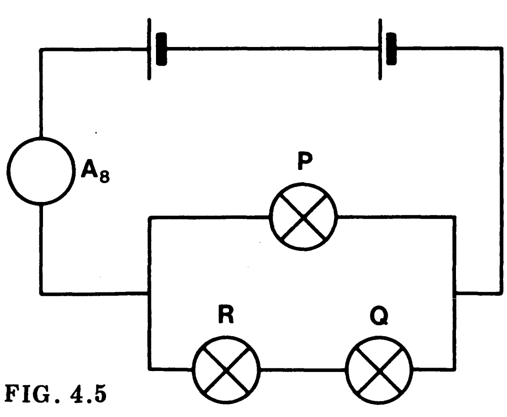


FIG. 4.5

(c) The third pin on an electric cable is the earth pin and connects the electric fire the earth. The earth can be considered to be at zero volts so that if the casing of the fire becomes live because of some internal short circuit this potentially dangerous voltage is shorted to earth through the earth pin.

(d) A fuse limits the maximum amount of current flowing in a circuit by 'blowing' (fusing) when this maximum current is exceeded and so breaking the circuit. A fuse works by the wire in it becoming sufficiently hot to melt and break when the maximum allowed current is exceeded.

(e) The current drawn by the fire $I = \dfrac{2.5\ \text{kW}}{250\ \text{V}} = 10\ \text{A}$

$$\text{Current drawn by iron} = \frac{0.5\ \text{kW}}{250\ \text{V}} = 2\ \text{A}$$

$$\text{Current drawn by dryer} = \frac{0.75\ \text{kW}}{250\ \text{V}} = 3\ \text{A}.$$

Hence the total current drawn = 10 A + 2 A + 3 A = 15 A, and therefore the fuse would be overloaded and would blow.

(f)

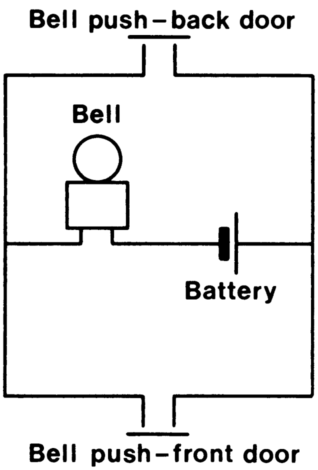


FIG. 4.6

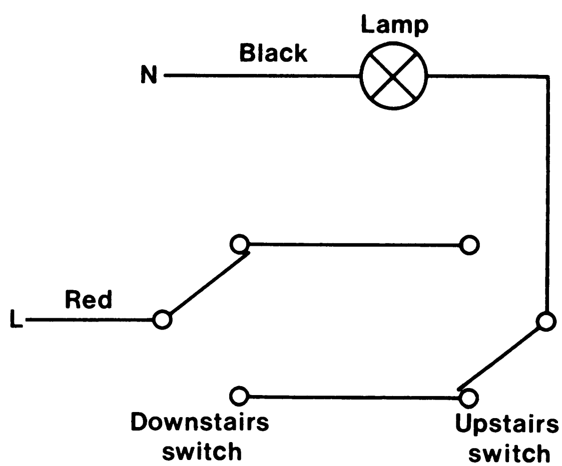


FIG. 4.7

23. The highest power W that can be taken is given by:

$$W = \text{p.d.} \times \text{current} = 240\ \text{V} \times 5\ \text{A} = 1200\ \text{W}.$$

24. The current in the heater is given by: $I = \frac{\text{power}}{\text{p.d.}} = \frac{750\text{ W}}{250\text{ V}} = 3\text{ A}$.

Hence the most suitable fuse would be a 5 A one. The 2 A fuse would blow and any higher rated fuse would be dangerous since it would allow too much current to flow into the heater if there was a short circuit or some other malfunction.

25. (a) (i) It can be seen from the graph that the output is at a maximum of 6 V when the input is 0.5 V.

(ii) Similarly the input has to be 1.25 V for the output to be at a minimum of 0.15 V (approximately).

(b) (i) The input voltage in (a) (i) to the basic unit is 0.5 V. Hence the thermistor has to drop the p.d. of the supply by an amount 6 − 0.5 = 5.5 V for the input to the basic unit to have a p.d. of 0.5 V.

The p.d. across the 200 Ω resistor will then be 0.5 V. Hence the current through the resistor, $I = \frac{0.5\text{ V}}{200\ \Omega}$

$= 2.5\text{ mA}$.

This is also the current passing through the thermistor (since the basic unit draws negligible current) and the resistance of the thermistor

$R = \frac{5.5\text{ V}}{2.5\text{ mA}} = 2.2\text{ k}\Omega$.

(ii) Following a similar line of reasoning to the above we have that the current through the thermistor, $I = \frac{1.25\text{ V}}{200\ \Omega} = 6.25\text{ mA}$.

Hence the resistance of the thermistor, $R = \frac{1.25\text{ V}}{6.25\text{ mA}} = 760\ \Omega$.

(c) (i) For the basic unit to have maximum output potential the thermistor has a resistance of 2.2 kΩ. This corresponds on the graph to a temperature of approximately 17°C.

(ii) Similarly at minimum output potential the thermistor has a resistance of 760 Ω, which corresponds to a temperature of approximately 40°C.

(d) As current flows through the thermistor it heats up 'internally', as any ordinary resistor does when current flows through it. The ambient temperature can therefore be less than the 'cut-off' temperature but internally this 'cut-off' temperature would have been reached due to the current flow, and hence the thermistor will appear to 'cut-off' before the expected ambient temperature.

26. Lamp 1 is the only lamp that will not light because the diode between it and the switch is in a 'reverse biased' position - it will not conduct. All the other diodes are 'forward biased' and will therefore conduct (see Explanation 3).

27. This diagram shows a half-wave rectifier circuit. The action of the diode in this circuit is amply discussed in Explanation 3. Trace C would be seen in this case.

28. Trace E appears on the oscilloscope. For a trace to appear a current must flow through the resistor. This does not occur because when one diode is conducting the other is not, and vice versa. Hence no current flows round the circuit.

