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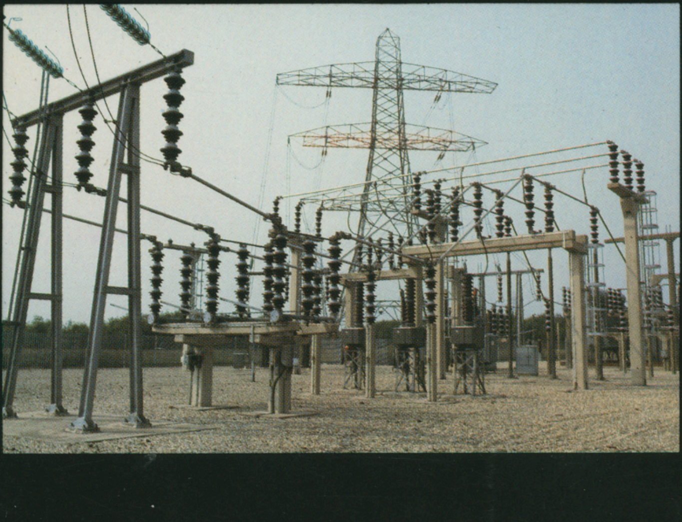

NOEL M. MORRIS

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MASTERING
ELECTRICAL ENGINEERING

NOEL M. MORRIS

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PREFACE

In common with other books in the *Mastering* series, the intention is to set out in one book the basis of a complete subject - *Electrical Engineering* in this volume.

This book reflects the modern thinking and needs of the *electrical technologist*, emphasis being placed on practical circuits and systems. Following modern teaching practice in many courses, the mathematics has been kept to a minimum consistent with covering the necessary background theory.

Mastering Electrical Engineering is suitable for use as a self-teaching book, each chapter being supported not only by worked examples but also by self-test questions and a summary of important facts. The latter feature is very useful for the reader who is in a hurry to get a 'feel' for the subject matter in the chapter.

Starting with the principles of electricity and sources of *electromotive force* (e.m.f.), the book covers the basis of 'heavy current' electrical engineering including *circuit theory*, *alternating current* (a.c.) and *direct current* (d.c.) *machines*, *single-phase* and *three-phase* calculations, *transformers*, *electrical power distribution*, *instruments* and *power electronics*.

The book contains a liberal supply of illustrations to highlight the features of each chapter, and it is hoped that the approach will stimulate the reader with the same enthusiasm for the subject that the author holds for it.

I would like to thank the electrical manufacturing industry at large for the support it has given, particular thanks being due to the following:

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North Staffordshire Polytechnic NOEL M. MORRIS

DEFINITIONS OF SYMBOLS USED IN EQUATIONS

A, a	area in m^2
B	magnetic flux density in tesla (T)
C	capacitance in farads (F)
C	unit of electrical charge (coulombs)
D	electric flux density in coulombs per square meter (C/m^2)
d	diameter and distance in metres (m)
E, e	e.m.f. or p.d. in volts (V)
E	electric field intensity or potential gradient in volts per metre (V/m)
e	base of Naperian logarithms = 2.71828
F	magnetomotive force in ampere-turns or in amperes (A)
F	mechanical force in newtons (N)
F	unit of capacitance (farads)
f	frequency in hertz (Hz)
f_O	resonant frequency in hertz (Hz)
G	conductance in siemens (S)
H	magnetic field intensity or magnetising force in ampere-turns per metre or amperes per metre (A/m)
H	unit of inductance (henrys)
I, i	current in amperes (A)
K	a constant of an electrical machine
k	magnetic circuit coupling coefficient (dimensionless)
L	self-inductance of a magnetic circuit in henrys (H)
l	length in metres (m)
M	mutual inductance between magnetic circuits in henrys (H)
N	number of turns on a coil
N, n	speed of rotation of the rotating part of a motor in revolutions per minutes (rev/min) or revolutions per second (rev/s)
P	power in watts (W)
Q	electric charge of electrostatic flux in coulombs (C)

Q	Q-factor of a resonant circuit (dimensionless)
Q	reactive volt-amperes (VAr) in an a.c. circuit
R, r	resistance in ohms (Ω)
S	magnetic circuit reluctance (resistance to flux) in ampere-turns per weber or amperes per weber (A/Wb)
S	shunt resistance connected to a meter
S	volt-amperes (VA) in an a.c. circuit
s	fractional slip of an induction motor rotor (dimensionless)
T	periodic time of an alternating wave in seconds (s)
T	time constant of an electrical circuit in seconds (s)
T	torque in newton metres (N m)
t	time in seconds (s)
V, v	voltage or p.d. in volts (V)
W	energy in joules (J) or in watt seconds (W s)
X_C	capacitive reactance in ohms (Ω)
X_L	inductive reactance in ohms (Ω)
Z	impedance of an a.c. circuit in ohms (Ω)
α	temperature coefficient of resistance in $(^\circ C)^{-1}$
ϵ	absolute permittivity of a dielectric in farads per metre (F/m)
ϵ_O	permittivity of free space = 8.85×10^{-12} F/m
ϵ_r	relative permittivity of a dielectric (dimensionless)
η	efficiency of an electrical machine
θ	temperature in °C or K
θ	angular measurement in degrees or radians
μ	absolute permeability of a magnetic material in henrys per metre (H/m)
μ_O	permeability of free space = $4\pi \times 10^{-7}$ H/m
μ_r	relative permeability (dimensionless)
π	a constant = 3.142
ρ	resistivity of an electrical conductor in ohm metres (Ω m)
σ	conductivity of a conductor in siemens per metre (S/m)
Φ	magnetic flux in webers (Wb)
ϕ	phase angle in degrees or radians
$\cos\phi$	power factor of an a.c. circuit
ω	angular frequency in rad/s of an a.c. supply
ω	speed of rotation of the rotating part of an electric machine in rad/s
ω_O	resonant frequency in rad/s

GLOSSARY

Words in *italics* are mentioned elsewhere in the Glossary.

a.c. An abbreviation for *alternating current*

acceptor circuit A *series resonant circuit* which has a very low resistance to current flow at the *resonant frequency*, that is, it 'accepts' a high current

a.c. machine An electromechanical energy convertor which converts energy from an *a.c.* source into mechanical energy or vice versa

accumulator An electrical *storage battery*, that is, a battery which can be recharged by passing *direct current* through it

alternating current A current which alternately flows in one direction and then in the opposite direction

alternator An alternating current *generator*

ammeter An instrument for the measurement of electrical *current*

ampere The unit of electrical *current*

ampere-turn The unit of *magnetic field intensity* (H) or *magnetising force*, which is calculated from amperes x turns on the coil; since 'turns' are dimensionless, it is given the unit of the 'ampere' by electrical engineers

anode (1) In a *diode* it is the *electrode* by which the *current* (*hole* flow) enters; (2) In *electrolysis*, it is the electrode to which negative *ions* are attracted

apparent power In an a.c. *circuit*, it is the product, volts x amperes (or the volt-ampere [VA] product)

armature (1) The rotating part of a *d.c. machine*; (2) In a relay, it is a piece of ferromagnetic material which is attracted towards the pole of the electromagnet

autotransformer A *transformer* having a single winding

average value The average value of an alternating wave. An alternative name is *mean value*

back e.m.f. The e.m.f. induced in an *inductor* when the *current* through it changes

battery A group of *cells* connected together

brush A piece of specially shaped carbon or graphite which connects either the *commutator* of a *d.c. machine* or the *rotor* of an *a.c. machine* to the external circuit

cage rotor motor A popular form of *induction motor* in which the *rotor* consists of metal rods (copper or aluminium) embedded in a *laminated* iron circuit, the bars being short-circuited by means of 'end rings' at the ends of the rotor

capacitance The property of a *capacitor* which enables it to store electrical charge

capacitive reactance The opposition of a *capacitor* to the flow of *alternating current*. No *power* is dissipated in a pure capacitive reactance. Symbol X_C, measured in ohms

capacitor Consists of two conducting surfaces or 'plates' separated by an insulating *dielectric*, which has the ability to store electric charge

cathode (1) In a *diode*, it is the *electrode* by which the *current* (*hole* flow) leaves; (2) In *electrolysis*, it is the electrode to which the positive *ions* are attracted

cell Converts chemical energy into electrical energy

circuit An interconnected set of *conductors*

coercive force The *magnetising force* needed to *demagnetise* completely a piece of magnetised material

commutator Consists of a large number of conducting segments connected to the *armature* winding of a *d.c. machine*, each segment being isolated from adjacent segments; Current enters the armature via graphite *brushes*

complex wave A wave which contains a *fundamental frequency* together with a number of *harmonic frequencies*

compound-wound machine A *d.c. machine* having part of its *field winding* in *series* with its *armature*, and part connected in *shunt* with the armature

conductance Reciprocal of *resistance.* Symbol G, and measured in siemens (S)

conductivity Reciprocal of *resistivity*

conductor An element which freely allows the flow of electric *current*

core loss Energy loss in an electrical machine as a result of the combined effects of *hysteresis loss* and *eddy current* loss

coulomb The unit of electrical charge, symbol C

current Rate of flow of electrical charge. Symbol I, and measured in *amperes* (A)

d.c. Abbreviation of *direct current*

d.c. machine An electromechanical energy convertor which converts energy from a *d.c.* source into mechanical energy or vice versa

depolarising agent A chemical included in a *cell* to prevent *polarisation*

dielectric An insulating material which separates the plates of a *capacitor*

diode A two-electrode device, the electrodes being the *anode* and the *cathode*

direct current *Current* which flows in one direction only, that is, a unidirectional current

eddy current *Current* induced in the iron circuit of an electrical machine because of changes in *magnetic flux*

efficiency Ratio of the power output from a machine or circuit to its input power; expressed as a per centage if the ratio is multiplied by 100, and is dimensionless

electric field intensity The potential gradient in volts per metre in the material

electric flux A measure of the electrostatic field between two charged plates; measured in coulombs

electric flux density The amount of *electric flux* passing through one square metre of material

electrode (1) In a *semiconductor* device it is an element which either emits *current* or collects it; (2) In an electrolytic cell it is a metallic conductor where the *ions* give up their charge

electrolysis A chemical change brought about by the passage of *direct current* through an *electrolyte*

electrolyte A substance which, when dissolved, produces a conducting path in the solvent (which may be water)

electromagnet A current-carrying coil with an iron core

electromagnetic induction The production of an *e.m.f.* in a circuit, arising from a change in the amount of *magnetic flux* linking the circuit

electromotive force The *p.d.* measured at the terminals of a *cell, battery* or *generator* when no *current* is drawn from it; abbreviated to *e.m.f.* and measured in *volts*

electron A negative charge carrier, and a constituent part of every atom

e.m.f. Abbreviation for *electromotive force*

energy meter A meter used to measure energy, usually in kilowatt hours (kWh)

exciter A d.c. *generator* which provides the *current* for (that is, it 'excites') the *field winding* of an *alternator* or *synchronous motor*

farad The unit of *capacitance*, symbol F; submultiples such as the microfarad, the nanofarad and the picofarad are in common use

Faraday's laws (1) The laws of *electrolysis* relate to the mass of substance liberated in the process of electrolysis; (2) the law of *electromagnetic induction* relates to the induced *e.m.f.* in a circuit when the *magnetic flux* associated with the circuit changes

ferromagnetic material A material which can be strongly magnetised in the direction of an applied *magnetising force*

field winding A winding on an electrical machine which produces the main magnetic field

Fleming's rules The left-hand rule relates to *motor* action, the right-hand rule relates to *generator* action

frequency The number of oscillations per second of an alternating wave;

measured in hertz (Hz)

full-wave rectifier A circuit which converts both the positive and negative half-cycle of an *alternating current* wave into *direct current* (more precisely, unidirectional current)

fundamental frequency The *frequency* of a sinusoidal wave which is the same as that of the complex wave of which it is a part

galvanometer A moving-coil meter used to measure small values of current

generator An electromechanical energy convertor which changes mechanical energy into electrical energy

half-wave rectifier Converts one of the half-cycle of an *a.c.* waveform into *direct (unidirectional) current*, but prevents current flow in the other half cycle

hard magnetic material A material which retains much of its magnetism after the *magnetising force* has been removed

harmonic frequency A multiple of the *fundamental frequency* of a *complex wave*

henry Unit of inductance, symbol H

hertz Unit of *frequency*, symbol Hz; equal to 1 cycle per second

hole A positive charge carrier; can be regarded as the absence of an *electron* where on would normally be found

hysteresis loss Energy loss caused by the repeated reversals of magnetic domains in a *ferromagnetic material* in the presence of an alternating *magnetic field*

impedance Total opposition of a *circuit* to the flow of *alternating current*; symbol Z, measured in *ohms*

induced e.m.f. *e.m.f.* induced in a *circuit* either by a changing *magnetic flux* or by a strong electric field

inductance A measure of the ability of a *circuit* to produce a *magnetic field* and store magnetic energy

induction motor An a.c. motor which depends for its operation on a 'rotating' or 'moving' *magnetic field*

inductive reactance The opposition of a pure *inductance* to the flow of *alterating current*; no *power* is dissipated in an inductive reactance; symbol X_L, measured in *ohns*

inductor A piece of apparatus having the property of *inductance*

instrument transformer A *transformer* designed to connect an electrical instrument either to a high *voltage* (a voltage transformer, VT, or potential transformer, PT) or to a high *current* (a current transformer, CT)

insulator A material which has a very high *resistance* to the flow of electrical *current*. Ideally, no current flows through an insulator

internal resistance The *resistance* 'within' a *cell, battery, generator* or power supply

invertor A circuit which converts direct voltage or *direct current* into alternating voltage or *alternating current*

ion An atom or molecule which is electrically charged; can be either negatively or positively charged

ionisation The process by which an atom or molecule is converted into an *ion*

joule The unit of energy equal to 1 watt x 1 second

junction The connection of two or more wires in a circuit; *node* is an alternative name

Kirchhoff's laws (1) The total *current* flowing towards a *junction* is equal to the total current flowing away from it; (2) the algebraic sum of the *p.d.s.* and *e.m.fs* around any closed mesh is zero

lamination A thin sheet of iron, many of which are grouped together to form a **magnetic circuit**; used to reduce *eddy current*

magnetic circuit An interconnected set of ferromagnetic branches in which a *magnetic flux* is established

magnetic coupling coefficient A dimensionless number having a value between zero and unity which gives the proportion of the *magnetic flux* which arrives at a second (*secondary*) coil after leaving the *primary* winding; symbol k

magnetic domain A group of atoms in a *ferromagnetic material* which form a localised magnetic field system

magnetic field intensity The *m.m.f.* per unit length of a *magnetic circuit*; symbol H; measured in ampere-turns per metre or amperes per metre

magnetic flux A measure of the magnetic field produced by a *permanent magnet* or *electromagnet*; symbol Φ; measured in webers (Wb)

magnetic flux density The amount of *magnetic flux* passing through an area of 1 m^2; symbol B, measured in tesla (T)

magnetic leakage *Magnetic flux* which does not follow the 'useful' magnetic path

magnetic leakage coefficient The ratio of the total *magnetic flux* to the 'useful' magnetic flux; has a value 1.0 or greater

magnetising force An alternative name for *magnetic field intensity*

magnetomotive force The 'force' which produces a *magnetic flux*; symbol F, measured in ampere-turns or amperes; abbreviation m.m.f.

mean value The *average value* of an alternating wave

motor An electromechanical energy convertor which changes electrical energy into mechanical energy

mutual inductance The property of a system which causes a change of *current* in one circuit to induce a *voltage* in another circuit

negative charge carrier An *electron*

node Alternative name for *junction*

non-linear resistor A *resistor* which does not obey *Ohm's law*

***n*-type semiconductor** A *semiconductor* material which has been 'doped' so that it has mobile *negative charge carriers*

ohm The unit of electrical *resistance* or *impedance*, symbol Ω

ohmmeter A moving-coil instrument used to measure *resistance*

Ohm's law This states that, at a constant temperature, the *current* in a pure *resistor* is directly proportional to the *p.d.* across it

parallel circuit A circuit in which all the elements have the same *voltage* across them

parallel resonant circuit An a.c. *parallel circuit* containing *resistance*, *inductance* and *capacitance* which resonates with the supply frequency; known as a *rejector circuit*, it has a high *impedance* at *resonance*, and the circulating *current* within the *circuit* is higher than the supply current

p.d. Abbreviation for *potential difference*

Peltier effect When a *current* flows in a *circuit* consisting of dissimilar *semiconductors* or metals, the Peltier effect describes why one junction is heated and the other is cooled

periodic time The time taken for one cycle of an *a.c.* wave to be completed

permanent magnet A piece of *ferromagnetic material* which has been permanently magnetised. Both its *remanence* or *retentivity* and its *coercive force* are high

permeability The ratio of the *magnetic flux density* (B) in a material to the *magnetic field intensity* (H) needed to produce it. Also known as the absolute permeability of the material. Symbol μ, measured in henrys per metre (H/m)

permeability of free space The permeability of a vacuum (or, approximately, of air), symbol $\mu_O = 4\pi \times 10^{-7}$ H/m

permeability (relative) The ratio of the absolute *permeability* of a magnetic material to the *permeability of free space*; symbol μ_r, and is dimensionless

phase angle The angular difference in degrees or radians between two sinusoidally varying quantities or between two *phasors*

phasor A line which is scaled to represent the *r.m.s.* value of a waveform and whose angle represents its displacement from a phasor in the horizontal 'reference' direction

piezoelectric effect The production of an *e.m.f.* between two faces of a crystal when it is subject to mechanical pressure. The effect is reversible

polarisation A chemical effect in a *cell* which causes the *anode* to be coated with hydrogen bubbles

pole (1) A terminal of a *cell*; (2) one end of a *permanent magnet* or an *electromagnet*

poly-phase supply An *a.c.* supply having many ('poly') phases; the *three-phase supply* is the most popular type

positive charge carrier A *hole*

potential A measure of the ability of a unit charge to produce *current*

potential difference The difference in electrical *potential* between two points in a *circuit*

potentiometer (1) A *resistor* having a sliding contact; (2) a device or *circuit* for comparing electrical *potentials*

power The useful output from an electrical machine and the rate of doing work; symbol P, measured in *watts* (W) or joules per second

power factor The ratio in an *a.c.* circuit of the *power* in *watts* to the *apparent power* in *volt-amperes*

primary cell A *cell* which cannot be recharged

primary winding The winding of a *transformer* which is connected to the *a.c.* supply source