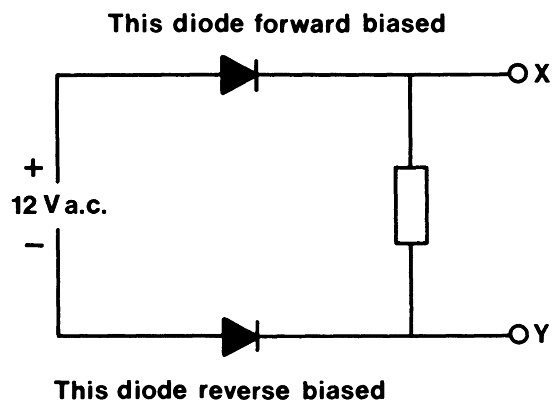


FIG. 4.8a

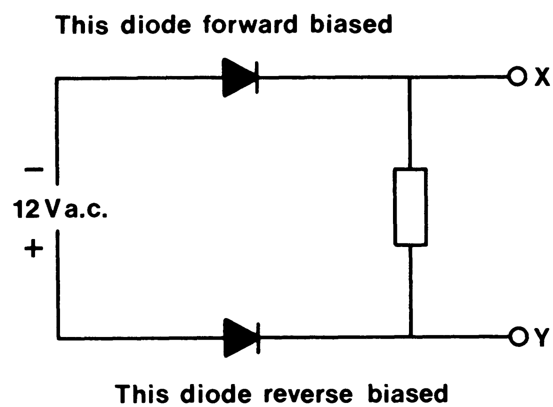


FIG. 4.8b

29. (a) The relevant formula for a transformer is:

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

where V_s is the secondary voltage,
V_p is the primary voltage,
N_s the number of turns in the secondary,
N_p the number of turns in the primary.

Hence $\frac{12\text{ V}}{240\text{ V}} = \frac{1}{12} = \frac{N_s}{N_p}$.

Therefore there are 12 times as many turns on the primary as on the secondary.

(b) The maximum value is greater than 12 V. The magnitude of an a.c. waveform is usually specified in terms of the root mean square (r.m.s.) value of the waveform. For the type of waveform shown this is approximately 2/3 ($1/\sqrt{2}$) of the greatest value of the waveform during each cycle. The maximum value of the 12 V r.m.s. waveform shown is therefore about 17 V.

(c) The diode allows current to flow through it in one direction only (left to right on the diagram). This is known as rectification. When the voltage output is positive then the diode will conduct current, but when the output is negative no current will flow (see Explanation 3).

(d)

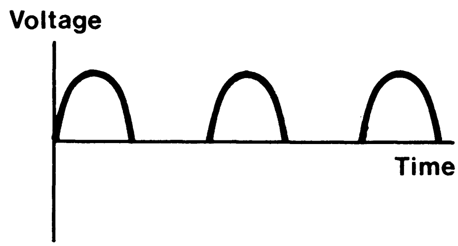


FIG. 4.9

(e) (i) Across the resistor.
(ii) The reading taken would be the voltage across the resistor. By measuring the maximum voltage (the maximum deflection on the screen) and then using Ohm's law the maximum current through the resistor could be calculated; this is also the maximum current through the diode.

(f) It would reduce the maximum current in the diode circuit.

30. Altering the frequency control means altering the number of cycles occurring every second. This control therefore alters the number of cycles on the screen. The time base will also affect the number of cycles since this control alters the time it takes for the spot to move across the screen. The faster the time base the more cycles appear on the screen. The volts and Y-gain only alter the amplitude of the trace.

31. The r.m.s. voltage of the waveform is given by:

$$V_{\text{r.m.s.}} = \frac{V_{\text{peak}}}{\sqrt{2}} = \frac{10\ \text{V}}{\sqrt{2}} \approx 7.0\ \text{volts.}$$

One cycle of the waveform takes place in 0.02 s and the frequency is therefore:

$$f = \frac{1}{0.02} = 50\ \text{Hz.}$$

32. Since the frequency of the wave is the number of cycles occurring in 1 s, the time T for one cycle of the wave is given by:

$$T = \frac{1}{\text{frequency}}$$

$$= \frac{1}{50}\ \text{s} = 20\ \text{ms.}$$

On moving across the screen the spot traces out $2\frac{1}{2}$ cycles, therefore the time taken $= 20\ \text{ms} \times 2\frac{1}{2}$
$= 50\ \text{ms.}$

33. Since the deflection of the spot is exactly half that of when a 9 V battery is connected, the p.d. across the bulb must be half, i.e. 4.5 V.

34. (a)

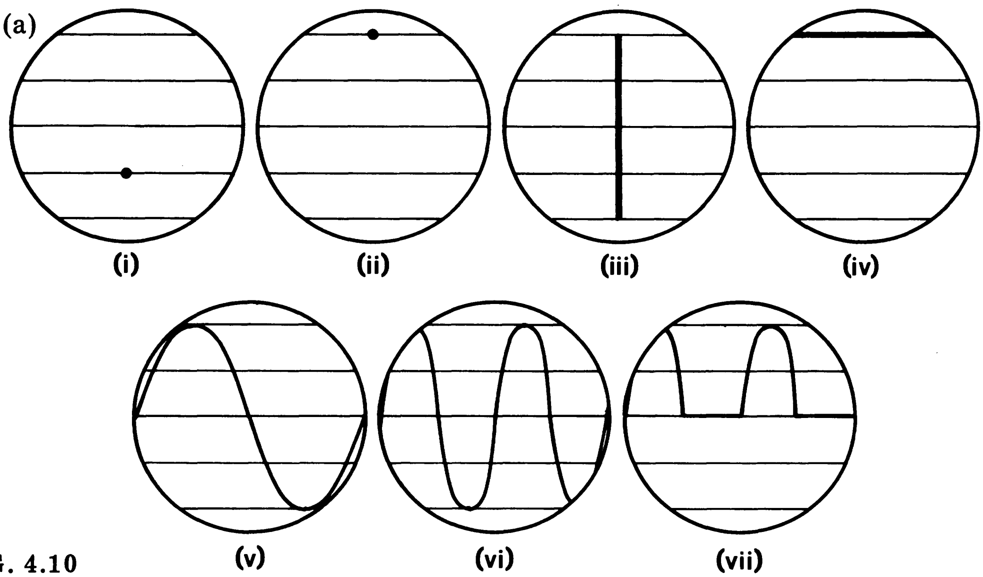


FIG. 4.10

(b) (i) 4 volts (2 cm X 2 v/cm).