***p*-type semiconductor** A *semiconductor* material which has been 'doped' so that it has mobile *positive charge carriers (holes)*

Q-factor The 'quality' factor of a *resonant circuit*; it indicates, in a *series resonant circuit*, the value of the *voltage* 'magnification' factor and, in a *parallel resonant circuit*, the value of the *current* 'magnification' factor

radian An angular measure given by the ratio of the arc length to the radius; there are 2π radians in a circle

reactance The property of a reactive element, that is, a pure *capacitor* or a pure *inductor*, to oppose the flow of *alternating current; power* is not consumed by a reactive element

reactive volt-ampere Also known as reactive 'power'; associated with *current* flow in a *reactive* element; 'real' power is not absorbed; symbol Q, measured in volt-amperes reactive (VAr)

rectifier A circuit which converts alternating voltage or current into direct (unidirectional) voltage or current

rejector circuit A *parallel resonant circuit* which has a very high *resistance* to *current* flow at the *resonant frequency*, that is, it 'rejects' current

reluctance The ratio of the *magnetomotive force* (F) in a *magnetic circuit* to the *magnetic flux* (Φ) in the circuit; it is the effective resistance of the circuit to magnetic flux; symbol S, measured in ampere-turns per weber or in amperes per weber

remanence The remaining *magnetic flux* in a specimen of magnetic material after the *magnetising force* has been removed; also known as the *residual magnetism* or *retentivity*

residual magnetism Another name for *remanence*

resistance A measure of the ability of a material to oppose the flow of *current* through it; symbol R, measured in ohms

resistivity The *resistance* of a unit cube of material, calculated by resistance × $\frac{\text{area}}{\text{length}}$. Symbol ρ, measured in ohm meters (Ω m)

resistor A circuit element having the property of *resistance*

resonance The condition of an *a.c.* circuit when it 'resounds' or resonates in sympathy with the supply *frequency*; the *impedance* of the circuit at this frequency is purely *resistive*

resonant frequency The *frequency* at which the circuit resonates. Symbol ω_0 (rad/s) or f_0 (Hz)

retentivity Another name for *remanence*

rheostat A variable *resistor*

r.m.s. Abbreviation for *root-mean-square*

root-mean-square The *a.c.* value which has the same heating effect as the equivalent *d.c.* value; abbreviated to *r.m.s.* and also known as the 'effective value'

rotor The rotating part of a machine (usually associated with *a.c. machines*)

saturation (magnetic) The state of a *ferromagnetic material* when all its *domains* are aligned in one direction

secondary cell A *cell* which can be recharged by passing *d.c.* through it

secondary winding The winding of a *transformer* which is connected to the electrical load

Seebeck effect The *e.m.f.* between two dissimilar metals when their junctions are at different temperatures

self-inductance An alternative name for *inductance*

semiconductor A material whose *conductivity* is mid-way between that of a good *conductor* and that of a good *insulator*

semiconductor junction A junction between an *n-type semiconductor* and a *p-type semiconductor*; a *diode* has one *p–n* junction, and a junction *transistor* has two *p–n* junctions

separately excited machine A *d.c.* machine whose *field windings* and *armature* are supplied from separate power supplies

series circuit A circuit in which all the elements carry the same current

series motor A *d.c. motor* whose *field windings* are connected in *series* with the *armature*; mainly used for traction applications

series resonant circuit An *a.c. series circuit* containing *reactive* elements which *resonates* with the supply *frequency*. Known as an *acceptor circuit*, it has a low *impedance* at resonance, so that the resonant current is high, i.e., it 'accepts' *current*. The *voltage* across each of the *reactive* elements (*inductance* and *capacitance*) is higher than the supply *voltage*

shunt An alternative name for *parallel connection*

shunt wound machine A *d.c. machine* whose *field windings* are connected in *shunt* (parallel) with the *armature*

single-phase supply An *a.c.* supply system carried between two lines, one line usually being 'live' and the other being 'neutral', that is, at 'earth potential'

slip (fractional) The difference between the synchronous speed of the rotating field and the rotor speed of an induction motor expressed as a ratio of the synchronous speed, symbol s, and is dimensionless

slip ring A metal ring which is on, but is insulated from, the shaft of a rotating electrical machine; its function is to convey *current* to or from the rotating part of the machine (usually an *a.c. machine*) via carbon *brushes*. An a.c. machine may have two or more slip rings

smoothing circuit A *circuit* which 'smooths' or 'filters' the variations in the output *voltage* from a rectifier circuit

soft magnetic material A *magnetic material* which easily loses its magnetism; its *coercive force* is low

solenoid A coil with an air core

squirrel cage motor Alternative name for a *cage rotor motor*

storage battery Alternative name for *accumulator*

synchronous motor An *a.c. motor* whose rotor runs at synchronous speed

terminal voltage The *p.d.* between the terminals of a *cell, battery* or *generator* when an electrical load is connected to it

tesla The unit of *magnetic flux density*, symbol T

thermistor A *semiconductor* device whose *resistance* changes with temperature (usually a decrease in resistance with increase in temperature, but could be an increase in resistance)

thermocouple A *junction* of two dissimilar metals which develops an *e.m.f.* when it is heated or cooled relative to the remainder of the circuit

thermopile Several *thermocouples* connected in *series* to give a higher *e.m.f.* than a single thermocouple

three-phase supply A *poly-phase supply* having three phases; a 'balanced' or 'symmetrical' three-phase supply has three equal voltages which are displaced from one another by 120°

tesla The unit of *magnetic flux density*, symbol T

thyristor A four-layer *semiconductor* device for the control of 'heavy' *current* by electronic means

torque Turning moment (force × radius) produced by a rotating machine

transformer Device which 'transforms' or changes *voltage* and *current* levels in an *a.c.* circuit; uses the principle of *mutual inductance*

transient A phenomenon which persists for a short period of time after a change has occurred in the circuit

transistor A three-layer *semiconductor n-p-n* or *p-n-p* device used in electronic amplifiers and computers

triac A multi-layer *semiconductor* device for the bidirectional control of *current* by electronic means; it is one of the *thyristor* family of elements

two-part tariff A method of charging for the cost of electricity; one part of the tariff is related to the 'standing' charges associated with the generating plant, the other being related to the 'running' charges

universal motor A *motor* which can operate on either *a.c.* or *d.c.*; a hand-held electrical drilling machine is an example

volt The unit of *electromotive force* and *potential difference*, symbol V

voltage dependent resistor A *resistor* whose *resistance* is dependent on the *p.d.* across it; it is a *non-linear* resistor

voltmeter An instrument for the measurement of *voltage*

watt The unit of electrical *power*, symbol W

wattmeter An instrument for measuring electrical *power*

weber The unit of *magnetic flux*, symbol Wb

Wheatstone bridge A circuit for the measurement of *resistance*

zener diode A *diode* with a well-defined reverse breakdown voltage, which can be operated in the reverse breakdown mode

CHAPTER 1

PRINCIPLES OF ELECTRICITY

1.1 ATOMIC STRUCTURE

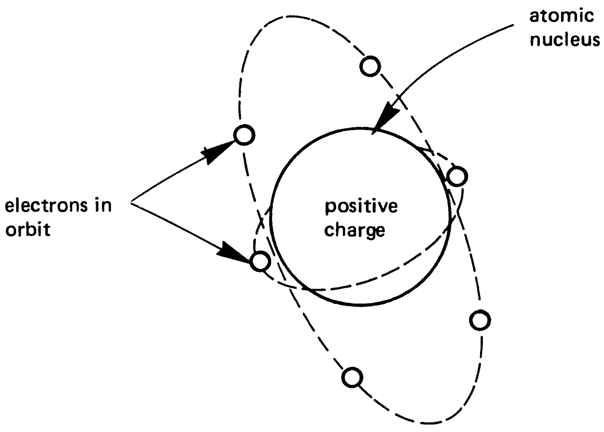
About 100 basic substances or **chemical elements** are known to man, each element consisting of a number of smaller parts known as **atoms**. Each atom comprises several much smaller particles, the principle ones being **electrons, protons** and **neutrons**.

The difference between the smaller particles lies not only in their difference in mass (a proton is 1840 times more 'massive' than an electron), but also in the **electrical charge** associated with them. For example, a proton has a *positive electrical charge* whilst an electron has a *negative electrical charge*; the charge on the proton is equal to but of opposite polarity to that on the electron. The electrical charge on either the proton or the electron is very small, in fact it is so small that one ampere of current is associated with the movement of over *six million billion electrons per second.*

The mass of the neutron is equal to that of the proton, but it has no electrical charge. In the latter respect it has little use in electrical circuits.

The nature of matter ensures that each atom is electrically balanced, that **it has as many electrons as it has protons.** Under certain circumstances an atom, or a molecule, or a group of atoms can acquire an electrical charge; the atom or group of atoms is then known as an **ion. A negative ion** (an **anion**) contains more electrons than are necessary for electrical neutrality; a **positive ion** (a **cation**) contains fewer electrons than necessary for neutrality.

The protons and neutrons are concentrated in the centre or **nucleus** of the atom as shown in Figure 1.1. The electrons *orbit around the nucleus* in what are known as **layers**, or **energy bands** or **shells**. A simple analogy of an atom is that of a multi-storey car park. The ground level, or 'zero energy' level can be regarded as the nucleus of the atom, whilst the higher found. The ground level is filled with 'car parking for staff cars' which we fig 1.1 *electrons in orbit around a nucleus*



will regard as protons and neutrons. As other people come along to park their cars, they must do so in the 'higher energy' levels. So it is with atoms - the lower shells are filled with electrons before the higher shells.

The electrons which take part in the process of electrical conduction are in the outermost shell or highest energy level shell of the electron; this is known as the **valence shell** or **valence energy band**. For an electron to take part in electrical conduction, it must be free to 'move' within its energy band. In the multi-storey car park analogy this is equivalent to the cars on the uppermost floor having the most room to move about.

1.2 ELECTRONIC 'HOLES'

The application of an electrical voltage to a conductor results in electrons in the outermost shell (the valence shell) being subjected to an electrical force. This force tries to propel the electrons towards the positive pole of the supply; if the force is sufficiently great, some electrons escape from the forces which bind them to the atom. The electrons which arrive at the positive pole of the battery constitute flow of **electrical current.**

However, when an atom loses an electron its electrical neutrality is lost, and the remainder of the atom takes on a net positive charge. This positive charge will attract any mobile electron in its vicinity; in this way, when an electron moves from one part of the conductor to another, it leaves behind it a resulting positive charge (arising from the loss of the electron at that point). Thus, as the electron 'moves' in one direction, a positive charge 'moves' in the opposite direction. On this basis, it is possible to describe the *mobile positive charge* as a **hole** into which any electron can fall (a 'hole' may be thought of as the absence of an electron where one would normally be found).

Electrical engineers therefore think of a *mobile negative charge carrier* as an *electron*, and a *mobile positive charge carrier* as a *hole.*

1.3 CONDUCTORS, SEMICONDUCTORS AND INSULATORS

A **conductor** is an electrical material (usually a metal) which offers very little resistance to electrical current. The reason that certain materials are good conductors is that the outer orbits (the valence shells) in adjacent atoms overlap one another, allowing electrons to move freely between the atoms.

An **insulator** (such as glass or plastic) offers a very high resistance to current flow. The reason that some materials are good insulators is that the outer orbits of the atoms do not overlap one another, making it very difficult for electrons to move through the material.

A **semiconductor** is a material whose resistance is midway between that of a good conductor and that of a good insulator. Other properties are involved in the selection of a semiconductor material for electrical and electronic purposes; these properties are discussed later in the book. Commonly used semiconductor materials include silicon and germanium (in diodes, transistors and integrated circuits), cadmium sulphide (in photoconductive cells), gallium arsenide (in lasers, and light-emitting diodes), etc. Silicon is the most widely used material, and is found in many rocks and stones (sand is silicon dioxide).

1.4 VOLTAGE AND CURRENT

Voltage is the electrical equivalent of mechanical potential. If a person drops a rock from the first storey of a building, the velocity that the rock attains on reaching the ground is fairly small. However, if the rock is taken to the twentieth floor of the building, it has a much greater potential energy and, when it is dropped it reaches a much higher velocity on reaching the ground. The *potential energy* of an electrical supply is given by its **voltage** and the greater the voltage of the supply source, the greater its potential to produce **electrical current** in any given circuit connected to its terminals (this is analagous to the velocity of the rock in the mechanical case). Thus the potential of a 240-volt supply to produce current is twenty times that of a 12-volt supply.

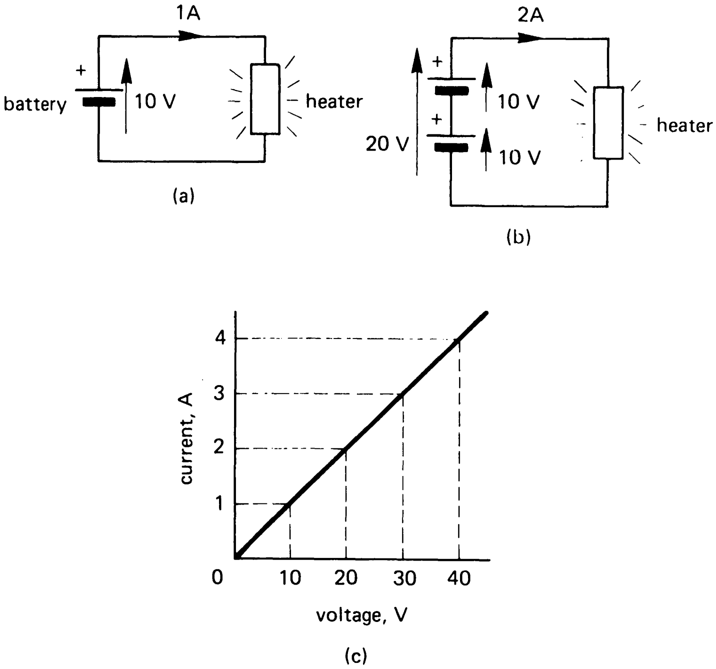
The electrical potential between two points in a circuit is known as the **potential difference** or **p.d.** between the points. A battery or electrical generator has the ability to produce current flow in a circuit, the voltage which produces the current being known as the **electromotive force**

(e.m.f.). The term electromotive force strictly applies to the source of electrical energy, but is sometimes (incorrectly) confused with potential difference. Potential difference and e.m.f. are both measured in **volts**, symbol V.

The **current** in a circuit is due to the movement of charge carriers through the circuit. The charge carriers may be either electrons (negative charge carriers) or holes (positive charge carriers), or both. Unless stated to the contrary, we will assume *conventional current flow* in electrical circuit, that is we assume that **current is due to the movement of positive charge carriers (holes) which leave the positive terminal of the supply source and return to the negative terminal.** The current in an electrical circuit is measured in **amperes**, symbol A, and is sometimes (incorrectly) referred to as 'amps'.

A simple electrical circuit comprising a battery of e.m.f. 10 V which is connected to a heater of fixed resistance is shown in Figure 1.2(a); let us suppose that the current drawn by the heater is 1 A. If two 10-V batteries are connected in series with one another, as shown in Figure 1.2(b), the

fig 1.2 *relationship between the voltage and current in a circuit of constant resistance*



e.m.f. in the circuit is doubled at 20 V; the net result is that the current in the circuit is also doubled. If the e.m.f. is increased to 30 V, the current is increased to 3 A, and so on.

A graph showing the relationship between the e.m.f. in the circuit and the current is shown in Figure 1.2(c), and is seen to be a straight line passing through the origin; that is, the current is zero when the supply voltage is zero. This relationship is summed up by Ohm's law in section 1.5.

1.5 OHM'S LAW

The graph in Figure 1.2(c) giving the relationship between the voltage across an element of fixed resistance and the current through it shows that the **current is proportional to the applied voltage**. This relationship (attributed to the German teacher G. S. Ohm) is given the name **Ohm's law**, and is stated below

$$\text{Current, } I = \frac{\text{e.m.f. } (E) \text{ or voltage } (V)}{\text{resistance, } R \text{ (ohms)}} \text{ amperes, A}$$

where I is the current in amperes flowing in the circuit of *resistance R ohms* (given the Greek symbol Ω [omega]). A ghoulish way of remembering Ohm's law is:

Interment (I) = Earth (E) over Remains (R)

Alternatively, Ohm's law may be stated in one of the following ways:

$$E \text{ or } V = IR \text{ (volts) (V)}$$

$$R = \frac{E \text{ or } V}{I} \text{ (ohms) } (\Omega)$$

The Greek symbol Ω (omega) was first used by W. H. Preece to represent the units of resistance in a lecture to Indian Telegraph Service cadets at the Hartley College (now the University, Southampton) in 1867.

The resistance of a conductor (or of an insulator) indicates the ability of the circuit to resist the flow of electricity; a low resistance, for example, 0.001 Ω, implies that the element is a poor resistor of electricity (or a good conductor!), whilst a high value, for example, 100 000 000 Ω implies that the element is a very good resistor (or a poor conductor).

Ohm's law is illustrated in the following simple examples. If a current of 0.5 A flows in a circuit of resistance 15 Ω, the p.d. across the circuit is

$$\text{voltage} = IR = 0.5 \times 15 = 7.5 \text{ V}$$

Also, if an e.m.f. of 10 V is applied to a circuit of resistance 10 000 Ω, the current in the circuit is

$$I = \frac{E}{R} = \frac{10}{10\,000} = 0.0001 \text{ A}$$

You should note that the resistance of a conductor may vary with temperature, and the effect of temperature on resistance is studied in detail in Chapter 3.