(ii) The resistance of the lamp $R = \frac{\text{p.d.}}{\text{current}} = \frac{4\text{ V}}{2\text{ A}} = 2\,\Omega.$

(iii) The power of the lamp $W = V \times I = 8\text{ W}.$

35. The time between pulses is 60 milliseconds = 0.06 s, therefore the distance the

$$\text{echo travels} = \frac{\text{velocity} \times \text{time}}{2}$$

$$= \frac{300\text{ m/s} \times 0.06\text{ s}}{2}$$

$$= 9\text{ m}.$$

One divides by 2 because the echo has to travel there *and* back.

36. In Circuit B the diode only allows current to flow through it in one direction. Hence when the diode is 'reverse biased' no current flows (see Explanation 3). Some resistance in the circuit must be assumed to limit the current flow when the diode conducts.

In Circuit C the capacitor is alternately charged and then discharges itself as the applied voltage changes. The capacitor can only be charged by the current generated in the circuit due to the alternating applied voltage. This means that there will be a maximum charging current as the voltage is increasing but no charging current when the voltage is at its maximum or minimum and is not

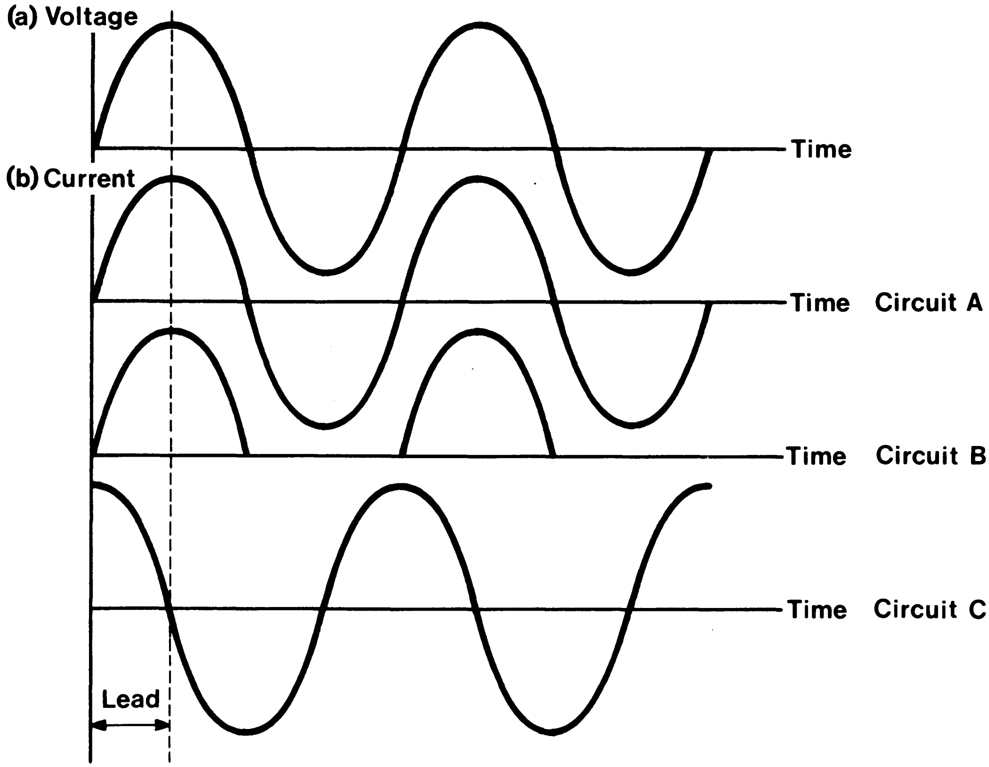


FIG. 4.11

changing. This accounts for the phase difference between the current and the applied voltage (see Explanation 4).

(c) (i) The current would flow through the resistor in one direction only. Current would only flow through the diode if the d.c. supply 'forward biased' the diode.

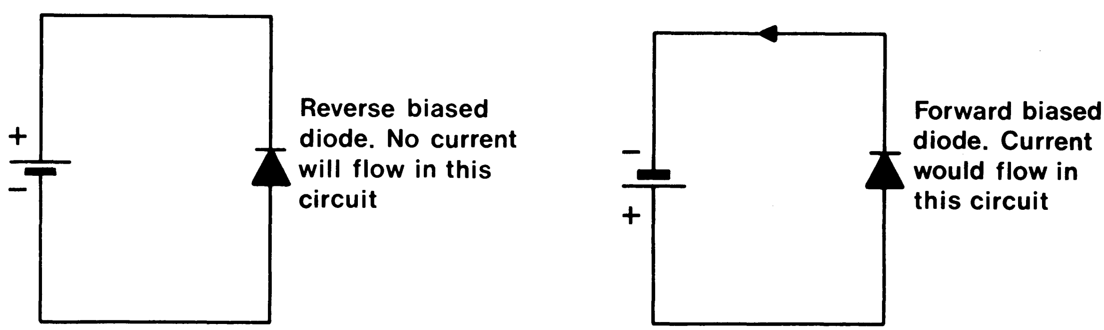


FIG. 4.12

(iii) No current would flow through the capacitor apart from an initial charging current lasting a few microseconds. Once charged, no current would flow.

(d) A choke is a wire-wound coil, with or without an iron or ferrite core, which when placed in an a.c. circuit produces a back e.m.f. opposing the applied voltage, thus limiting the current flowing through the circuit. It is useful in radio circuits for allowing low frequency currents to pass through it and preventing high frequency currents from flowing because of its high impedance at these frequencies. (See Explanation 6.)

37. The answer is A. Part 4 of Explanation 7 explains fully the answer to this question.

38. The current through a 'pure' or 'perfect' capacitance leads the applied voltage by a $\frac{1}{4}$ of one cycle of the waveform (see Fig. 4.13). The current through a perfect inductor lags behind the applied voltage by $\frac{1}{4}$ of a cycle. Instead of using the term cycle one uses the term 'phase difference'. A difference of $\frac{1}{4}$ of a cycle corresponds to a phase difference of 90° (see Explanation 6).