1.6 CONDUCTANCE

In some cases it is convenient to use the reciprocal of resistance, that is $\frac{1}{R}$ rather than resistance itself. This reciprocal is known as the **conductance**, symbol G, of the conductor; this value indicates the ability of the circuit to *conduct* electricity. The unit of conductance is the **siemens** (symbol S), and

$$\text{conductance, } G = \frac{1}{R} \text{ S}$$

A very low value of conductance, e.g., 0.000 000 0001 S implies that the circuit is a poor conductor of electricity (and is a good insulator), whilst a high value of conductance, e.g., 1000 S implies that it is a good conductor (or poor resistor). For example, a conductor of resistance 0.001 Ω has a conductance of

$$G = \frac{1}{R} = 1/0.001 = 1000 \text{ S}$$

whilst an insulator of resistance 10 000 000 Ω has a conductance of

$$G = \frac{1}{R} = \frac{1}{10\,000\,000} = 0.000\,000\,1 \text{ S}$$

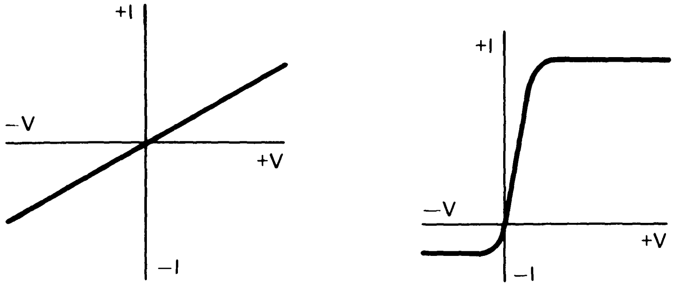
1.7 LINEAR AND NON-LINEAR RESISTORS

The majority of metals are good conductos and the current–voltage relationship for these materials obeys Ohm's law; that is, the I–V graph passes through the origin (see Figure 1.3(a)), and an increase in voltage (either positive or negative) produces a proportional change in the current. That is to say

$$I \alpha V$$

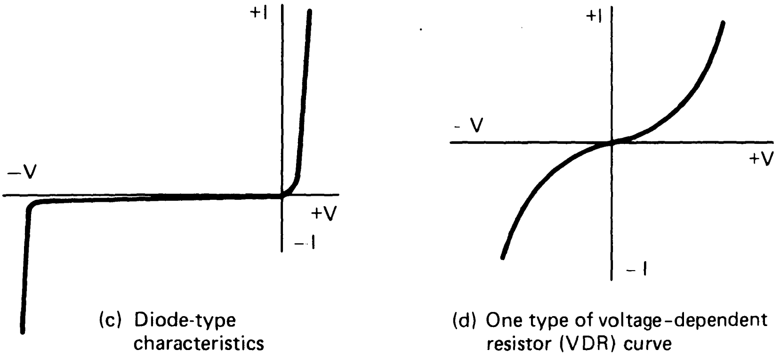
where the Greek symbol α (alpha) means 'is proportional to'. In such a circuit element, doubling the voltage across the element has the effect of doubling the current through it.

fig. 1.3 *the linear resistor (or conductor) in (a) obeys Ohm's law; the circuit elements having the characteristics shown in (b), (c) and (d) do not obey Ohm's law*



(a) Linear (conductor or resistor)

(b) Transistor-type characteristic



(c) Diode-type characteristics

(d) One type of voltage-dependent resistor (VDR) curve

However, there are other circuit elements which do not obey Ohm's law. These are known as **non-linear resistors** or **non-linear conductors**. The characteristics in diagrams (b) to (d) correspond to practical non-linear devices.

In the case of a *transistor* (Figure 1.3(b), the current increases rapidly from the origin of the graph but, when the p.d. across it is about 0.6 to 1.0 V, the current becomes more-or-less constant; the value of the current depends whether the voltage is positive or negative. In the case of a *semiconductor diode* (Figure 1.3(c)), the current rises very rapidly for positive voltages; for negative voltages the current is practically zero up to a fairly high voltage, at which point the current increases rapidly (this is known as reverse breakdown). In the case of a *voltage dependent resistor*, VDR (Figure 1.3(d)), the current through it increases at a progressively rapid rate as the voltage across it increases.

Although the *I-V* characteristic of the devices in Figure 1.3 may not obey Ohm's law, each finds its own special applications in electrical engineering. The following applications are typical:

Transistors - amplifiers and computers
Diodes - rectifiers and invertors (the first converts a.c. to d.c. while the latter converts d.c. to a.c.)
Voltage dependent resistor - protection of electrical circuits from voltage surges.

1.8 ALTERNATING CURRENT

So far we have discussed the use of **direct current** (d.c.) or **unidirectional current**. Many forms of electrical generator produce an **alternating** power supply; that is, the voltage on the 'live' line (L) is alternately positive and negative with respect to the 'neutral' line (N).

A very simple alternating voltage generator is shown in Figure 1.4, and comprises a battery which is connected to two **sliders** or **wipers** on a circular potentiometer. The sliders are driven round at a constant speed by means of a *prime mover* (not shown. When the sliders are at points X and Y, the potential at point L is the same as that at point N, so that the potential difference between L and N is zero. As the sliders rotate in the direction shown, the potential of point L progressively becomes more positive with respect to point N; after 90° rotation, the potential at L reaches its maximum positive potential $+E_m$.

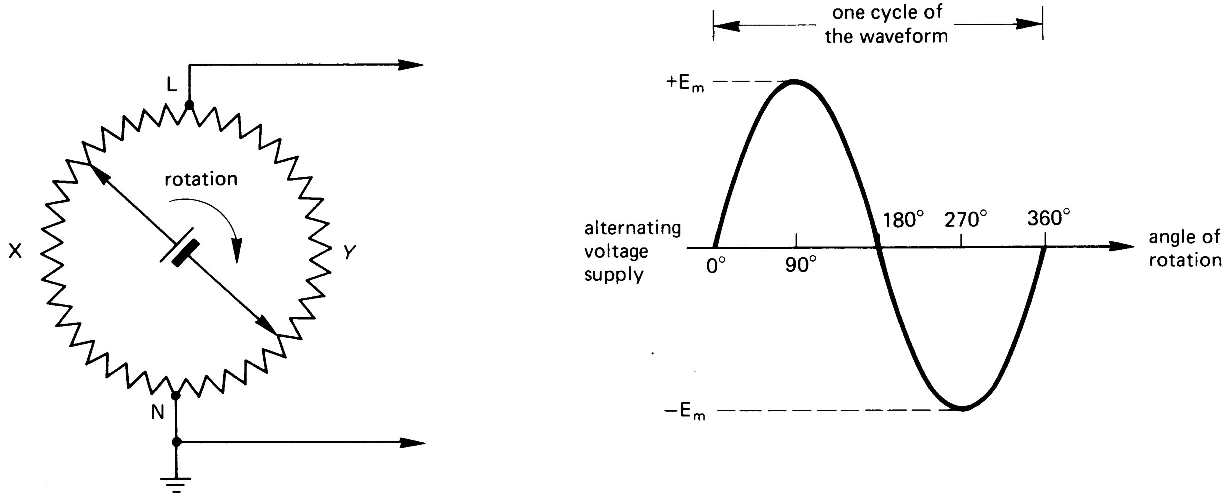
As the sliders rotate further, the potential of point L becomes less positive with respect to N until, when they reach X and Y again once more, the p.d. between L and N is zero once more.

Further rotation causes point L to become negative with respect to point N. When the slider connected to the positive pole of the battery reaches N, point L is at its maximum negative potential, $-E_m$. Further rotation causes point L to become less negative with respect to point N until, after 360° rotation from the start of the waveform, the sliders reach their original position. Consequently, the potential of point L with respect to point N *alternates* about zero, as shown in the waveform in Figure 1.4.

For safety reasons, many electrical circuits have one point of the electrical circuit connected to earth potential. In the case of Figure 1.4 this is the *N*-line or **neutral line**; the other line (line *L*) is known as the **live line.**

One cycle of an alternating electrical supply is shown in the waveform in Figure 1.4, and commences at point O and finishes at the start of the following cycle. This corresponds to a rotation of 360° or 2π radians.

The time taken to complete one cycle of the supply frequency is fig 1.4 *a simple alternating current generator*



known as the **periodic time** of the wave. If this time is T seconds, then the **frequency**, f, of the wave (the number of cycles per second) is given by

$$\text{frequency}, f = \frac{1}{T} \text{ hertz (Hz)}$$

where 1 hertz is 1 cycle per second. If the periodic time of the wave is 1 ms, the frequency is

$$\text{frequency}, f = \frac{1}{1\text{ ms}} = \frac{1}{1 \times 10^{-3}} = 1000\text{ Hz.}$$

1.9 MULTIPLES AND SUBMULTIPLES OF UNITS

The units associated with many practical quantities are in some cases inconveniently small and, in other cases, inconveniently large. For example the unit of power, the watt (W), is convenient when describing the power consumed by an electric light bulb, e.g., 100 W, but is much too small to be used when describing the power consumed either by a large electrical heater (which may be many thousand watts) or by a generating station (which may be many millions of watts). At the other extreme, the watt is much too large to use when discussing the power consumed by a low-power transistor (which may be only a few thousandths of a watt).

It is for this reason that a range of multiples and submultiples are used in Electrical Engineering. Table 1.1 lists the range of multiples and submultiples used in association with SI units (*Système International*

Table 1.1 *SI multiples and submultiples*

Multiplying factor	*Prefix*	*Symbol*
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10	deca	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

d'Unitès), which is the system of units adopted by Electrical and Electronic Engineers.

For example, 11 000 000 watts could be written either as 11×10^6 W or as 11 MW; 0.0001 W could be written either as 10^{-4} W or as 0.1 mW or as 100 μW. Strictly speaking, any of the prefixes in Table 1.1 can be used but, in practice, deca- and hecto- are practically never used; femto- and atto- refer to very small values indeed, and have only a limited use.

You should also note that compound prefixes are avoided wherever possible; for example, the multiple 10^{-9} is described as nano- rather than milli-micro. That is, 10^{-9} metre (m) is described as 1 nm and not as 1 m μm.

1.10 SOME BASIC ELECTRICAL QUANTITIES

Some of the more commonly used units in electrical and electronic engineering are briefly described below.

Electrical quantity (symbol Q)

The quantity of electricity passing a point in an electrical circuit is

$$\text{Quantity, } Q = I\,(\text{amperes}) \times t\,(\text{seconds}) \quad \text{coulombs (C)}$$

For example, if a circuit carries a current of 5 amperes for 15 seconds, the quantity of electricity is

$$\text{Quantity, } Q = It = 5 \times 15 = 75 \text{ C}$$

Electrical power (symbol *P*)

Power is the rate of dissipation of energy and is given by

$$\text{Power, } P = E\,(\text{volts}) \times I\,(\text{amperes}) \quad \text{watts (W)}$$

If the electrical voltage across a resistive circuit element is 240 V, and if the current passing through it is 13 A, the power consumed is

$$\text{Power, } P = EI = 240 \times 13 = 3120 \text{ W}$$

Also from Ohm's law, $E = IR$, hence

$$\text{Power, } P = EI = (IR) \times I = I^2R \text{ W}$$

Since $I = \frac{E}{R}$, then

$$\text{Power, } P = EI = E \times \frac{E}{R} = \frac{E^2}{R} \; W$$

Electrical energy (symbol *W*)
The energy dissipated in an electrical circuit is given by

Energy, $W = E$ (volts) × I (amperes) × t (seconds) joules (J)

If the p.d. across a circuit element is 100 V and it carries a current of 10 A for 15 s, the energy consumed is

Energy, $W = EIt = 100 \times 10 \times 15 = 15\,000$ J or watt-seconds.

The **commercial unit of electrical energy** is the **kilowatt-hour** or kWh, which corresponds to 1 kilowatt of power being consumed continuously for a period of one hour.

SELF-TEST QUESTIONS

1. What is the difference btween an atom and a chemical element? How do electrons, protons and neutrons differ?
2. Copper is a conductor and glass is an insulator. Why do these materials have different electrical resistance? Why is a 'semiconductor' so named?
3. Explain the terms 'voltage' and 'potential drop'.
4. Using Ohm's law, calculate the current flowing in a resistance of 100 Ω which has a p.d. of 20 V across it.
5. Calculate the conductance in siemens of a circuit which carries a current of 100 A, the p.d. across the circuit being 10 V.
6. The following values of current were measured in a circuit when the voltage across the circuit was (i) 10 V, (ii) 20 V, (iii) 30 V: 10 A, 40 A, 150 A. Plot the I–V characteristic of the circuit and state if it is linear or non-linear.
7. An alternating current waveform has a periodic time of 1 ms, calculate the frequency of the current. What is the periodic time of an alternating voltage of frequency 100 kHz?
8. A current of 20 A flows in a circuit for 20 s, the voltage applied to the circuit being 20 V. Calculate the electrical quantity, the power and the energy consumed.

SUMMARY OF IMPORTANT FACTS

A chemical **element** is built up from **atoms**. Each atom is made up of **electrons, protons** and **neutrons**. The electron has a **negative charge** and the proton a **positive charge**; the two electrical charges are **equal and opposite**, but the mass of the proton is **1840 times greater** than that of the electron.

Current flow is a combination of **electron flow** (negative charge carriers) and **hole flow** (positive charge carriers).

A **conductor** offers low resistance to current flow, an **insulator** offers high resistance. The resistance of a **semiconductor** is mid-way between the two extremes.

Voltage or **e.m.f.** is a measure of the potential of an electric circuit to produce current flow.

Ohm's law states that

$$E = IR$$

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

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

where E is in volts, I in amperes and R in ohms.

The **conductance** (G) of an electrical circuit is measured in siemens (S) and $G = \frac{1}{R}$ (R in ohms).

A **linear circuit element** is one whose resistance is constant despite fluctuations of voltage and current. The resistance of a **non-linear circuit element** varies with fluctuations of voltage and current.

A **direct current** or **unidirectional current** always flows in the same direction around a circuit. An **alternating current** periodically reverses its direction of flow. If the **periodic time** of an alternating wave is T seconds, the **frequency** of the alternating wave is $f = \frac{1}{T}$ Hz.

CHAPTER 2

ELECTROCHEMISTRY, BATTERIES AND OTHER SOURCES OF e.m.f.

2.1 ELECTROCHEMICAL EFFECT

The chemical effect of an electric current is the basis of the *electroplating industry*; the flow of electric current between two **electrodes** (one being known as the **anode** and the other as the **cathode**) in a liquid (the **electrolyte**) causes material to be lost from one of the electrodes and deposited on the other.

The converse is true, that is, chemical action can produce an e.m.f. (for example, in an electric battery).

All these electrochemical effects depend on the electrolyte. The majority of **pure liquids** are good insulators (for example, *pure water* is a good insulator), but **liquids containing salts** will conduct electricity. You should also note that some liquids such as mercury (which is a liquid metal) are good conductors.

2.2 IONS

An atom has a nucleus (positively charged) surrounded by electrons (negatively charged) which orbit around the nucleus in shells or layers. In an electrically neutral atom, the positive and negative charges are equal to one another and cancel out. However, the electrons in the outermost orbit (the valence electrons) are fairly loosely attracted to the parent atom and can easily be detached. In fact, it is possible for either a chemical reaction or an electric field to cause an atom either to lose an electron or to gain one.

When an atom loses an electron, its charge balance is upset and the parent atom (which has lost the negatively charged electron) is left with a charge of +1 unit of electricity (equivalent to the charge on a proton). In this case the parent atom is described as a **positive ion** or a **cation**; *the ion retains the characteristics of the original element because the nucleus*

remains intact. When an atom gains an electron, it has a net charge of −1 unit of electricity (equivalent to the charge on one electron) and is described as a **negative ion** or **anion.**

Since like charges attract and unlike charges repel, a ***negative ion is attracted to a positively charged electrode*** and is ***repelled by a negatively charged electrode*** (and vice versa for a positive ion). For this reason, current flow can take place in ionised material as follows: in liquids such as electrolytes and in gases (for instance, in fluorescent tubes) current flow is due to the movement of ions between two oppositely charged electrodes, the current flow being known as **ionisation current.**

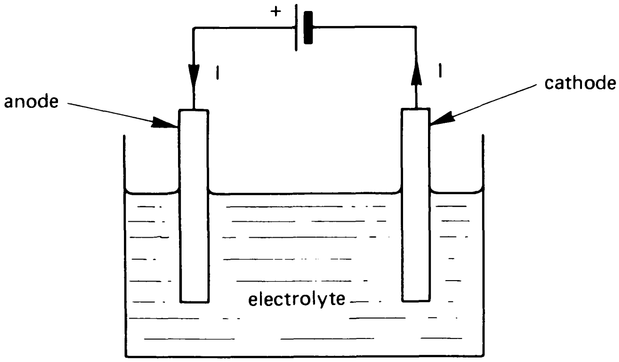
Ions are formed in a liquid either when a salt or an acid is dissolved in it; additionally, when a metal is immersed either in an alkaline or an acid solution, ionisation occurs. The resulting liquid is a fairly good conductor of electricity and is known as an **electrolyte.**

2.3 ELECTROLYSIS

Electrolysis is the process of decomposing an electrolyte by passing an electric current through it. The chemical action is seen at the **electrodes** (where the current enters or leaves the electrolyte in which the electrodes are immersed - see Figure 2.1). The electrode by which the current enters the electrolyte is known as the **anode**; the current leaves via the **cathode** electrode.

Electrolysis is the basis of the **electroplating industry** in which one metal is plated with another metal. It is also used in the **extraction** and **refining** industry; copper, zinc and aluminium being examples of metals extracted by this means. It is also the basis of other **electrolytic processes** involved in the production of certain types of gas; for example, hydrogen

fig 2.1 *electrolysis*



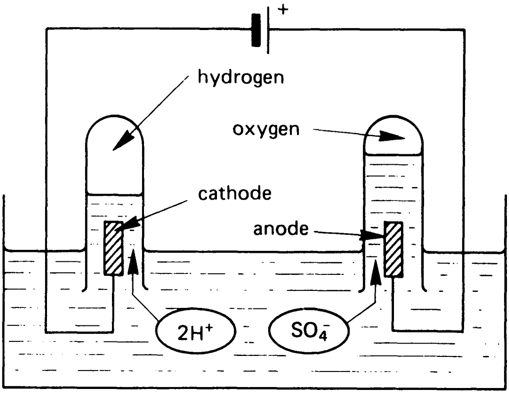
and oxygen can be produced by breaking down water into its basic chemical constituents.

2.4 AN EXAMPLE OF ELECTROLYSIS

To simplify the representation of ions in chemical processes, a form of shorthand is used to denote different types of ion. Positive ions have a positive sign associated with them in the form of a superscript, for example, a hydrogen ion is shown as H^+. Each 'unit' positive charge associated with the ion is shown as a 'plus'; thus Cu^{++} means that the copper ion is **doubly charged**. Negative ions have a negative subscript, for example, the sulphate ion SO_4^{--} is a doubly-charged anion.

Consider the example in Figure 2.2 in which sulphuric acid is added to water to form dilute sulphuric acid. The sulphuric acid molecule, H_2SO_4, splits in the water into two hydrogen cations ($2H^+$) and a sulphate anion (SO_4^{--}). When the two electrodes in the solution are connected to the battery, the sulphate ions (negative ions) are attracted to the anode and the hydrogen ions (positive ions) to the cathode.

fig 2.2 *production of hydrogen and oxygen*



When a hydrogen ion arrives at the negatively charged cathode it picks up an electron; this discharges the ion, leaving the neutral atom of hydrogen gas to rise to the surface where it is collected in a test tube (see Figure 2.2).

The reaction when a sulphate ion arrives at the anode is rather more complex. The sulphate ion combines with water to give the following reaction:

$$SO_4^{--} + 2H_2O = SO_4^{--} + 2(H^+ + OH^-)$$

$$= (2H^+ + SO_4^{--}) + 2OH^-$$
$$= H_2SO_4 + 2OH^-$$

The first line shows that the water dissociates into H^+ and OH^- ions, which further combine to produce sulphuric acid (H_2SO_4) and OH^- ions. The OH^- ions rearrange themselves into water and oxygen as follows:

$$2OH^- = H_2O + O^{--}$$

The negative charge associated with the O^{--} is discharged at the anode, the resulting neutral atoms of oxygen rise to the surface and are collected in the test tube.

From this, you will see that the sulphuric acid is constantly being replaced by the process and is not diminished, but the water is converted into its basic elements, namely, hydrogen and oxygen gas. Clearly, unless the water is replenished, the concentration of the acid increases slowly with time. Since the amount of acid is constant, it can be regarded as a **catalyst**.

2.5 ELECTROPLATING

When two different metals are immersed in a solution which is a salt *of the same material as the anode*, and a current is passed between the two metals, metal ions from the anode dissolve into the solution and, at the same time, ions of the anode material are deposited on the cathode.

Copper plating

If the anode is of copper and the electrolyte is copper sulphate, the cathode (of, say, iron) is plated with copper.

Silver plating

A silver anode is used and the electrolyte is cyanide of silver; the cathode must be a metal which does not chemically react with the electrolyte.

2.6 FARADAY'S LAWS OF ELECTROLYSIS

In the process of electrolysis, ions migrate towards the electrodes and, on arrival at the electrodes, give up some electrical charge. The charge given up *per ion* is

charge per ion = ze coulombs

where z is the number of valence electrons and e is the charge per electron. Hence the total charge Q given up by N ions is

$$Q = Nze \text{ coulombs} \qquad (2.1)$$

or

$$\text{number of ions}, N = \frac{Q}{ze}$$

Michael Faraday discovered this relationship in 1833, and stated two laws which govern electrolysis as follows:

First law:

> *The mass of material deposited (or gas released) is proportional to the quantity of electricity (current × time) which passes through the electrolyte.*

(This is suggested by Eqn (2.1).)

Second law:

> *The mass of material in grammes deposited by the passage of 26.8 ampere hours of electricity is equal to the chemical equivalent of that material.*

Example

When an electrical current passes through a solution of sodium chloride in water, sodium hydroxide and hydrochloric acid are produced. If the chemical equivalent of sodium hydroxide is 40 and that of hydrochloric acid is 36.5, determine how much hydrochloric acid and sodium hydroxide are produced when 100 A flows for 10 mins.

Solution

$$I = 100\ \text{A}, t = 10\ \text{mins} = \frac{1}{6}\ \text{hour}$$

$$Q = It = 100 \times \frac{1}{6} = 16.67\ \text{Ah}$$

From Faraday's second law of electrolysis:

mass of material deposited

$$= \text{chemical equivalent} \times \frac{\text{quantity of electricity in Ah}}{26.8}$$

hence

$$\text{mass of sodium hydroxide} = 40 \times \frac{16.67}{26.8} = 24.88 \text{ g (Ans.)}$$

and

$$\text{mass of hydrochloric acid} = 36.5 \times \frac{16.67}{26.8} = 22.7 \text{ g (Ans.)}$$

2.7 CELLS AND BATTERIES

A **cell** contains two **plates** immersed in an **electrolyte**, the resulting chemical action in the cell producing an e.m.f. between the plates. Cells can be grouped into two categories. A **primary cell** cannot be recharged and, after the cell is 'spent' it must be discarded (this is because the chemical action inside the cell cannot be 'reversed'). A **secondary cell** or **storage cell** can be recharged because the chemical action inside it is reversed when a 'charging' current is passed through it. Table 2.1 lists the e.m.f. associated with a number of popular cells.

Cells are also subdivided into 'dry' cells and 'wet' cells. A **dry cell** is one which has a *moist electrolyte*, allowing it to be used in any physical position (an electric torch cell is an example). A **wet cell** is one which has a *liquid electrolyte* which will spill if the cell is turned upside down (a cell in a conventional lead-acid auto battery is an example). There is, of course, a range of sealed rechargeable cells which are capable of being discharged or charged in any position; the electrolyte in these cells cannot be replaced.

Table 2.1 *Cell voltages*

Type of cell	*Category*	*e.m.f.*
Carbon zinc	primary	1.5
mercury oxide	primary	1.35
silver oxide	primary	1.5
zinc chloride	primary	1.5
manganese dioxide	primary or secondary	1.5
lead acid	secondary	2.1
nickel cadmium	secondary	1.35
nickel iron	secondary	1.25
silver cadmium	secondary	1.1
silver zinc	secondary	1.5

A **battery** is an interconnected group of cells (usually connected in series) to provide either a higher voltage and/or a higher current than can be obtained from one cell.

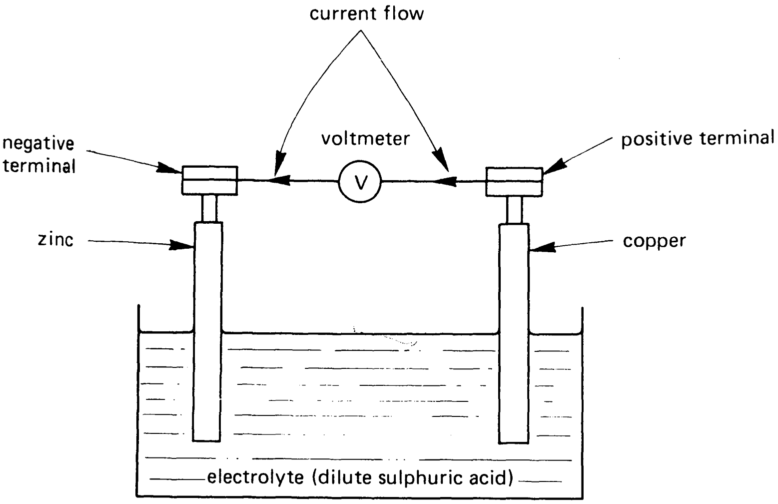
2.8 A SIMPLE VOLTAIC CELL

A simple **voltaic cell** is shown in Figure 2.3, the e.m.f. produced by the cell being given by the algebraic difference between the 'contact potential' e.m.fs of the two electrodes; the contact potential of commonly used materials are listed in Table 2.2.

In the cell in Figure 2.3, zinc reacts with the acid in the electrolyte, the electrons released in the process giving the zinc electrode a negative potential.

The copper electrode does, to some extent, react with the acid but to a far lesser degree than does the zinc. The sulphuric acid in the electrolyte dissociates into its negative sulphate ions, SO_4^{--}, and its positive ions, $2H^+$. The negative ions give up their charge to the zinc electrode and the positive ions move to the copper electrode where they give up their charge, causing the copper plate to be positive. Once the hydrogen ions give up their charge, they can be seen as hydrogen bubbles on the surface of the copper electrode; they can then float to the surface to be absorbed into the atmosphere.

fig **2.3** *a simple voltaic cell*



The e.m.f. produced by the cell can be deduced from the electrochemical series in Table 2.2. The e.m.f. of the copper-zinc cell is *the difference in potential between the elements*. In this case it is

$$0.34 - (-0.76) = 1.1 \text{ V}.$$

Table 2.2 *Electrode potentials*

Element	*Potential (V)*
magnesium	−2.40
aluminium	−1.70
zinc	−0.76
cadmium	−0.40
nickel	−0.23
lead	−0.13
hydrogen	0.00
copper	0.34
mercury	0.80
gold	1.50

2.9 INTERNAL RESISTANCE OF A CELL

A cell produces a theoretically 'ideal' e.m.f. E (see Figure 2.4) which can be predicted from the table of electrochemical elements. If you measure the p.d. between the terminals of the cell **when the load R is disconnected** (that is when the load current is zero) you are measuring the e.m.f., E; this voltage is known as the **no-load terminal voltage of the cell.**

When the load resistance, R, is connected, a current flows through the cell; that is, it flows not only through the electrolyte but also through the contact between the electrolyte and the electrodes. Since, at normal temperature, no material is resistanceless, the cell has an **internal resistance**, r (see Figure 2.4), which is in series with the e.m.f., E.

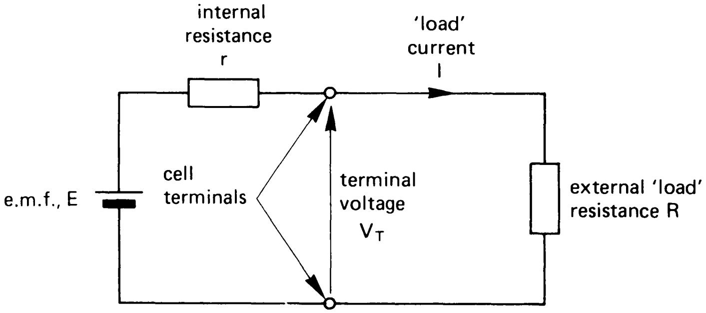
The potential drop in the internal resistance r (known as the *internal voltage drop*) of the cell causes the **terminal voltage**, V_T, under 'loaded' conditions to be less than the no-load terminal voltage, E. The equation for the terminal voltage is:

Terminal voltage = e.m.f. − internal voltage drop

or

$$V_T = E - Ir$$

fig 2.4 *equivalent electrical circuit of a cell*



Example

Calculate (a) the current flowing from and (b) the terminal voltage of a cell of e.m.f. 1.5 V and internal resistance 2 Ω when the load resistance is (i) 100 Ω, (ii) 10 Ω, (iii) 2 Ω, (iv) zero (that is, when the terminals of the cell are shorted together).

Solution

Since $E = 1.5$ V, $r = 2\ \Omega$, the current, I, drawn by the load resistor R (see Figure 2.4) is given by

$$I = \frac{1.5}{(2 + R)}\ \text{A}$$

The terminal voltage, V_T, is calculated from the expression

$$V_T = IR\ \text{V}$$

An example calculation is given below for $R = 100\ \Omega$.

(a) $I = \dfrac{1.5}{(2 + \text{R})} = \dfrac{1.5}{(2 + 100)} = 0.0147$ A (Ans.)

and

(b) $V_T = IR = 0.0147 \times 100 = 1.47$ V (Ans.)

The above calculation shows that the internal resistance has caused an 'internal' voltage drop of $1.5 - 1.47 = 0.03$ V. The results for the remainder of the calculation are listed below, and it would be an interesting exercise for the reader to verify them.

R (ohm)	100	10	2	0
I (amperes)	0.0147	0.125	0.375	0.75
V_T (volts)	1.47	1.25	0.75	0

In the case where the cell terminals are short-circuited ($R = 0$), the terminal voltage is zero because the load resistance is zero. What, you may ask, has happened to the e.m.f.? The explanation is that the p.d. across the internal resistance r is

$$Ir = I \times r = 0.75 \times 2 = 1.5 \text{ V}$$

In this case, the whole of the e.m.f. is 'dropped' across the internal resistance of the cell. That is:

$$\begin{aligned} \text{p.d. across load } &= E - \text{'internal voltage drop'} \\ &= 1.5 - 1.5 = 0 \text{ V} \end{aligned}$$

leaving zero volts between the terminals of the cell. **You are advised against the practice of short-circuiting the terminals of a cell because of the risk of the cell exploding as a result of the intense chemical activity in the cell.**

2.10 LIMITATIONS OF SIMPLE CELLS

In practice the terminal voltage of a cell is not only less than the e.m.f. of the cell but, with use, it falls to an even lower value. The principal reason for the latter is **polarisation** of one of the electrodes, and is due to hydrogen gas bubbles collecting on its surface.

Consider the copper-zinc cell in Figure 2.3. In the process of producing a voltage, hydrogen gas bubbles form on the surface of the copper electrode. If all the surface of the copper was covered with hydrogen bubbles, the cell would become a hydrogen-zinc cell having a theoretical e.m.f. of

$$0.00 - (-0.76) = 0.76 \text{ V}$$

(see also Table 2.2). Moreover, since hydrogen is a poor conductor of electricity, the internal resistance of the cell would be very high. This has a further effect of reducing the terminal voltage when current is drawn from it.

The effects of polarisation are overcome by adding a chemical to the electrode; the function of the chemical is to combine with the hydrogen to form water. Such a chemical is described as a **depolarising agent** or **depolariser**. In some cases, powdered carbon is added to the depolariser to improve its conductivity and therefore reduce the internal resistance of the cell.

Another problem with cells using a zinc electrode is known as **local action**. Local action is due to the difficulty of obtaining zinc which is free from impurities such as iron or lead. If the impurity is on the surface of the zinc, it form a 'local' cell which, because of the intimate contact between the impurity and the zinc, is short-circuited. Because of the short-circuiting action, each local cell is almost instantaneously discharged, the energy appearing as heat in the cell; the action also causes some of the zinc to be consumed in the process. A remedy is to use an **amalgamated zinc electrode**, which is zinc which has been treated with mercury; the impurities normally in the zinc are not soluble in the mercury and so do not present a problem.

2.11 THE ‘DRY’ CELL

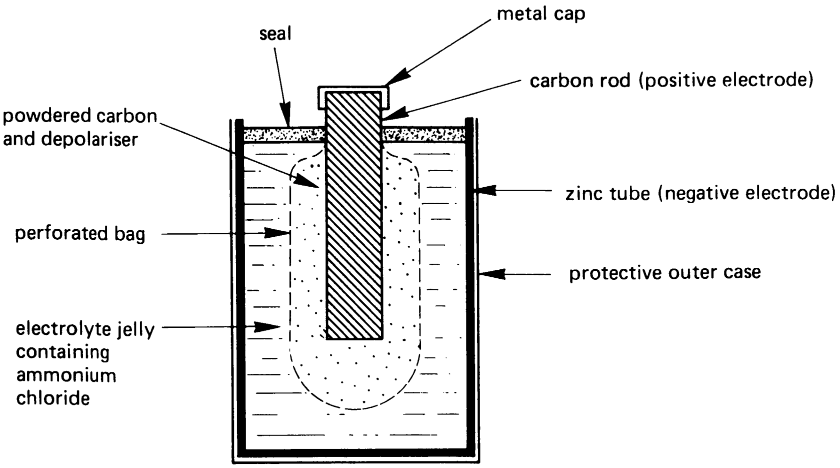
Early ‘dry’ cells were versions of the Leclanché ‘wet’ cell, in which the positive electrode was a rod of carbon which passed into a porous pot packed with a mixture of powdered carbon and manganese dioxide, the latter being a depolarising agent.

The powdered carbon inside the porous pot effectively increased the volume of the positive electrode; the function of the porous pot was simply to keep the mixture in close contact with the carbon rod. The porous pot stood in a glass vessel containing the zinc (negative) electrode together with the electrolyte of dilute ammonium chloride. This type of cell had an almost indefinite life, the maintenance consisting of the following:

1. the zinc rod needed to be replaced from time-to-time;
2. some ammonium chloride needed to be added occasionally;
3. the electrolyte needed ‘topping up’ with tap water from time-to-time.

A simplified cross-section of a modern dry cell is shown in Figure 2.5.

fig 2.5 *the construction of a ‘dry’ cell*



The positive electrode (the **anode**) is a carbon rod (as it was in the Leclanché cell), which is in intimate contact with a mixture of powdered carbon and an depolariser which are contained in a perforated bag. The perforations in the bag allow the electrolyte to come into contact with the powdered carbon. The electrolyte is in the form of a jelly, so that the cell can be used in any physical position. The negative electrode (the **cathode**) is a zinc tube which provides a rigid case for the cell.

Different types of dry cell are manufactured for a range of applications. For example, some cells are specifically designed for use with calculators, some for use with clocks, and others for use with torches, etc. Two of the features allowing a specific performance to be achieved are the number and size of the holes in the perforated bag which holds the depolariser; these affect the rate of discharge of current from the cell.

2.12 OTHER TYPES OF PRIMARY CELL

The zinc chloride cell

This is generally similar to the dry cell described in section 2.11, but the electrolyte contains zinc chloride.

The mercury cell

The anode in this type of cell is made of zinc, the cathode being a mercury compound, and the electrolyte is sodium or potassium hydroxide. These cells are manufactured in cylindrical and 'button' shapes, and they maintain a fairly constant voltage over their working life. The terminal voltage is typically 1.35–1.4 V per cell.

The silver oxide cell

The anode in this cell is made of zinc, the cathode is silver oxide, and the electrolyte is potassium or sodium hydroxide. The button-shape cells give a terminal voltage of about 1.5 V and are widely used in many popular applications including electronic watches, hearing aids and cameras.

The lithium cell

This type of cell can provide about ten times more energy than an equivalent size of carbon–zinc cell but, since lithium is a chemically active element, there may be a risk of explosion without warning. Depending on the electrolyte, the e.m.f. is in the range 2.9 to 3.7 V per cell.

2.13 STORAGE BATTERIES

Rechargable cells are often connected in series to form a **storage battery**, a *car battery* being an example; a storage battery is frequently called an

accumulator. The cells of the battery have a reversible chemical action and, when current is passed through them in the 'reverse' direction (when compared with the discharging state), the original material of the electrodes is re-formed. This allows the battery to be repeatedly discharged and charged. The chemical action is rather complex, and one of the most important of them – the lead-acid battery – is described here.