When these two components are in parallel then the resultant current at any one time in the circuit will be the sum of the currents in the capacitive branch and in the inductive branch. If we add these currents as has been done on the graph we

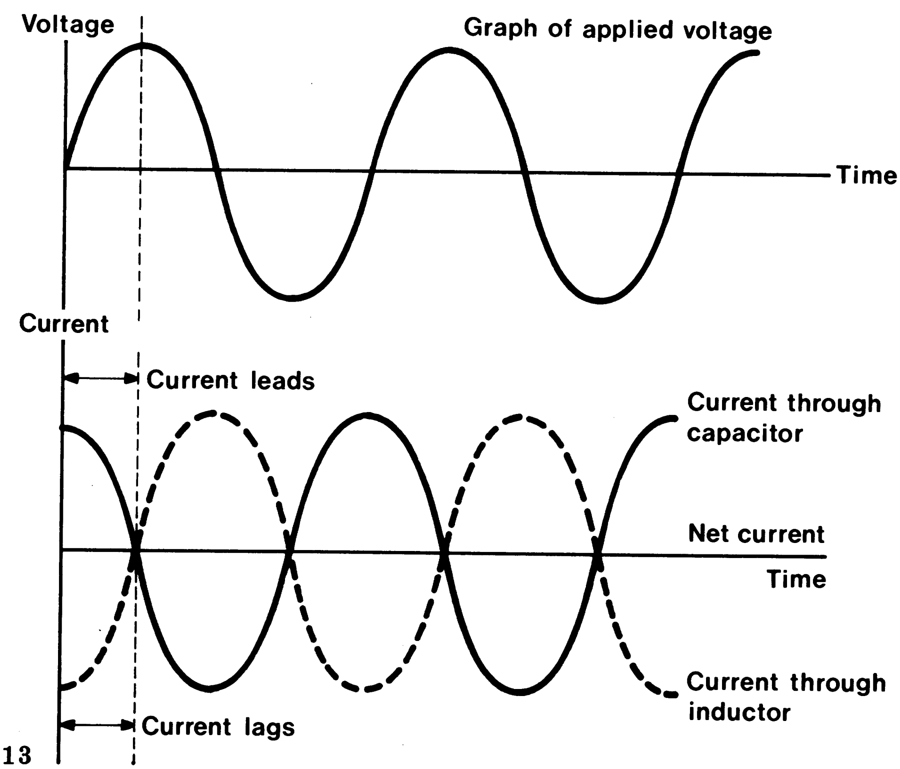


FIG. 4.13

see that the net result is zero current when the two currents are equal in amplitude. If they are not equal in amplitude then they do not exactly 'cancel' each other out and some current remains flowing through the circuit (see Explanation 7).

If the inductor current is larger, therefore, than the capacitor current, the effect of adding the capacitor will be to reduce the net current flowing in the circuit. The decrease in the ammeter reading is therefore due to the currents in the inductor and capacitor being out of phase.

39. As the oscilloscope is connected across the output, a voltage is being measured. In this case the voltage is an oscillating voltage which is 'damped' i.e. the oscillations get smaller with time.

First of all something has to be charged up when S_1 is closed. This can only be a capacitor connected across the battery as in circuit A or B. When the capacitor is discharged through a resistor on closing S_2 as in circuit B, then the voltage decreases exponentially with time – it does not oscillate. However, if the capacitor is discharged through an inductor as in circuit A, the voltage does oscillate. The oscillations are produced by the alternate discharging and charging of the capacitor and the corresponding growth and decay of the magnetic field of the inductor. When S_2 is closed the electric charge stored in the capacitor moves through the inductor and in so doing generates a magnetic field in the inductor. In this way the energy previously stored in the capacitor is now stored in the magnetic field of the inductor. As soon as the capacitor has no more charge on it the magnetic field, which is at that moment at a maximum, begins to decay. In so doing it generates a an e.m.f. which drives a current through the circuit and so charges up the capacitor. This current flows in the opposite direction to that from the capacitor. The capacitor now discharges and the process begins again. These oscillations in the circuit would continue indefinitely if the components were perfect and therefore had no losses. However there is some resistance in the circuit and this dissipates energy which would otherwise go to the capacitor or the inductor. This dissipation of energy produces the 'damping' effect on the oscillations, and will eventually cause the oscillations to stop altogether (see Explanation 10).

40. (a) Switching on the a.c. would cause the electromagnet to become alternately energized (attracting) and de-energized (non-attracting), at the point where the output voltage drops to zero. In one cycle of the a.c. the electromagnet will become energized twice. When energized the electromagnet will attract the steel ball downwards towards itself. On hitting the water the ball will cause a ripple. As the electromagnet becomes de-energized the spring will pull the ball back up, and the process will start again. The oscillations of the steel ball will cause a continuous ripple to be produced.

(b) If d.c. was used the electromagnet would become permanently energized so that the ball would be pulled down and would stay down.

(c) At a frequency of 50 Hz the changes in state of the electromagnet between energized and non-energized occur so quickly that to the steel ball the electromagnet appears as a permanent magnet. The ball is attracted downwards and stays down. If the frequency is reduced the time when the ball is not attracted sufficiently to pull it down, is longer, and the spring has time to pull the ball up, so producing oscillations. Furthermore, if the frequency of the oscillations corresponds to the natural frequency of oscillation of the ball and spring system, then 'forced' oscillation due to the electromagnet and the natural oscillation of the system complement each other producing powerful oscillations.

(d) This can be done by: (1) making the mass of the ball smaller; (2) making the spring stronger.
These two factors both increase the natural frequency of the a.c. vibration of the system. The frequency of the a.c. for which powerful oscillations occur is thus higher.

(e) A pulse of ripples could be shown by switching on the a.c. for a short space of time.

(f) This is an optical refraction effect and a suitable optics textbook should be consulted for an explanation of this phenomenon.

41. The charge stored in a capacitor, Q = capacitance in farads × p.d. in volts, and is measured in coulombs ($Q = C\,V$ coulombs).
When electric charge moves through a conductor it constitutes current, and the current in amperes is the number of coulombs of charge that flow in one second. Hence in case 1: the larger V is the larger is Q, and so the current through M is larger and the deflection is greater. In terms of its physical parameters the capacitance of a parallel plate capacitor is proportional to A/d, where A is the area of the plates in metres^2 and d the separation of the plates in metres. Therefore if d increases C decreases and the deflection of M decreases.

The resultant capacitance C_r of two capacitors C of equal value in series is given by:

$$\frac{1}{C_r} = \frac{1}{C} + \frac{1}{C}.$$

Therefore $C_r = \dfrac{C}{2}$.

Thus C_r is half the value of C, hence Q will be less and the deflection of M will be less (see Explanation 4).

42. (a) A capacitor, when charged through a resistor, charges exponentially, i.e. the rate at which electric charge builds up on the capacitor decreases with time. Since current is the rate at which charge flows per second then it can be seen that the current is large at first and decreases with time (see Fig. 4.14).

(i) It follows from what has been said above that when switch S is closed the ammeter shows a high reading.

(ii) When the current stops flowing, the ammeter reads zero and the p.d. across the capacitor is at its maximum, and equal to the p.d. of the battery. If the p.d. across the capacitor were less than that of the battery then current would continue to flow and the ammeter would show a reading.

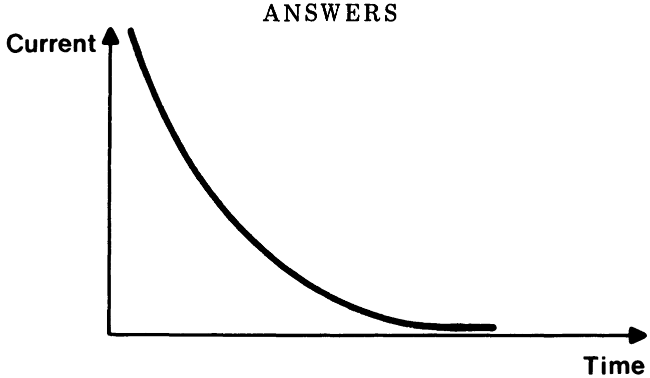


FIG. 4.14

(iii) The maximum current in the circuit occurs when the p.d. across the capacitor is zero and all the p.d. of the battery is lost across the resistor.

Therefore by Ohm's law the maximum current $= \dfrac{\text{p.d.}}{\text{resistance}}$

$$= \frac{9\ \text{V}}{10\ \text{k}\Omega}$$

$$= 0.9\ \text{mA}.$$

Hence a suitable range for the ammeter would be 0 to 1 mA.

(iv) The maximum p.d. across the capacitor occurs when no current flows in the circuit. Replacing the resistor with one of higher value will therefore have no effect on the maximum p.d. It will only affect the rate at which the capacitor is charged (see Explanation 10).

(b) (i) The neon lamp cannot conduct until the voltage across it reaches 100 V (called the 'firing' voltage). During this time the capacitor is charged through R. When the voltage across the capacitor reaches the firing potential of the neon lamp, it begins to conduct. This is indicated by a glow of the lamp. Its resistance value is very low when it is conducting and the capacitor is discharged. After the capacitor has discharged to 80 V (called the 'quenching' voltage) the lamp goes off and the capacitor begins to charge. The overall result is that the neon lamp flashes ON and OFF at a rate depending on the values of R and C.

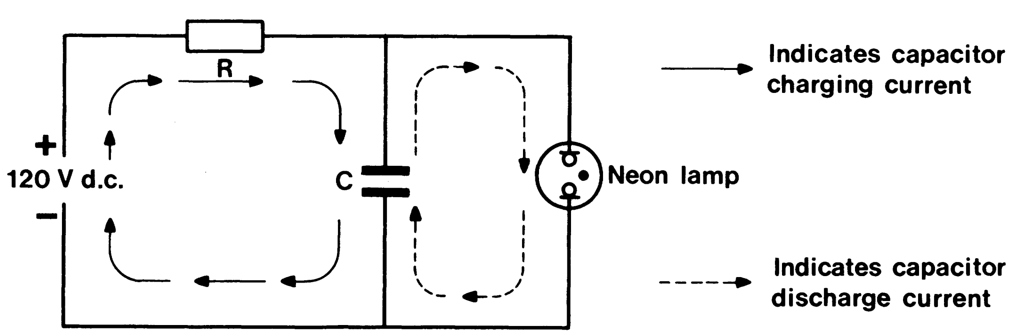


FIG. 4.15

(ii) The 'flash rate' depends upon the time constant of the RC circuit. Increasing the value of either R or C will increase the time constant of the circuit. This means that the capacitor will take longer to reach the firing potential, hence the firing rate will decrease (see Explanations 10 and 13).

43. (a) Using Ohm's law we have that the resistance of the diode $R = \frac{\text{p.d.}}{\text{current}}$,

hence at $V = -50$ V, $I = 0$ A and $R = \frac{-50\text{ V}}{0\text{ A}} = \infty\,\Omega$.

Similarly at $V = 0.5$ V, $I = 0$ A and $R = \infty\,\Omega$.

However, at $V = 0.7$ V, $I = 0.5$ mA and $R = \frac{0.7\text{ V}}{5\text{ mA}} = 140\,\Omega$;

at $V = 0.9$ V, $I = 35$ mA and $R = \frac{0.9\text{ V}}{35\text{ mA}} = 26\,\Omega$.

(b) The two diodes provide current overload protection for the galvanometer whatever the polarity of the overload current. As can be seen from the graph in Question 43 the diode conducts heavily once a certain voltage, called the threshold voltage, is reached. Hence if the galvanometer is connected in a circuit where the p.d. across it is less than the threshold voltage of the diode, the galvanometer will accurately measure what it has been set up to measure. If, however, the p.d. across it increases past the threshold voltage of the diode, the diode will conduct and divert much of the potentially damaging overload current.

(c) The charge Q on the capacitor is given by $Q = C\,V$, where C is the capacitance in farads and V is the voltage in volts. Therefore each time the capacitor is discharged a charge equal to $C\,V$ flows through the branch XY. This occurs 100 times each second. Hence the current (charge per second) in the branch XY $= CV \times 100$ A.