The lead-acid accumulator

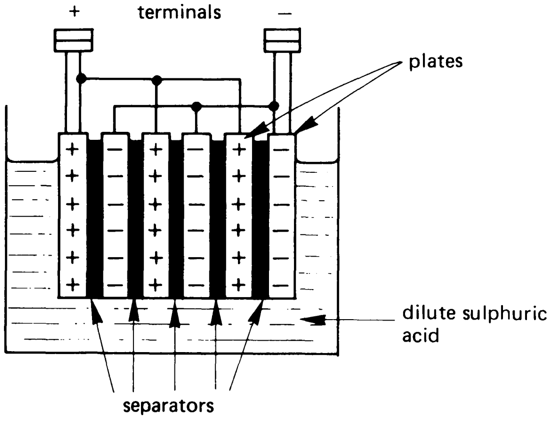
A simplified cross-section through a lead-acid battery is shown in Figure 2.6. The accumulator has as many positive plates as it has negative plates, the **separators** between the plates being porous insulators. The accumulator is usually houses in a glass or plastic vessel containing the electrolyte which is dilute sulphuric acid.

Different types of chemical activity occur at each of the two plates both during the electrical charging process and during its discharge. However, the process can be summarised and simplified by the following equation:

$$\overbrace{\overset{\text{positive plate}}{PbO_2} \quad + \quad \overset{\text{negative plate}}{Pb} \quad + \quad \overset{\text{electrolyte}}{2H_2SO_4}}^{\text{condition when charged}} \quad \rightleftharpoons \quad \overbrace{\overset{\text{both plates}}{2PbSO_4} \quad + \quad \overset{\text{electrolyte}}{2H_2O}}^{\text{condition when discharged}}$$

Both plates are a lead alloy grid, the holes in the grid being packed with a chemical substance. In the case of the **positive plate** of a charged accumulator (see the above equation), the grids contain lead peroxide (PbO_2) and,

fig 2.6 *cross-section through a lead-acid battery*



in the case of the **negative plate**, it is spongy lead (Pb). During the charging process of the battery, the **specific gravity**, that is, the strength of the electrolyte gradually increases to a value in the range 1.26–1.28.

The instrument used to test the 'condition' of the charge or discharge of a cell of the battery is known as a **hydrometer**, and consists of a glass tube containing a calibrated float. When the hydrometer is partly-filled with electrolyte, the level of the calibrated float indicates the density of the electrolyte. Typical values of density are:

Condition	*Density*
fully charged	1.26 to 1.28 (indicated as 1260 to 1280)
half charged	1.25 (indicated as 1250)
discharged	1.15–1.2 (indicated as 1150 to 1200)

At the end of the charging process (described below), each cell in the battery has an e.m.f. of about 2.5 V. When the battery has had a period of rest and the electrolyte has diffused throughout each cell, the e.m.f. per cell falls to about 2–2.1 V.

During the early part of the discharge period (say the first hour), the terminal voltage of the battery falls fairly quickly to give an equivalent voltage per cell of about 2 V. During the major part of the discharge period the terminal voltage falls fairly slowly because the electrolyte in the pores of the separators is used up more quickly than fresh electrolyte can flow in. At the end of the discharge period the terminal voltage falls to about 1.8 V per cell, by which time the plates are covered with lead sulphate ($PbSO_4$) and the specific gravity has fallen to 1.2 or lower.

During the charging process, the lead sulphate in the paltes is converted into lead peroxide (in the positive plates) and lead (in the negative plates), and the specific gravity gradually increases (indicating the formation of more sulphur acid). The charging process is complete when the lead sulphate is exhausted, and is indicated by a sharp rise in the terminal voltage to give an e.m.f. per cell of about 2.5 V. At this time electrolysis of the water in the electrolyte occurs, causing hydrogen and oxygen gas to be produced at the negative and positive plates, respectively (see section 2.4 for details). When this occurs in a cell, it is said to be **gassing**.

The nickel-iron (NiFe) alkaline accumulator

This is known in the US as the **Edison** accumulator. This type of battery has a positive plate made of nickel oxide, a negative plate made of iron, the electrolyte being a dilute solution of potassium hydroxide with a small amount of lithium hydroxide.

This type is more robust than the lead-acid accumulator but produces a lower e.m.f. per cell (about 1.2 V). The efficiency of the charge–discharge process is lower than that of the lead-acid accumulator, being about 60 per cent compared with about 75 per cent for the lead-acid type.

The Nickel-Cadmium (NiCd) alkaline accumulator

The electrodes and the electrolyte in this accumulator are generally similar to those in the nickel-iron accumulator with the exception that the negative electrode is either made of cadmium or a mixture of iron and cadmium. The average e.m.f. per cell is about 1.2 V; this type of accumulator is widely used in radios, televisions, power tools, etc. Nickel-cadmium batteries are used as 'on-board' power supplies in many computer systems; their function being to maintain a power supply to electronic memories in the event of a power failure.

An interesting feature of the NiCd cell is that the chemical expression, KOH, for the electrolyte does not appear in the charge-discharge equation. This means that the specific gravity of the electrolyte does not change with the state of the charge of the cell; that is to say, the specific gravity of the electrolyte does not give an indication of the state of charge.

Other storage batteries

Research not only into specialised electronic applications but also into electric traction (the 'electric' car) has given rise to a number of new accumulators. These include the **zinc-chloride cell** (about 2.1 V per cell), the **lithium-iron sulphide cell** (about 1.6 V per cell) and the **sodium-sulphur cell**. Another interesting cell is the **plastic cell** which uses a conductive polymer; this cell is claimed to have a much reduced weight and volume combined with a higher capacity than the lead-acid cell.

Capacity of an accumulator

The capacity of an accumulator is expressed in terms of the number of *ampere-hours (Ah) that may be taken from it* during the discharge period. Thus, a 20 Ah battery is capable of supplying a current of 2 A for a period of time given by

$$\text{time} = \frac{\text{ampere-hour capacity (Ah)}}{\text{discharge current (A)}}$$

$$= \frac{20}{2} = 10\text{ h}$$

In addition to the ampere-hour rating, the manufacture specifies the maximum discharge current. If this current is exceeded, the ampere-hour rating of the accumulator is reduced. For example, in the example shown the capacity of the battery may be reduced to, say, 10 Ah if the maximum current is stated as 2 A and the current drawn is 4 A.

The charge-discharge ampere-hour efficiency of the battery must also be taken into account when determining the charge given to a battery as follows:

$$\text{ampere-hour charge} = \frac{\text{ampere-hour discharge}}{\text{efficiency}}$$

For a lead-acid battery whose capacity is 20 Ah and whose charge-discharge efficiency is 75 per cent, the amount of charge needed, in ampere-hours is

$$20 \div \frac{75}{100} = 20 \times \frac{100}{75} = 26.7 \text{ Ah}$$

2.14 THERMOELECTRICITY

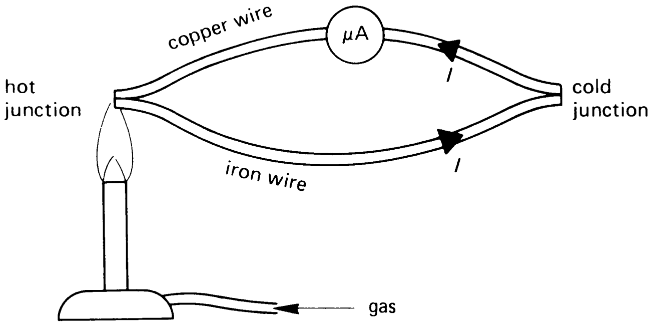
There are a number of ways in which thermal effects can directly produce electricity and we shall consider two of them.

The Seebeck effect - the thermocouple

When two different metals are brought into contact with one another, it is found that electrons can leave one of the metals more easily than they can leave the other metal. This is because of the difference in what is known as the **work function** of the two metals. Since electrons leave one metal and are gained by the other, a potential difference exists between the two metals; this e.m.f. is known as the **contact potential** or **contact e.m.f.**

If two metals, say copper and iron, are joined at two points as shown in Figure 2.7, and both junctions are at the same temperature, the contact potentials cancel each other out and no current flows in the loop

fig 2.7 *the Seebeck effect*



of wire. However, Thomas Johann Seebeck (1770–1831) discovered that if the two junctions are kept at different temperatures, there is a drift of electrons around the circuit, that is to say, current flows.

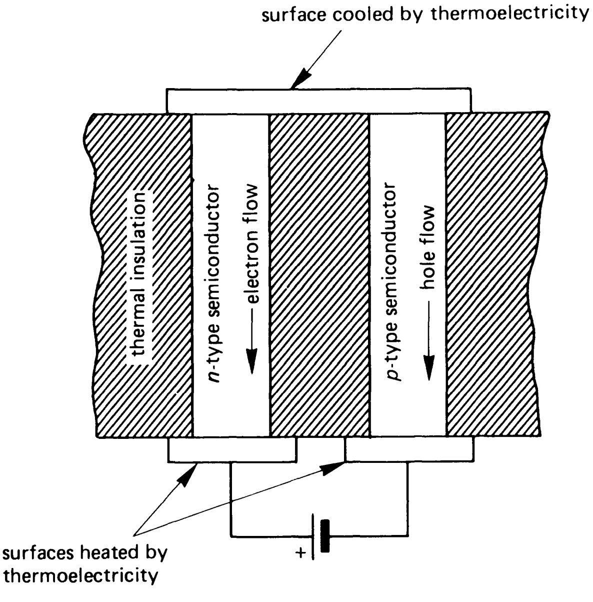
The magnitude of the voltage produced by this method is small - only a few millivolts per centigrade degree - but it is sufficient to be able to measure it. The current flow is a measure of the temperature of the 'hot' junction (the 'cold' junction meanwhile being maintained at a low temperature - often 0 °C). Each junction is known as a **thermocouple**, and if a number of thermocouples are connected in series so that alternate junctions are 'hot' and the other junctions are 'cold', the total e.m.f. is increased; this arrangement is known as a **thermopile**.

The Peltier effect

This was discovered by Pierre Joseph Peltier (1788–1842), who showed that when an electric current flows across the junction of two different substances, heat is either absorbed or liberated at the junction. The 'direction' of heat flow is the same as the flow of the 'majority' charge carriers in the material; these charge carriers may be either electrons or holes (depending on the material).

The basis of one such device is shown in Figure 2.8. It comprises two surfaces connected in one case by an *n*-type semiconductor and in another

fig 2.8 *the basis of a thermoelectric heat-transfer device*



case by a *p*-type semiconductor. In the *n*-type material, the 'majority' charge carriers are electrons, and in the *p*-type material they are holes.

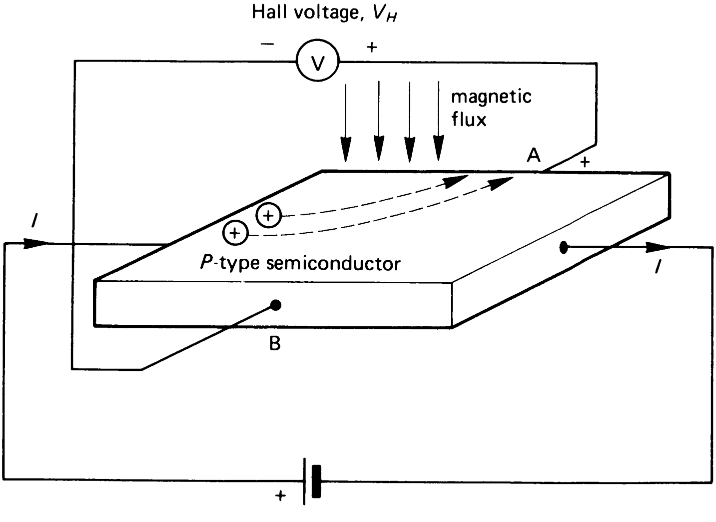
When current flows in the circuit, the current in the *n*-type semiconductor is largely electron flow (towards the positive pole of the battery), so that heat is transferred from the upper surface to the lower surface via the *n*-type material. At the same time, the current in the *p*-type semiconductor is largely hole flow (towards the negative pole of the battery), so that heat is once more transferred from the upper surface to the lower surface by the *p*-type material. In this way, the flow of electricity cools the upper surface while heating the lower surfaces.

2.15 THE HALL EFFECT

When experimenting in 1879 with current flowing in a strip of metal, E. M. Hall discovered that some of the charge carriers were deflected to one of the faces of the conductor when a strong magnetic field was applied. This gave rise to an e.m.f. (the **Hall voltage**) between opposite faces of the conductor. The e.m.f. is only a few microvolts in the case of a metal conductor, but is much larger when the current flows in a semiconductor.

The general principle is illustrated in Figure 2.9. As mentioned earlier, current flow in a *p*-type semiconductor is largely due to the movement of holes or mobile positive charge carriers. When a magnetic flux passes through the semiconductor in the direction shown in Figure 2.9, the holes

fig 2.9 *Hall effect in a* p*-type semiconductor*



experience a force which deflects them towards face A of the semiconductor (the reader should refer to Fleming's Left-Hand Rule in Chapter 9 for details on how to determine the direction of the force). This gives rise to the Hall voltage, V_H, which makes face A positive with respect to face B.

If the current flow through the semiconductor is maintained at a constant value, the *Hall voltage is proportional to the magnetic flux density passing through the semiconductor.*

One application of the Hall effect is the measurement of magnetic fields; instruments used for this purpose are known as **magnetometers.** Another application is to **contactless keys** on a computer keyboard (or any keyboard for that matter); the semiconductor element is fixed to the frame of the keyboard and the magnet is mounted in the movable keypad. When the key is pressed, the magnet is moved down to the semiconductor, the resulting Hall voltage being amplified and transmitted to the computer.

2.16 THE PIEZOELECTRIC EFFECT

Certain crystals and semiconductors produce an e.m.f. between two opposite faces when the mechanical pressure on them is either increased or reduced (the polarity of the e.m.f. is reversed when the pressure changes from an increase to a decrease). This e.m.f. is known as the **piezoelectric e.m.f.**

This effect is used in a number of devices including **semiconductor strain gauges** and **crystal pick-ups** for gramophones. As the mechanical pressure on the crystal is altered, a varying voltage which is related to the pressure is produced by the crystal. The voltage can be as small as a fraction of a volt or as large as several thousand volts depending on the crystal material and on the pressure. A very high voltage is produced by the material lead zirconate titanate, which is used in ignition systems for gas ovens and gas fires.

The piezoelectric effect is reversible, and if an alternating voltage is applied between two opposite faces of the crystal, it vibrates in a direction at right-angles to the applied electric field. If the correct frequency of voltage is applied, the crystal **resonates** in sympathy with the alternating voltage. This is the principle of **crystal-controlled** watches which keep an accurate time to within a few seconds a year.

2.17 THE PHOTOVOLTAIC CELL OR SOLAR CELL

A **photovoltaic cell** generates an e.m.f. when light falls onto it. Several forms of photovoltaic cell exist, one of the earliest types being the selenium photovoltaic cell in which a layer of selenium is deposited on iron, and any light falling on the selenium produces an e.m.f. between the selenium and the iron.

Modern theory shows that the junction at the interface between the two forms what is known as a semiconductor *p–n* junction in which one of the materials is *p*-type and the other is *n*-type. The most efficient photovoltaic cells incorporate semiconductor *p–n* junctions in which one of the regions is a very thin layer (about 1 μm thick) through which light can pass without significant loss of energy. When the light reaches the junction of the two regions it causes electrons and holes to be released, to give the electrovoltaic potential between the two regions.

Applications of the photovoltaic cell or solar cell include camera exposure-meters, electricity supply to batteryless calculators and to satellites.

SELF-TEST QUESTIONS

1. What is meant by the electrochemical effect? Write down a list of applications of this effect.
2. Explain what is meant by a 'positive ion' and a 'negative ion', and give an example showing where they occur in electrolysis.
3. State Faraday's Laws of electrolysis. Explain how the laws are used to calculate the mass of material deposited in an electrochemical process.
4. Explain the difference (i) between a 'cell' and a 'battery', (ii) between a primary cell and a secondary cell.
5. A battery has a no-load terminal voltage of 12 V. When a current of 20 A is drawn from the battery, the terminal voltage falls to 10 V. Determine the internal resistance of the battery.
6. Describe the operation of (i) one type of dry cell and (ii) one type of storage battery.
7. Explain what is meant by (i) the Seebeck effect, (ii) the Peltier effect, (iii) the Hall effect, (iv) the piezoelectric effect and (v) the photovoltaic effect.

SUMMARY OF IMPORTANT FACTS

Pure liquids are good insulators, but liquids **containing salts** conduct electricity.

An **ion** is an atom which has either *lost an electron* (a **positive ion**) or has *gained an electron* (a **negative ion**).

Electrolysis is the process of decomposing an electrolyte by the passage of electric current through it; this results in chemical action at the **electrodes**, that is, the **anode** and the **cathode**. Electrolysis is the basis not only of many forms of chemical **extraction** and **refining** but also of the **electroplating** industry.

A **catalyst** is a material which, when present in association with certain other materials, causes a chemical action to occur but is not itself affected.

The laws which govern electrolysis are described by **Faraday's laws.**

An electrical **cell** consists of two sets of **plates** immersed in an **electrolyte**. Cells can be either **dry** or **wet**. A **primary cell** cannot be recharged, but a **secondary cell** can be recharged. A **battery** is an interconnected group of cells. All cells have an **internal resistance** whose value is reduced by the use of a **depolariser**.

Electricity can be produced by a number of different methods including **chemical action**, **thermoelectricity**, the **Hall effect**, the **piezoelectric effect** and the **photovoltaic effect**.

CHAPTER 3

RESISTORS AND ELECTRICAL CIRCUITS

3.1 RESISTOR TYPES

A resistor is an element whose primary function is to limit the flow of electrical current in a circuit. A resistor is manufactured either in the form of a **fixed resistor** or a **variable resistor**, the resistance of the latter being alterable either manually or electrically. Many methods are employed for the construction of both fixed and variable resistors, the more important types being described in this chapter.

3.2 FIXED RESISTORS

Carbon composition resistors or carbon resistors

The resistive element of this type is manufactured from a mixture of finely ground carbon compound and a non-conducting material such as a ceramic powder. The material is moulded into the required shape (cylindrical in Figure 3.1) and each end is sprayed with metal to which a wire is connected (alternatively, metal end-caps are pressed onto the resistor).

fig 3.1 *a carbon composition resistor*

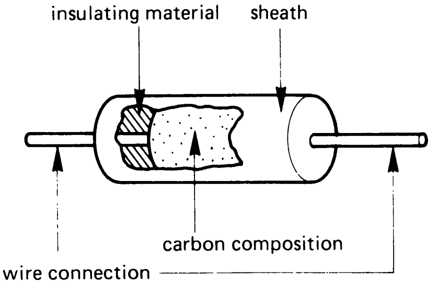
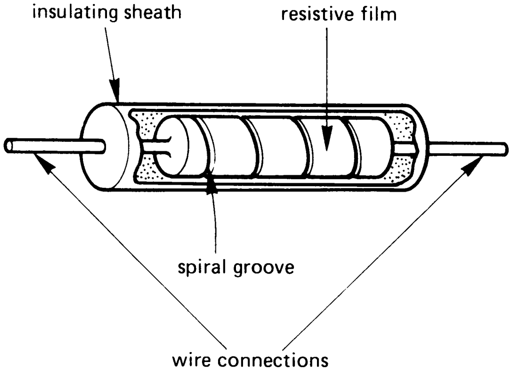


fig 3.2 *a film resistor*



Film resistors

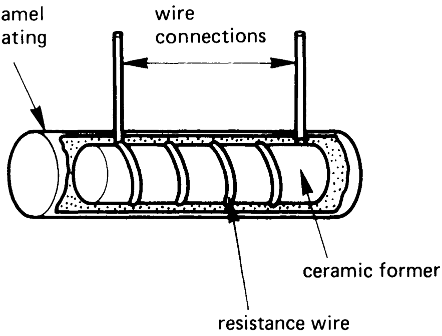
The resistive element is a thin film of resistive material which is deposited on an insulating ‘former (see Figure 3.2). The resistance of the resistor is increased to the desired value at the manufacturing stage by cutting a helical groove in the film (thereby increasing the length of the resistive path). There are three popular types of film resistor, namely *carbon film* (or *cracked carbon resistors*), *metal oxide film resistors* and *metal film resistors.*

A *carbon film resistor* is formed by depositing a thin film of carbon on an insulating rod. This type of resistor is subject to damage by atmospheric pollution, and is protected by several layers of lacquer or plastic film. *Metal oxide film resistors* (also known as *oxide film resistors*) comprise a tin-oxide film deposited on a ceramic former; this type of resistor can be run at a higher temperature than can a carbon film resistor. A *metal film resistor* is formed by evaporating a nickel–chromium alloy onto a ceramic substrate.

A form of resistor known as a *thick film resistor* or *cermet resistor* is manufacturted by depositing a ‘thick’ film (about 100 times thicker than on a carbon film resistor) of a mixture of a ***cer***amic and ***met***al (which is abbreviated to **cermet**) on to a ceramic foundation or substrate. Yet another type of resistor known as a *thin film resistor* is produced by evaporating a thin film of either nickel-chromium or nickel–cobalt onto an insulating substrate; alternatively, the thin film may be of tantalum doped with aluminium.

Wirewound resistors

This type is produced by winding a ceramic former with wire made from an alloy of nickel and cobalt, as shown in Figure 3.3. These materials have fig 3.3 *a wirewound resistor*



good long-term stability, and their resistance is reasonably constant despite temperature variation.

3.3 PREFERRED VALUES OF RESISTANCE FOR FIXED RESISTORS

The accuracy to which a resistor is manufactured is, to some extent, related to the cost of the resistor; the greater the accuracy, the greater the cost. Within the limits of manufacturing cost, every resistor is produced to within a certain percentage tolerance; typical tolerances are 5 per cent, 10 per cent and 20 per cent. Thus a nominal 10 Ω resistor with a 5 per cent tolerance will have a value in the range 9.5–10.5 Ω; if the tolerance was 20 per cent, its value would lie in the range 8.0–12.0 Ω.

The international range of 'nominal' preferred values of resistance used in electrical and electronic engineering is given in Table 3.1. The values are selected so that, within each tolerance range, the resistance of a resistor at its lower tolerance limit is approximately equal to the value of the resistance of the next lower resistor at its upper tolerance limit. Similarly, its resistance at its upper tolerance limit is approximately equal to the value of the next higher resistance at its lower tolerance limit.

Table 3.1 uses a starting value of 10 Ω, but it could equally well be, say, 0.1 Ω, or 1.0 Ω, or 1.0 kΩ or 1.0 MΩ, etc.

3.4 RESISTANCE COLOUR CODE

The value of the resistance of many resistors (but not wirewound types) used in low-power electrical circuits is indicated on the resistor itself by means of a **colour band** coding. This is an international coding, and is given in Table 3.2, and illustrated in Figure 3.4.

Table 3.1 *Preferred values of resistors*

	Percentage tolerance		
	5	*10*	*20*
Preferred resistance value	10	10	10
	11		
	12	12	
	13		
	15	15	15
	16		
	18	18	
	20		
	22	22	22
	24		
	27	27	
	30		
	33	33	33
	36		
	39	39	
	43		
	47	47	47
	51		
	56	56	
	62		
	68	68	68
	75		
	82	82	
	91		

fig 3.4 *resistor colour-band coding*

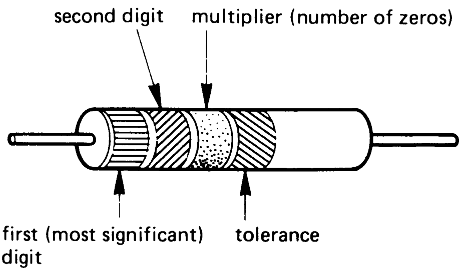


Table 3.2 *Resistance colour code*

Colour	*Value of first and second digits*	*Multiplier*	*Number of zeros to left of decimal point*	*Tolerance (per cent)*
No tolerance band				20
Silver		0.01		10
Gold		0.10		5
Black	0	1.00		
Brown	1	10.00	1	1
Red	2	10^2	2	2
Orange	3	10^3	3	3
Yellow	4	10^4	4	4
Green	5	10^5	5	
Blue	6	10^6	6	
Violet	7	10^7	7	
Grey	8	10^8	8	
White	9	10^9	9	

The reader will find the following mnemonic useful as an aid to remembering the colour sequence. It is based on the old British Great Western Railway Company, the first letter in each word in the mnemonic is the first letter of the colour used to identify the value of the first and second digits of the resistor value.

Bye Bye Rosie, Off You Go, Bristol Via Great Western

corresponding to the colours

Black Brown Red Orange Yellow Green Blue Violet Grey White

The use of the colour code is illustrated in the example given in Table 3.3. This resistor is a 4700 Ω resistor with a tolerance of 10 per cent in other words, its value lies in the range 4230 Ω-5170 Ω.

Table 3.3 *Example of colour coding*

Band	*Colour*	*Comment*
First	Yellow	Most significant digit = 4
Second	Violet	Least significant digit = 7
Third	Red	Multiplier = 2 (two zeros)
Fourth	Silver	Tolerance = 10 per cent

3.5 VARIABLE RESISTORS, RHEOSTATS AND POTENTIOMETERS

A **variable resistor** or **rheostat** is a resistor whose value can be varied (see Figure 3.5(a)); it is sometimes connected in the form of a **potentiometer** (abbreviated to '**pot**') - see Figure 3.5(b) - which can be used as a *voltage divider*.

A variable resistor consists of a resistive element which either has several tapping points on it or has a sliding contact (known as the **slider** or **wiper**). The unused connection can either be left unconnected or it may be connected to the tapping point or wiper (see Figure 3.5(a)). When used as a potentiometer, it is used to supply an electrical load with voltage V_2, the output voltage being given by the equation

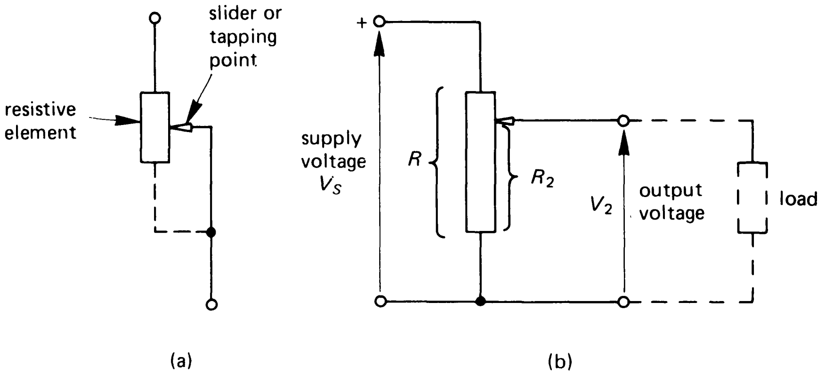
$$V_2 = \frac{R_2 V_S}{R} \text{ volts (V)}$$

where V_S is the supply voltage.

In a **linear potentiometer**, the resistance between the wiper and the 'bottom' end of the pot increases in a linear or 'straight line' manner as the slider is moved along the resistive element. Thus, doubling the movement of the slider, doubles the resistance between the slider and the bottom end of the pot.

Many potentiometers used in electronic circuits have a resistance whose value varies in a *logarithmic* ratio with the movement of the slider (typical applications of this type include volume controls on radios and TVs). Such potentiometers are known as **logarithmic potentiometers** or **log pots**. This type of pot allows the response of the human ear to be matched to the electronic equipment.

fig 3.5 *(a) variable resistor, (b) a resistive potentiometer*



The name used to describe variable resistors is related to the track shape, the most popular types being

(a) rectilinear
(b) arc
(c) helical or multi-turn.

A **rectilinear variable resistor** has a slider which can be moved in a straight line along the resistor (see Figure 3.6(a). A **single-turn** or **arc shaped variable resistor** has its resistive element in the form of an arc (see Figure 3.6(b)), the arc angle being on the range 300° to 330°. A few highly specialised potentiometers provide 360° rotation for such purposes as trigonometric function generators. A **helical track** or **multi-turn potentiometer** (see Figure 3.6(c)) has its resistive element in the form of a multi-turn helix. A ten-turn helical track potentiometer gives an equivalent angular rotation of 3600°.

Types of resistive element used in fixed and variable resistors

The main types in use are

(a) wirewound
(b) carbon
(c) cermet
(d) conductive plastic

Types (a), (b) and (c) have been described earlier in connection with fixed resistors. A *conductive plastic* resistive track consists of carbon particles distributed throughout a thermosetting resin; the resulting track provides a life expectancy which exceeds that of all other types. Unfortunately, the contact resistance between the slider and the track is fairly high, and this limits the output current which can be taken from the slider.

3.6 RESISTANCE OF A CONDUCTOR

The resistance of an electrical circuit depends on several factors, including the dimensions of the conductor, that is, its length and its cross-sectional area.

Consider for a moment a conductor having a length l and area a whose resistance is R ohms (see Figure 3.7(a)). If two such conductors are connected in series with one another (see Figure 3.7(b)) to give an effective length of $2l$ then, in order to force the same value of current, I, through the circuit, double the potential drop is required across the two series-connected conductors. That is to say, **doubling the length of the con-**

fig 3.6 *(a) a rectilinear variable resistor, (b) resistor element in the form of an arc, (c) a helical variable resistor*

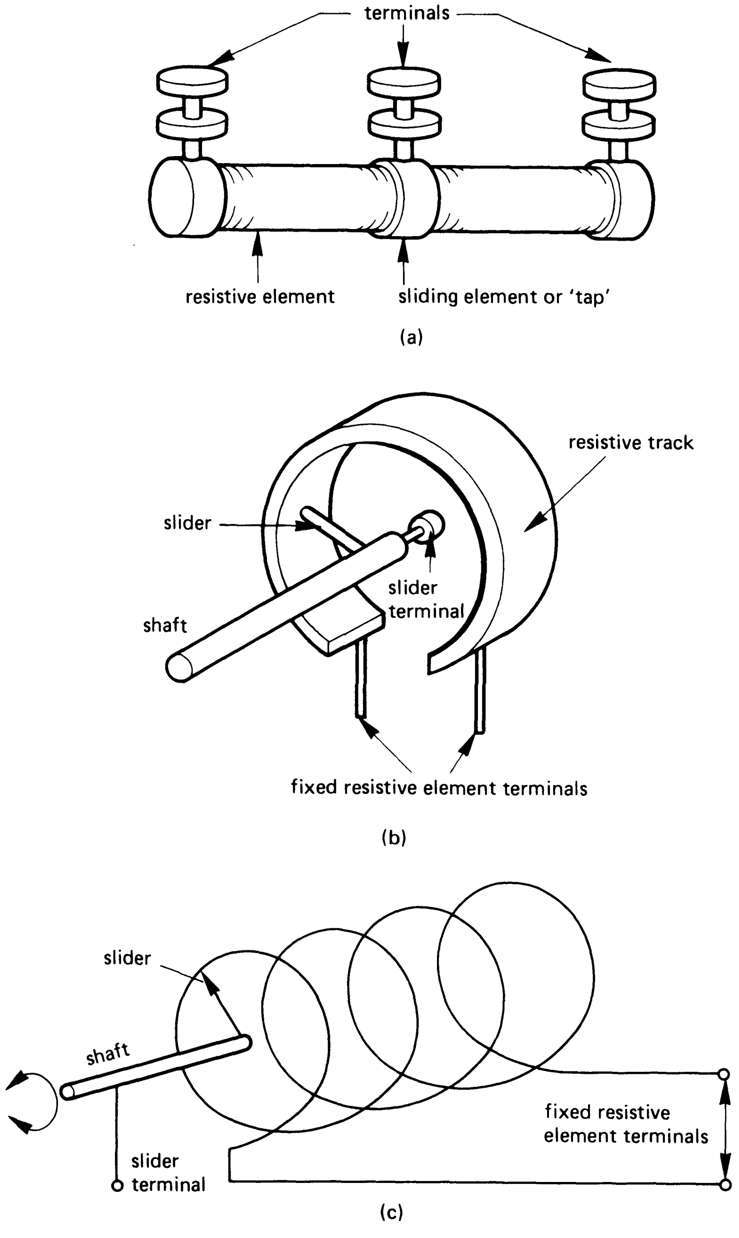
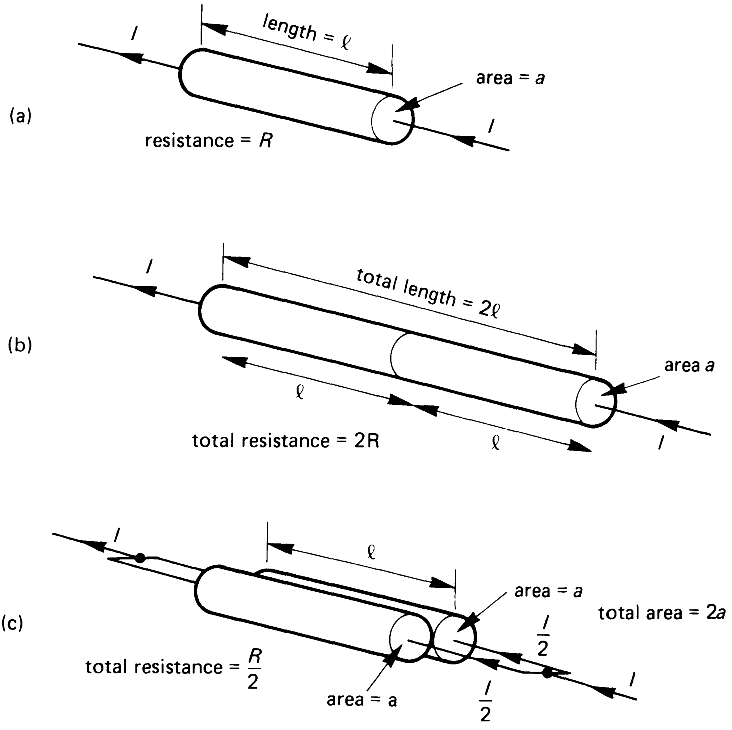


fig 3.7 *(a) original conductor having resistance R; effect of (b) an increase in length; and (c) an increase in area of the resistance of a conductor*



ductor has doubled its resistance. Hence, **the resistance is proportional to the lenngth of the conductor**, or

resistance α length of the conductor

or

$$R \alpha l \qquad (3.1)$$

If the two identical conductors of resistance R are connected in parallel with one another as shown in Figure 3.7(c), each conductor carries one-half of the total current, that is, $\frac{I}{2}$. Since this current flows through a resistor of resistance R, the p.d. across each conductor is therefore one-half that across the conductor in diagram (a) [which carries current I]. Since the total current carried by the parallel combination is I, and the p.d. across the combination is reduced to one-half the value across the conductor in diagram (a), the resistance of the parallel combination in Figure 3.7(c) is one-half that of the conductor in diagram (a). This arises because *the total area of the conducting path has doubled*; that is, **the resistance is inversely proportional to the area, *a*, of the conductor**, or

$$\text{resistance} \propto \frac{1}{\text{area}}$$

or

$$R \propto \frac{1}{a} \tag{3.2}$$

Combining eqns (3.1) and (3.2) gives

$$R \propto \frac{l}{a} \tag{3.3}$$

The proportionality sign in eqn (3.3) is converted into an equals sign simply by inserting a 'constant of proportionality' into the equation. This constant is known as the **resistivity** of the conductor material; resistivity is given the Greek symbol ρ (pronounced rho). Hence

$$R = \frac{\rho l}{a}\ \Omega \tag{3.4}$$

The dimensions of resistivity are worked out below. From eqn (3.4)

$$\rho = \frac{Ra}{l}$$

hence

$$\begin{aligned}\text{dimensions of } \rho &= \text{dimensions of } \frac{Ra}{l}\\ &= \frac{\text{no. of ohms} \times \text{area}}{\text{length}}\\ &= \frac{\text{no. of ohms} \times [\text{length} \times \text{length}]}{\text{length}}\\ &= \text{no. of ohms} \times \text{length or ohm metres } (\Omega\ \text{m})\end{aligned}$$

Typical values for the resistivity of materials used in electrical engineering are given in Table 3.4. The materials manganin and constantan have high resistivity combined with a low temperature coefficient of resistance (see section 3.8), and are widely used in ammeter shunts and in voltmeter multiplier resistors (see also Chapter 4). Nichrome has a very high resistivity and is used as a conductor in heating elements in fires and ovens, and operates satisfactorily at temperatures up to 1100 °C. The reader should

Table 3.4 *Resistivity of metals at 0 °C*

Material	*Resistivity (Ω m)*
Silver	1.47×10^{-8}
Copper	1.55×10^{-8}
Aluminium	2.5×10^{-8}
Zinc	5.5×10^{-8}
Nickel	6.2×10^{-8}
Iron	8.9×10^{-8}
Manganin	41.5×10^{-8}
Constantan	49.0×10^{-8}
Nichrome	108.3×10^{-8}

note that the resistivities listed in Table 3.4 may vary with temperature. For example, the resistivity of copper increases to 1.73×10^{-8} Ωm at 20 °C, but the resistivity of constantan remains unchanged when the temperature changes from 0° to 20 °C.