$= 10^{-9}\text{ F} \times 50\text{ V} \times 100$

$= 5\,\mu\text{A}$.

(d) Unless the voltage across the galvanometer is less than the threshold voltage of the diodes protecting it most of the current flowing in branch XY of the circuit will flow through the diodes rather than the galvanometer. Since the capacitor is charged each time to 50 V by the battery it follows that the capacitor will have nearly discharged before its voltage drops below 0.5 V, the threshold voltage of the diodes. The greater part of the discharge thus takes place through the protecting diodes rather than the galvanometer and the reading of this will therefore be considerably less than the average current flowing in XY.

(e) With a 10 kΩ resistance in the circuit the highest voltage across the galvanometer

$$= \frac{25\,\Omega}{10\text{ k}\Omega + 25\,\Omega} \times 50\text{ V},$$

$$= 0.125\text{ V},$$

and since this is less than the threshold voltage of the protection diode they do not conduct, and all the capacitor discharge takes place through the galvanometer. The average reading of this is therefore equal to the calculated value.

44. When the input to the circuit changes from 0 volts to 1 volt the voltage across the capacitor is initially zero, and therefore the voltage at point A in the circuit will also change from 0 to 1 volt. However as the capacitor charges up to 1 volt through the resistor the voltage at point A falls back to zero. The time constant of the capacitor–resistor combination is given by

$$T = CR$$
$$= 1\,\mu\text{f} \times 1\,\text{k}\Omega = 1\,\text{ms}.$$

After 10 ms therefore the charging of the capacitor will to all intents and purposes be completed and the output voltage at A will be close to 0 volt. At the instant the input voltage changes from 1 volt to 0 volt the voltage across the capacitor will be 1 volt and the voltage at point A will therefore change from 0 to 1 volt. Again as the capacitor discharges through the resistor the voltage at B will approach zero. The waveform is as shown in Fig. 4.16a below.

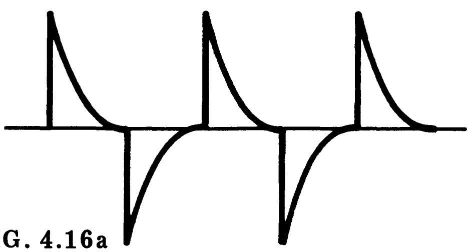


FIG. 4.16a

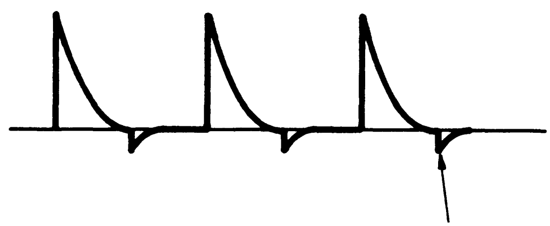


FIG. 4.16b

The diode only conducts for positive voltages at point A and therefore the waveform at point B in the circuit is a rectified version of the waveform at A, as shown in Fig. 4.16b above.

In practice small negative spikes would occur in the waveform at the instant of the negative transition. This is due to a capacitive effect within the diode itself.

45. A coil has the property of self-inductance which cuases an e.m.f. to be induced in the coil whenever the value of the current in the coil changes. This e.m.f. is known as a 'back' e.m.f. The direction or polarity of the back e.m.f. is always such as to oppose the change in current which induced the e.m.f.

(a) Once the p.d. across AB is constant and the current in the circuit has settled down to a steady value then no e.m.f. is induced in the induction and hence it acts like an ordinary piece of conducting wire which has no resistance. P.d. therefore will be developed across it.

(b) When the pulse appears across AB and there is a very sharp rise in the current in the circuit a back e.m.f. is induced in the inductor in a direction which opposes the rise in current. Initially the back e.m.f. is equal to the value of the supply voltage, V (this accounts for the initial peak of the spike in the graph of p.d. across XY), so that there is no current flow in the circuit. The back e.m.f. slowly decays, and with it the current gradually rises (hence the gradual drop in the p.d. on the graph) until finally the back e.m.f. falls to zero and the current reaches its maximum value (see Explanation 6).

(c) The time taken for the current to reach its final value is related to the time constant of the circuit, and is given by:

$$\text{time constant } t = \frac{L}{R} \text{ seconds,}$$

where L is the inductance of the coil in henrys and R the resistance in ohms. The time constant is the time taken for the p.d. across the inductor to fall to approximately 37% of its initial value.
To make the p.d. across XY fall to zero more quickly, which means in effect making the time constant shorter, we can see from the formula that we could
either (a) decrease L, i.e. use a smaller value of inductor;
or (b) increase R, i.e. make the value of the resistor larger.

46. (i) Increasing the resistance in the primary will reduce the current and hence the power in the primary. This in turn will reduce the power and consequently the brightness of the lamp in the secondary.
(ii) Decreasing the number of turns in the secondary decreases the voltage in the secondary. Consequently the current in the circuit will be less and the lamp dimmer.
(iii) This will also decrease the brightness of the lamp since the magnetic flux through the secondary coil will be reduced, limiting the current flowing in the secondary.

47. Power in the primary = p.d. × current.
= 24 W.
Power in the secondary is similarly 24 W. Therefore the ratio of power = 1 : 1.

48. The current in the secondary is given by the formula:

$$\frac{N_p}{N_s} = \frac{I_s}{I_p},$$ where N_p is the number of turns in the primary
N_s is the number of turns in the secondary
I_p is the current in the primary
I_s is the current in the secondary.

$$\text{Hence } I_s = \frac{N_p \times I_s}{N_s} = \frac{200 \times 10\,\text{mA}}{5} = 400\,\text{mA}.$$

49. S_1 and S_2 must be closed to supply current to the base of the transistor. S_4 must also be closed to link up the amplifying part of the circuit through the transistor. S_3 must not be closed as this will only short out the lamp and it will not light (see Explanation 5).

50. The diagram shows the classical configuration of a transistorized amplifying circuit (see Circuit 11). The differences between the question and the circuit is the addition of a 'decoupling' capacitor into the base of the transistor.

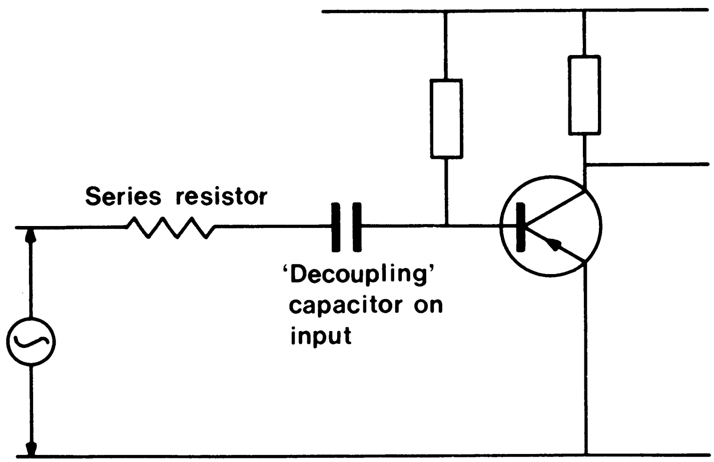


FIG. 4.17

Note this is a current amplifier since the voltage on the base of the transistor cannot be changed significantly. A resistor would have to be added in series with the input decoupling capacitor in order to produce a true voltage amplifier.

51. Including the effects of input and output impedance in Fig. 4.18,

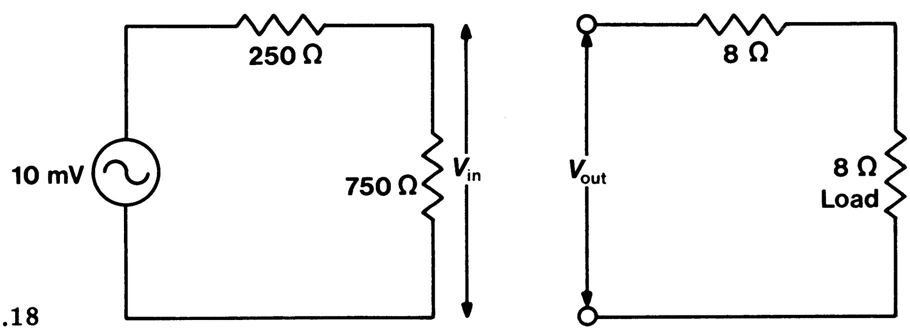


FIG. 4.18

$$V_{in} = \frac{750\,\Omega}{250\,\Omega + 750\,\Omega} \times 10\,\text{mV}$$

$$V_{out} = 400 \times V_{in},$$

and the voltage across the load is therefore

$$= \frac{8\,\Omega}{8\,\Omega + 8\,\Omega} \times 400 \times \frac{750\,\Omega}{250\,\Omega + 750\,\Omega} \times 10\,\text{mV}$$

$$= 1.5 \text{ volt.}$$

52. A - a diode - it allows current to flow through it in one direction only.
B - a transformer - it changes the value of the input voltage (primary voltage) with almost no loss of energy.
C - a high voltage battery or d.c. power pack - it puts opposite charges on the

plates at the top and bottom of the screen and thus deflects the electron beam. D - a transistor - it increases the power of the signal from the microphone using the energy of the battery E.

53. (a) Since the voltage across the Zener is 4 volts the voltage across the 100 Ω resistor is 10 V − 4 V = 6 V. The current through the resistor and hence through the Zener diode is therefore given by

$$I_Z = \frac{6\text{ V}}{100\,\Omega} = 60\text{ mA}.$$

(i) If the supply voltage rises to 12 V the voltage across the 100 Ω resistor is now 8 V and the current in the Zener is thus

$$I_Z = \frac{8\text{ V}}{100\,\Omega} = 80\text{ mA}.$$

(ii) If a load of 100 Ω is connected across the Zener the current through the load is given by

$$I_1 = \frac{4\text{ V}}{100\,\Omega} = 40\text{ mA}.$$

The current through the 100 Ω resistor now divides between the Zener and the load thus the current through the Zener is now

$$I_Z = 60\text{ mA} - 40\text{ mA} = 20\text{ mA}.$$

The minimum load resistor would be that which drew all the current from the Zener resistor so that none flowed through the Zener. The resistor value R is therefore given by

$$R = \frac{4\text{ V}}{60\text{ mA}} = 66\tfrac{2}{3}\,\Omega$$

If the load resistor fell below this value the voltage across the load would drop below 4 volts.

(b) (i) This circuit illustrates another application of the emitter follower (see Explanation 10). When the supply voltage rises the voltage across the Zener remains constant and as the base-emitter voltage of the transistor is small it follows that the voltage across the emitter resistor R_e also remains constant. The emitter current will thus also remain constant and since

$$I_e = I_c + I_b = I_c\ (1 + 1/\beta)$$

(β being the current gain of the transistor), the collector current will also remain constant.

(ii) The collector current as can be seen from the above argument is independent of the load resistance as long as the transistor is operating as an amplifier.

(iii) If the load were reduced to zero this would not affect the validity of the above statement.

(iv) The transistor would saturate when the load became too large. This would happen when the collector voltage dropped below the base voltage.

54.

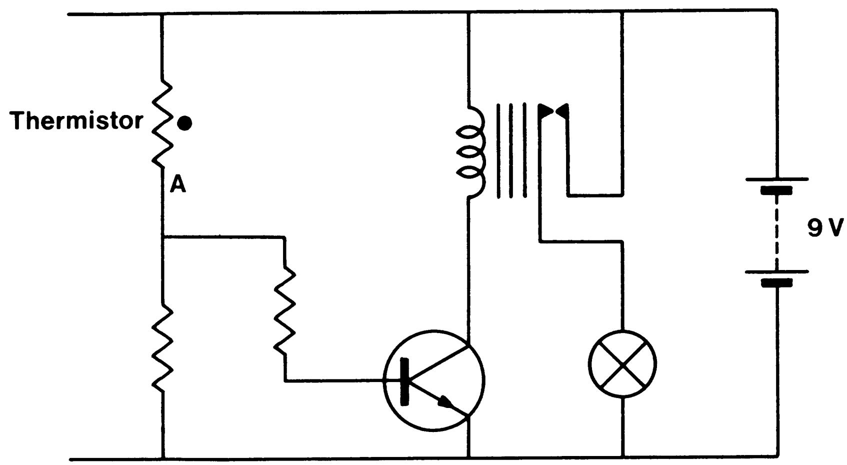


FIG. 4.19

Assuming the thermistor has characteristics similar to those described in the graph of Question 25, then when the resistance of the thermistor is above about 500 Ω the voltage at point A of the potential divider will be less than 0.7 volt. The base-emitter voltage of the transistor will therefore be less than 0.7 volts and will be switched off. No collector current will flow and consequently the relay will be de-energized. When the temperature rises above about 50°C the thermistor resistance falls below 500 Ω and the voltage at point A is greater than 0.7 V. The transistor switched on and the relay is energized. The relay contacts close and the p.d. of the battery is applied across the bulb causing it to light up.