Insulators have much higher values of resistivity, typical values in Ωm being

Glass	10^{9}-10^{12}
Mica and mineral oil	10^{11}-10^{15}
Plastic	10^{7}-10^{9}
Wood	10^{8}-10^{11}
Water (distilled)	10^{2}-10^{5}

Example

Determine the resistance of a 200 m length of copper wire of diameter 1 mm at a temperature of 20 °C. The resistivity of copper at this temperature is

1.73×10^{-8} Ωm.

Solution

$l = 200$ m, $\rho = 1.73 \times 10^{-8}$ Ωm, $d = 1$ mm $= 10^{-3}$ m

Note

When dealing with submultiples such as mm (and with multiples for that matter), the dimensions should be converted into the basic unit (the metre in this case) before using the value in any equation. This avoids a possible cause for error later in the calculation.

$$\text{Area of conductor} = \frac{\pi \times d^2}{4} = \frac{\pi \times (10^{-3})^2}{4}$$
$$= 0.785 \times 10^{-6}\ \text{m}^2$$

hence

$$\text{Resistance}, R = \frac{\rho l}{a}$$
$$= 1.73 \times 10^{-8} \times \frac{200}{0.785} \times 10^{-6}\ (\text{m})$$
$$= 4.41\ \Omega\ (\text{Ans.})$$

3.7 CONDUCTIVITY AND CONDUCTANCE

The **conductivity** of a material is the **reciprocal of its resistivity**. It is given the Greek symbol σ (sigma) and has the units siemens per metre (S/m). Thus, at 0 °C, copper has a conductivity of

$$\sigma = \frac{1}{\rho} = \frac{1}{1.55 \times 10^{-8}}$$
$$= 64.52 \times 10^{6}\ \text{S/m}$$

Also, the **conductance**, G, of a material is the **reciprocal of its resistance** and is

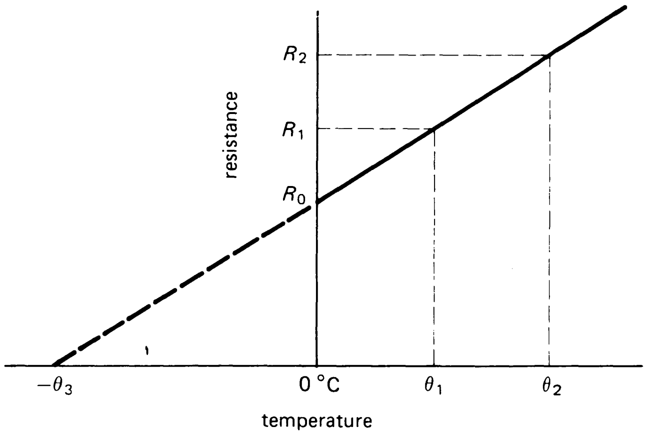
$$G = \frac{1}{R} = \frac{1}{\rho\, l/a} = \frac{1}{\rho} \times \frac{a}{l} = \sigma \times \frac{a}{l}$$

3.8 EFFECT OF TEMPERATURE CHANGE ON CONDUCTOR RESISTANCE

As the temperature of a conductor rises, the atomic nuclei gain energy and become 'excited'. When this happens, the current in the circuit (which can be regarded as electrons in motion) experience increasing difficulty in moving through the conductor. That is, **increase in temperature causes an increase in conductor resistance**. Conversely, *a reduction in temperature causes a decrease in the resistance of the conductor.* The change in resistance is proportional to the change in temperature over the normal operating range of temperature.

This effect is shown graphically in Figure 3.8; the resistance of the conductor represented by the graph at 0 °C is given the value R_0, at temperature θ_1 °C the resistance is R_1, at θ_2 °C it is R_2, etc.

fig 3.8 *change in the resistance of a conductor with change in temperature*



The change in resistance of the resistor as the temperature changes from, say, 0 °C to temperature θ_1, expressed as a fraction of its original resistance R_0 is called the **temperature coefficient of resistance** referred to the original temperature (0 °C in this case). This coefficient is given the Greek symbol α (alpha), where

$$\alpha_0 = \frac{R_1 - R_0}{(\theta_1 - 0)R_0} = \frac{R_1 - R_0}{\theta_1 R_0} \qquad (3.5)$$

Note: the value of α is given the value α_0 in the above equation since the original temperature was 0 °C.

The units of α can be determined from the above equation as follows:

$$\text{Units of } \alpha = \frac{\text{resistance}}{(\text{temperature} \times \text{resistance})}$$

$$= \frac{1}{\text{units of temperature}}$$

That is, α is expressed in 'per degree C' or $(^\circ\text{C})^{-1}$.
From eqn (3.5)

$$R_1 - R_0 = \alpha_0 \theta_1 R_0$$

or

$$R_1 = R_0 + \alpha_0 \theta_1 R_0 = R_0(1 + \alpha_0 \theta_1) \qquad (3.6)$$

In general, eqn (3.6) can be rewritten in the form

$$R_T = R_0(1 + \alpha_0 \theta) \qquad (3.7)$$

where

R_T = resistance of the resistor at θ °C

R_0 = resistance of the resistor at 0 °C

θ = temperature change in °C

α_0 = resistance-temperature coefficient referred to 0 °C

The value of the temperature coefficient of resistance referred to 0 °C for a number of elements is listed in Table 3.5.

Table 3.5 *Temperature coefficient of resistance of some conductors (in 'per °C')*

Material	*Coefficient, α*
Aluminium	0.00435
Copper	0.00427
Iron	0.00626

Example

The resistance of a coil of copper wire at 20 °C is 25 Ω. What current will it draw from a 10-V supply when in a room at 0 °C? The temperature coefficient of resistance of the copper being 0.00427 per °C referred to 0 °C.

Solution

$R_T = 25\ \Omega,\ \theta_1 = 20\ °\mathrm{C},\ E = 10\ \mathrm{V},\ \alpha_0 = 0.00427\ (°\mathrm{C})^{-1}$

From eqn (3.7)

$$R_0 = \frac{R_T}{(1 + \alpha_0\theta)} = \frac{25}{(1 + [0.00427 \times 20])}$$

$$= 23.033\ \Omega$$

Hence

$$\text{current at } 0\ °\mathrm{C}, I_0 = \frac{E}{R_0} = \frac{10}{23.033}$$

$$= 0.434\ \mathrm{A}\ (\text{Ans.})$$

3.9 SUPERCONDUCTIVITY

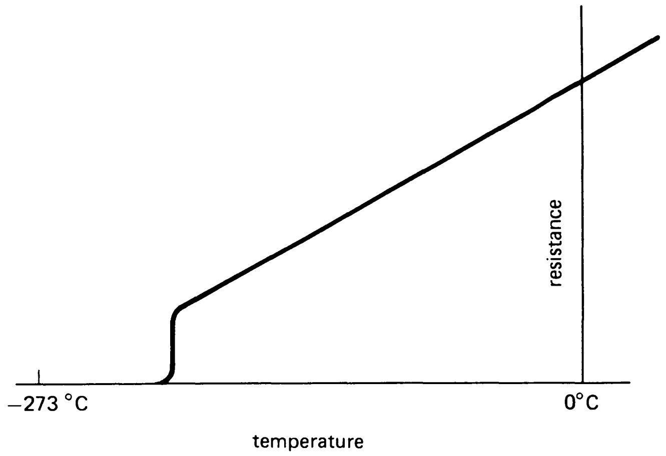
It is shown in Figure 3.8 that if the temperature of a conductor is progressively reduced, its resistance would reach zero at some temperature $-\theta_3$. However, scientific tests have shown that, for a limited range of conductors, the resistance falls to a value which is too small to be measured at a temperature within 10° of absolute zero temperature (–273 °C) - see Figure 3.9. Included in these are tin (within 3.7° of absolute zero), mercury (within 4.1°) and lead (within 7.2°).

3.10 TEMPERATURE EFFECTS ON INSULATORS AND ON SEMICONDUCTORS

Insulators and semiconductors behave in a different way when the temperature increases, because their resistivity *decreases*. That is: **the resistance of an insulator and of a semiconductor decreases with temperature increase**, (their resistance-temperature coefficient is negative!). This feature can be used to advantage as the following example shows.

One example of this effect occurs in a **thermistor**, which is a THERMally sensitive resISTOR whose resistance alters with temperature; a **negative temperature coefficient (n.t.c.) thermistor** is one whose resistance reduces with increase in temperature. A thermistor is used in the cooling-water temperature-measuring circuit of a car or lorry; it is inserted in the cooling water and connected in series with the battery and temperature gauge. As the water temperature rises, the resistance of the n.t.c. thermistor falls and

fig 3.9 *superconductivity*

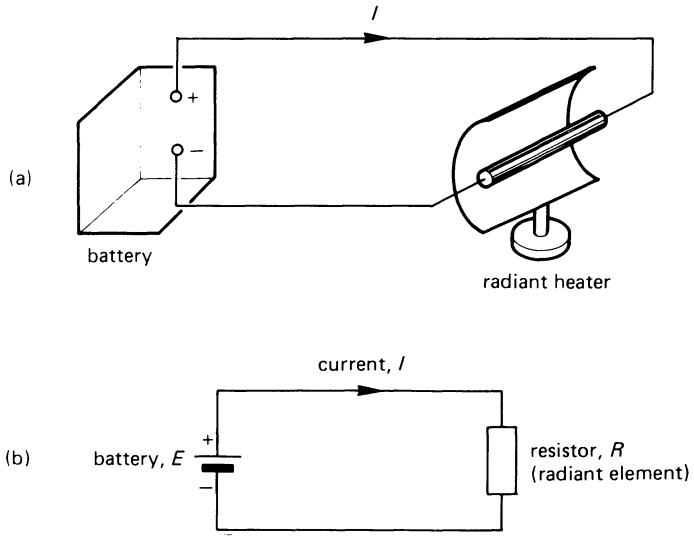


allows more current to flow through the temperature gauge; this causes the gauge to indicate variations in water temperature.

3.11 WHAT IS AN ELECTRICAL CIRCUIT?

The function of an electrical circuit, no matter how complex, is to provide a path for the flow of electrical current. In its simplest form, it consists of a battery which is connected via a pair of wires to a load (a heater in the example shown in Figure 3.10(a)). The **circuit diagram** in Figure 3.10(b) represents the physical circuit in diagram (a), the heating element being shown as a resistor (which is the rectangular symbol) in Figure 3.10(b). You will note that the **current**, I, flows *out of the positive pole* of the battery and *returns to the negative pole*; this notation is adopted in both electrical and electronic circuits.

fig 3.10 *a simple electrical circuit*



3.12 CIRCUIT ELEMENTS IN SERIES

Circuit elements are said to be connected in **series** *when they all carry the same current*, that is they are connected in the form of a daisy-chain (Xmas-tree lights are an example of this method of connection). Breaking the circuit at one point (equivalent to one bulb on the Xmas tree being removed) results in the current falling to zero.

The *series connection of three resistors* is shown in diagram (a) of Figure 3.11. Since the current must pass through each resistance in the circuit, the **effective resistance** or **total resistance,** R_S, of the series circuit is the sum of the individual resistors in the circuit. That is

$$R_S = R_1 + R_2 + R_3$$

In a series circuit, the total resistance is always greater than the largest individual resistor in the circuit

For Figure 3.11(a), the effective resistance is

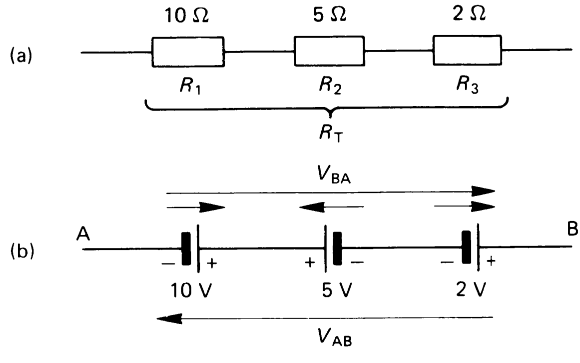
$$R_S = 10 + 5 + 2 = 17\ \Omega$$

In the general case where '*n*' resistors are connected in series with one another, the total resistance of the circuit is

$$R_S = R_1 + R_2 + R_3 + \ldots + R_n$$

When three *e.m.fs are connected in series* with one another (see Figure 3.11(b)), some care must be taken when determining both the magnitude and polarity of the resulting voltage. For example, to determine the potential of point B with respect to point A (which is written as V_{BA}), the procedure is as follows. First, it is necessary to indicate the polarity of each e.m.f. on the diagram *by means of a 'potential' arrow drawn by the side of each e.m.f.* The method adopted here is to draw an arrow *pointing towards the positive pole of the battery*, that is, pointing in the direction in which the e.m.f. would urge current to flow. Second, the starting at point A we *add together* the e.m.fs whose *potential arrows point in the direction in which we are moving*, that is, arrows pointing from A towards

fig 3.11 *series connection of (a) resistors, (b) e.m.fs*



B and we *subtract* the em.fs whose *potential arrows point in the opposite direction.* Thus

$$V_{BA} = +10 - 5 + 2 = 7\text{ V}$$

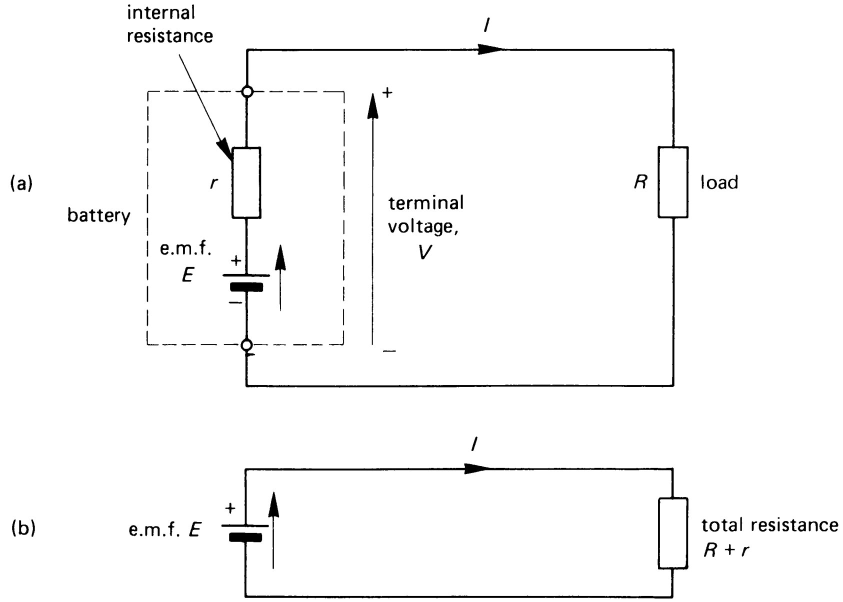
Some circuits may be complicated by the fact that the battery supplying the circuit may itself have some internal resistance (see also Chapter 2). This resistance may significantly affect the current in the circuit, and the following is one method of dealing with this problem.

Suppose that the battery in Figure 3.10(a) has some internal resistance; the circuit diagram is redrawn in Figure 3.12(a) to show the internal resistance r as an integral part of the battery. The circuit can be drawn as shown in Figure 3.12(b), which combines the load resistance with the internal resistance of the battery to give a total circuit resistance of $(R + r)$ ohms. The current in the circuit is calculated from the equation

$$I = \frac{\text{e.m.f. } (E)}{\text{total resistance } (R + r)}$$

Suppose that $R = 10\ \Omega$ and that either of two 10-V batteries may be connected to R. Calculate the current in both cases if the internal resistance of one battery is 5 Ω and of the other is 0.005 Ω.

fig 3.12 *a circuit which account for the internal resistance, r, of the battery*



(a) For r = 5 Ω

Total resistance = $R + r = 10 + 5 = 15\ \Omega$

$$\text{Current} = \frac{E}{(R+r)} = \frac{10}{15} = 0.667\ \text{A (Ans.)}$$

(b) For r = 0.005 Ω

Total resistance = $R + r = 10 + 0.005 = 10.005\ \Omega$

$$\text{Current} = \frac{E}{(R+r)} = \frac{10}{10.005} = 0.9995\ \text{A (Ans.)}$$

Clearly, a battery with a large internal resistance gives a low current. You will have experienced the case of, say, a car or torch battery which is 'flat'; its internal resistance is high and it can supply little energy to the connected load.

3.13 RESISTORS IN PARALLEL

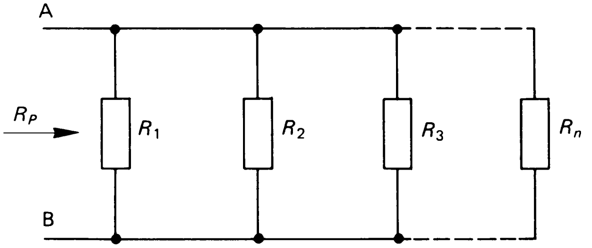
Resistors are said to be connected in **parallel** with one another *when they each have the same voltage across them.* Electric lights in a house are all connected in parallel to the mains electricity supply; when one lamp is switched off, it does not affect the supply voltage or current to the other lamps.

Figure 3.13 shows a number of resistors connected in parallel with one another between the points A and B. The **effective resistance**, R_P, is calculated from the equation

$$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots + \frac{1}{R_n}$$

If, for example the three resistors $R_1 = 10\ \Omega$, $R_2 = 5\ \Omega$ and $R_3 = 2\ \Omega$ are connected in parallel with one another, then

fig 3.13 *parallel-connected resistors*



$$\frac{1}{R_P} = \frac{1}{10} + \frac{1}{5} + \frac{1}{2} = 0.8$$

hence

$$R_P = \frac{1}{0.8} = 1.25\ \Omega$$

In a parallel circuit, the total resistance is always less than the smallest individual resistance in the circuit

In the *special case* of two resistors R_1 and R_2 connected in parallel, the effective value of the parallel circuit is given by

$$R_P = \frac{R_1 R_2}{R_1 + R_2}$$

Example

Calculate the effective resistance of a parallel circuit containing a 50-ohm and a 20-ohm resistor.

Solution

Given that $R_1 = 50\ \Omega, R_2 = 20\ \Omega$

$$R_P = \frac{(R_1 R_2)}{(R_1 + R_2)}$$

$$= \frac{(50 \times 20)}{(50 + 20)} = \frac{1000}{70} = 14.29\ \Omega \text{ (Ans.)}$$

Note: the value of R_P is less than either R_1 or R_2.

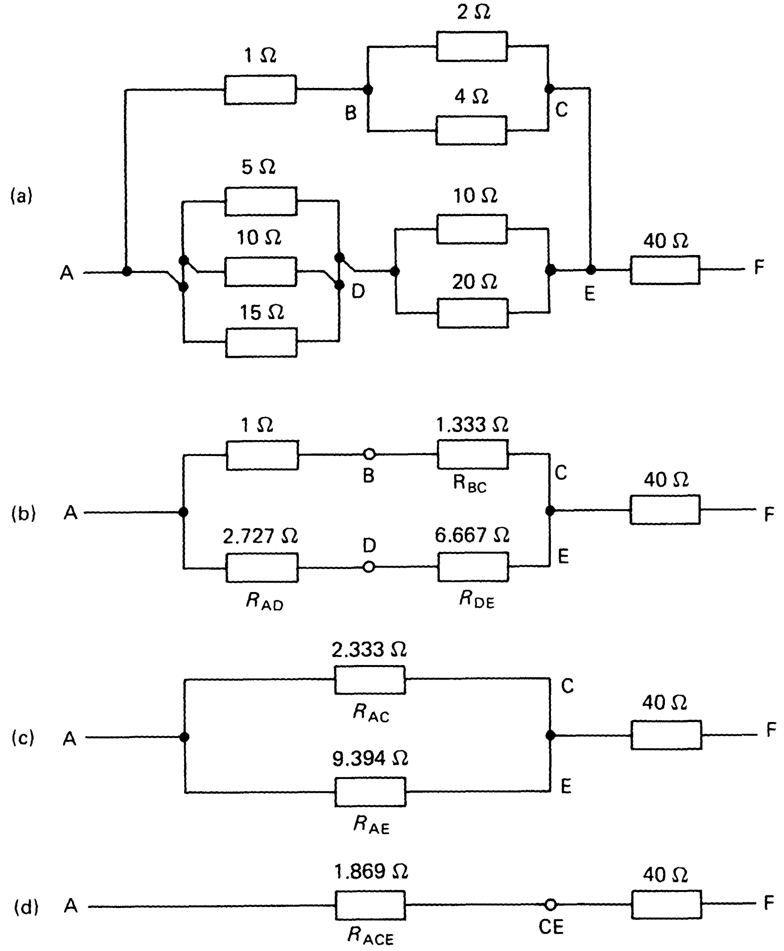
3.14 SERIES-PARALLEL CIRCUITS

Many practical circuits contain both series and parallel combinations of resistors. Each circuit must be treated on its merits, appropriate series and parallel groups being converted to their equivalent values before combining them with the remainder of the circuit. A typical problem is considered below.

Consider the series-parallel circuit in Figure 3.14(a). The 2 Ω and 4 Ω parallel-resistor combination between B and C can be replaced by a single equivalent resistor R_{BC} as follows

$$R_{BC} = \frac{(2 \times 4)}{(2 + 4)} = 1.333\ \Omega$$

fig 3.14 *a series-parallel circuit*



The three parallel-connected resistors in the bottom branch between A and D can be replaced by the single resistor R_{AD} calculated below

$$\frac{1}{R_{AD}} = \frac{1}{5} + \frac{1}{10} + \frac{1}{15} = 0.3667$$

hence

$$R_{AD} = \frac{1}{0.3667} = 2.727\ \Omega$$

The 10-Ω and 20-Ω parallel-connected resistors between the points D and E can be replaced by R_{DE} as follows

$$R_{DE} = \frac{(10 \times 20)}{(10 + 20)} = 6.667\ \Omega$$

The resulting diagram is shown in Figure 3.14(b). In Figure 3.14(c), the series-connected resistors between A and C are combined to form R_{AP} having the value $(1 + 1.333) = 2.333\ \Omega$, and the series-connected pair of resistors between A and E are replaced by R_{AE} having the value $(2.727 + 6.667) = 9.394\ \Omega$.

In Figure 3.14(d), the parallel combination of resistors R_{AC} and R_{AE} are replaced by an equivalent resistor R_{ACE} having the value

$$R_{ACE} = \frac{(2.333 \times 9.394)}{(2.333 + 9.394)} = 1.869\ \Omega$$

Finally, the resistance R_{AF} between points A and F is calculated as follows

$$R_{AF} = R_{ACE} + 40\ \Omega = 41.869\ \Omega$$

That is, a single 41.869-Ω resistor can be used to replace the circuit in Figure 3.14(a).

3.15 KIRCHHOFF'S LAWS

To determine the current flow in an electrical circuit, we need certain rules or laws which allow us to write down the circuit equations. Two laws laid down by Gustav Robert Kirchhoff, a German physicist, form the basis of all methods of electrical circuit solution.

First law

> *The total current flowing towards any junction of node in a circuit is equal to the total current flowing away from it.*

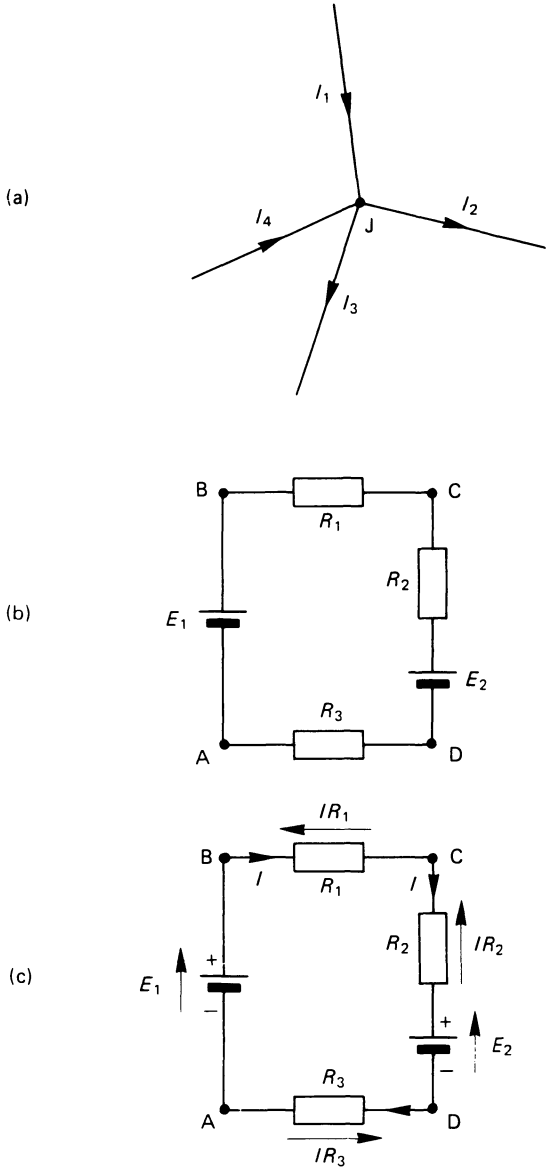
Second law

> *In any closed circuit or mesh, the algebraic sum of the potential drops and e.m.fs is zero.*

The *first law* is illustrated in Figure 3.15(a). The total current **flowing towards junction** J is $(I_1 + I_4)$, and the total current **flowing away from it** is $(I_2 + I_3)$. Hence, at junction J

$$I_1 + I_4 = I_2 + I_3$$

fig 3.15 *(a) Kirchhoff's first law and (b) Kirchhoff's second law*



The *second law* is illustrated in Figure 3.15(b) and (c). In the **closed loop** ABCDA (remember, you *must* always return to the point from which you start in a *closed* loop), there are two e.m.fs (produced by the cells) and three potential drops ('dropped' across the resistors). In order to write down the equation relating the e.m.fs and p.ds in Figure 3.15(b), it is necessary to add some information as shown in Figure 3.15(c); to do this the following steps must be taken:

1. Draw **on the circuit** the direction in which the current flows (if this is not known, simply *assume a direction of flow* [as will be seen later, the assumed direction is unimportant so far as the calculation is concerned]).
2. Draw an *e.m.f. arrow* by the side of each e.m.f. in the circuit which points towards the positive pole of the cell.
3. Draw a *potential drop arrow* by the side of each resistor which points towards the more positive terminal of the resistor (*Note*: the potential arrow *always* points in the opposite direction to the current flow through the resistor). At the same time, *write down the equation of the p.d. across the resistor*, that is, IR_1, IR_2, etc.

Having completed these steps (see Figure 3.15(c) and **starting at any point in the circuit**, proceed around the circuit and **return to the same point** writing down the e.m.fs and p.ds as they are reached. A *positive sign* is given to any e.m.f. or p.d. if the e.m.f. arrow or potential arrow points in the direction in which you move around the loop; a *negative sign* is given if the arrow points in the opposite direction. We will now apply these rules to Figure 3.15(b).

First, draw an arrow showing the direction of the current. Since you do not know the value of E_1 and E_2, the current is arbitrarily chosen to circulate around the loop in a clockwise direction. The direction in which the current is assumed to flow therefore 'fixes' the direction of the 'potential' arrows associated with the p.d. across each resistor.

In order to write down the circuit equation, we need to proceed around the closed loop ABCDA and write down each e.m.f. and p.d. according to the procedure outlined. We will traverse around the loop in a clockwise direction; starting at point A, the circuit equation is written down according to Kirchhoff's second law as follows.

Loop ABCDA

$$+E_1 - IR_1 - IR_2 - E_2 - IR_3 = 0$$

Collecting e.m.fs on the left-hand side of the equation gives

$$E_1 - E_2 = IR_1 + IR_2 + IR_3 = I(R_1 + R_2 + R_3)$$

You would find it an interesting exercise to write down the equation for the circuit starting at, say, point C and circulating around the loop in the opposite direction. The resulting equation should be the same as the one obtained above. (Since the circuit has not changed, the equation of the circuit should not change either!)

3.16 AN APPLICATION OF KIRCHHOFF'S LAWS

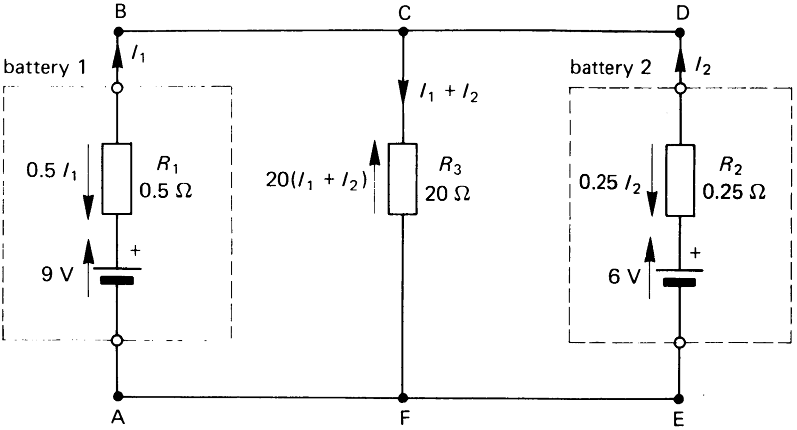
One form of procedure for applying Kirchhoff's laws, known as the **branch current method** is outlined below.

1. Assign a current to each branch of the circuit.
2. Apply Kirchhoff's first law to each junction in the circuit (take care to eliminate redundant currents! [see example below]).
3. Apply Kirchhoff's second law to each closed loop to give an equation for each loop (you need as many equations as you have unknown currents in step 2).
4. Solve the resulting equations for the unknown currents.

To illustrate this method, we will solve the electrical circuit in Figure 3.16. The circuit contains two batteries, battery 1 having an e.m.f. of 9 V and internal resistance 0.5 Ω, battery 2 having an e.m.f. of 6 V and internal resistance 0.25 Ω. The batteries are connected in parallel with one another, the two being connected to a 20-Ω load.

An inspection of the circuit shows that current flows in both batteries and in the load resistor. However, you will note that the current flowing in the load (the current from junction C to junction F) is the sum of the current from the two batteries (it is assumed for the moment that both batteries discharge into the load resistor). That is to say, there are only

fig 3.16 *solving an electrical circuit*



two unknown currents, namely I_1 and I_2 (the current in the 20-Ω resistor being equal to $I_1 + I_2$).

The circuit contains *three closed loops*, namely ABCFA, ABCDEFA and CDEFC. Any pair of loops can be used to give the equations we need, the first two being chosen in this case.

Loop ABCFA

The current directions selected are shown in Figure 4.16, and the e.m.f. and p.d. arrows are drawn according to the rules laid down earlier. Starting at point A and proceeding around the loop in the direction ABCFA, the loop equation is

$$9 - 0.5I_1 - 20(I_1 + I_2) = 0$$

or

$$9 = 20I_1 + 0.5I_1 + 20I_2$$

$$= 20.5I_1 + 20I_2 \qquad (3.8)$$

Loop ABCDEFA

Starting at point A and proceeding around the loop in a clockwise direction gives the equation

$$9 - 0.5I_1 + 0.25I_2 - 6 = 0$$

or

$$3 = 0.5I_1 - 0.25I_2 \qquad (3.9)$$

Equations (3.8) and (3.9) are collected together as follows

$$9 = 20.5I_1 + 20I_2 \qquad (3.8)$$

$$3 = 0.5I_1 - 0.25I_2 \qquad (3.9)$$

To eliminate I_2 from the pair of equations, eqn (3.9) is multiplied by 80 and added to eqn (3.8) as follows

$$9 = 20.5I_1 + 20I_2 \qquad (3.8)$$

$$240 = 40.0I_1 - 20I_2 \qquad 80 \times (3.9)$$

Adding these together gives

$$249 = 60.5I_1$$

hence

$$I_1 = \frac{249}{60.5} = 4.116\text{ A (Ans.)}$$

The value of I_2 is calculated by substituting the value of I_1 either into eqn (3.8) or eqn (3.9). We will use eqn (3.9) as follows:

$$3 = 0.5I_1 - 0.25I_2 = (0.5 \times 4.116) - 0.25I_2$$

$$= 2.058 - 0.25I_2$$

hence

$$0.25I_2 = 2.058 - 3 = -0.942$$

therefore

$$I_2 = \frac{-0.942}{0.25} = -3.768 \text{ (Ans.)}$$

The negative sign associated with I_2 merely implies that the current in battery 2 flows in the opposite direction to that shown in Figure 3.16. That is to say, battery 2 is 'charged' by battery 1!

The current in the 20-Ω load is calculated by applying Kirchhoff's first law to junction C (you could equally well use junction F for that matter). *You must be most careful always to use the value of I_2 calculated above*, that is, −3.768 A, *wherever I_2 appears in the circuit equations.*

$$\begin{aligned}\text{Current in the 20-ohm load} &= I_1 + I_2\\ &= 4.116 + (-3.768)\\ &= 0.348 \text{ A (Ans.)}\end{aligned}$$

The value of I_2 can be used to calculate the p.d. across the load as follows:

$$V_{CF} = 20(I_1 + I_2) = 20 \times 0.348 = 6.96 \text{ V (Ans.)}$$

SELF-TEST QUESTIONS

1. Describe the various types of fixed and variable resistors used in electrical engineering.
2. Why are 'preferred' values of fixed resistors used in low-power electrical circuits?
3. What is meant by the 'resistivity' of a material? Explain how the resistance of a conductor varies with its resistivity, length and cross-sectional area. Calculate the resistance in ohms of a 10-m length of copper at 20 °C whose diameter is 2 mm.
4. Calculate the conductance of the 10 m length of wire in question 3.3.
5. A heater coil has 500 turns of wire on it. The resistivity of the wire at its working temperature is 1.1 μΩm, and the coil is wound on a former of diameter 25 mm. Calculate the resistance of the wire at its working temperature if the cross-sectional area of the wire is 0.5 mm^2.

6. Three resistors of 10, 20 and 10 ohms, respectively, are connected (i) in series, (ii) in parallel. Determine the effective resistance of each combination. If the current drawn by each combination is 10 A, calculate (iii) the voltage across each combination and (iv) the power consumed in each case.
7. If, in Figure 3.16, $V_1 = 15$ V, $V_2 = 20$ V, $R_1 = 10\,\Omega$, $R_2 = 20\,\Omega$ and $R_3 = 30\,\Omega$, calculate the current in each of the resistors.

SUMMARY OF IMPORTANT FACTS

A **resistor** may either be fixed or varaible. A range of **fixed resistors** are manufactured including **carbon composition, film resistors** and **wirewound resistors.** 'Light current' and electronics industries use a range of **preferred values** for fixed resistors whose values are coded in a **colour code.**

Variable resistors may either have a sliding contact or may be 'tapped' at various points along their length; they may be connected as **potentiometers** to provide a variable output voltage. A variable resistor can either have a **linear** resistance change with movement of the slider, or it can be **non-linear**, that is, logarithmic. The resistor track shape can have any one of several forms including **rectilinear, arc** or **multi-turn.**

The **resistance** of a resistor depends on several factors including the **resistivity**, the **length**, the **cross-sectional area** and the **temperature** of the material. The **conductance** of a conductor is equal to the *reciprocal of the resistance.*

In the case of a **conductor,** an increase in temperature causes an increase in resistance, and vice versa. In an **insulator** and a **semiconductor**, an increase in temperature causes a decrease in resistance.

When resistors are **connected in series**, *the resistance of the circuit is greater than the highest individual value of resistance in the circuit.* When they are connected in **parallel**, *the resistance of the circuit is less than the lowest individual value of resistance in the circuit.*

Electrical circuits can be solved by using **Kirchhoff's laws.** The **first law** states that the total current flowing towards a junction in the circuit is equal to the total current flowing away from the junction. The **second law** states that in any closed circuit the algebraic sum of the e.m.fs and p.ds is zero.