55. An explanation of the multivibrator is given in Explanation 14. The collector and base voltage waveforms are shown below.

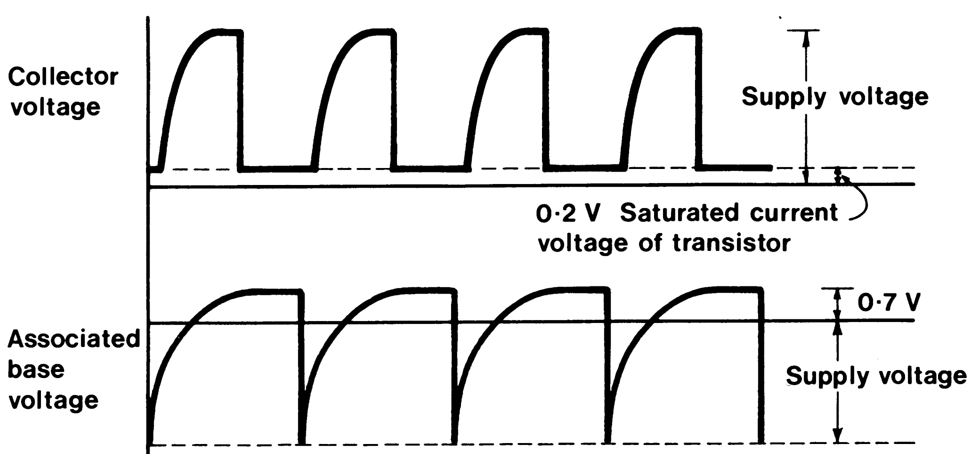


FIG. 4.20

As indicated in Explanation 14, the frequency of the oscillation is defined by

$$f = 1/0.7\,(C_1R_1 + C_2R_2),$$

where C_1 and C_2 are the two coupling capacitors and R_1, R_2 are the associated base resistors. Changing any of the components will change the frequency.

If $C_1R_1 = C_2R_2$ each transistor is switched on for an equal length of time and the mark space ratio is 1 : 1. If this is not the case then the mark space ratio will be different and a non-symmetrical wave will result. If the supply voltage is changed then only the amplitude of the waveforms changes.

56. (a) The accuracy of any measuring instrument depends not only on the accuracy of its display but on the measuring techniques it uses. The main factors influencing the accuracy of the DVM are: (i) the linearity of the input amplifier to the meter; (ii) the linearity of the ramp voltage; (iii) the range of input voltages X and Y to the comparator over which the comparator switches. In other words how much Y has to be greater than X before the comparator switches; (iv) the frequency of the pulse generator. The higher this is the more accurately the time the comparator is switched on can be measured. One advantage of a digital display is of course, that parallax errors are avoided.

(b) The voltage range of a DVM is determined primarily by the range of gains the input amplifier can be set to. To measure large voltages, small (if not fractional) gains will be required, while to measure small voltages very large gains will be required.

(c) If an alternating voltage were applied without rectification the input voltage X will no longer be a steady value but will constantly be changing in value and polarity.

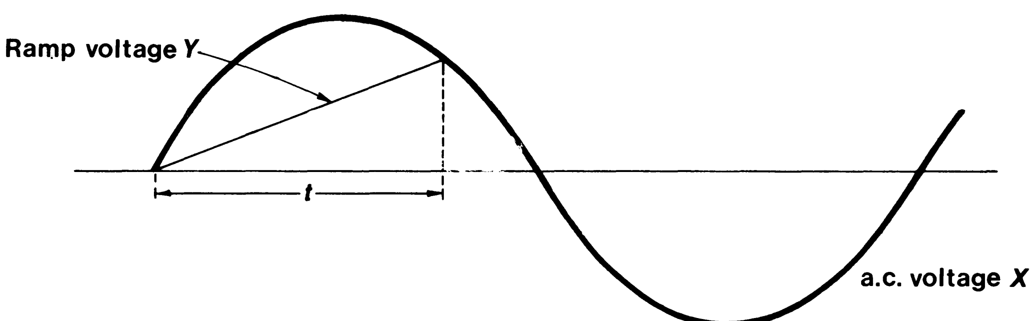


FIG. 4.21

From the diagram above it can be seen that the time taken to switch on the comparator t depends now on a variety of factors: (i) the frequency of the a.c. waveform; (ii) the phase of the waveform at the instant the ramp commences; (iii) the amplitude of the incoming a.c. waveform. No clear information could therefore be obtained of the input waveform amplitude.

(d) For the DVM to distinguish between a voltage of 1.001 and 1.002 volts the voltmeter must be accurate to one part in 1001. This means that the number of cycles of the pulse generator occurring during the period the comparator is switched on is at least 1001. The frequency of the pulse generator must therefore be changed accordingly.

(e) The decimal number 999 in binary is 1 111 100 111. Ten binary digits are therefore involved in specifying the number and hence 10 bistable circuits will be needed in the register.
The maximum reading possible with this arrangement will be 1023.

(f) In general a high impedance input to a DVM is a good thing in that the amplifier does not take a significant amount of current from the circuit to produce a reading. This means that it will be less likely to change the characteristics of the circuit being measured.

Index

Carefully used, the index will enable you to write notes on a number of topics which are not dealt with explicitly in the text. We include only those references which add something of interest to the entry.