Electronics Engineer's Reference Book

4th Edition

edited by

L.W. Turner

Butterworths

ELECTRONICS ENGINEER'S REFERENCE BOOK

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Edited by

L. W. TURNER

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With specialist contributors

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FOREWORD

by
Sir Harold Bishop, CBE, B.Sc. (Eng.), Hon.: F.I.E.E., F.I.Mech.E., F.I.E.E.E.
Past President, Institution of Electrical Engineers.

The appearance of the fourth edition of this Reference Book indicates not only the value of the previous editions but also the huge and continuing strides in the science and practice of electronic engineering. Whatever profession one may practice the difficulty of keeping up-to-date is so well recognised that it is hardly an exaggeration to say that a nagging concern is ever present in those whose academic studies are ten or more years behind them.

Many professions can boast of a history of maybe hundreds of years and in this period a state of knowledge has been built up by the labours of many practitioners. Not so in electronics. Twenty-five years ago the word was hardly in current use. Indeed the older electrical engineer in the power field and even some of those in telecommunications felt some resentment that this new term in electrical science should be given so much attention.

The astonishing developments from the late forties after the war to the present day have created a new and highly technical atmosphere which has made possible extensions of knowledge and application too numerous to mention but now taken for granted by the public at large. All of which, or at any rate those things which are wisely and humanely used, is of value to civilisation generally in improving our way of life.

But to the technological expert, be he engineer, scientist or teacher or a combination of all three, the ever-expanding state of knowledge as techniques become more complex, means inevitably that specialisation is intensified. The trap of over-specialisation is wide open and for the technologist who seeks broad professional leadership it is wise to avoid it. By the nature of any job this is inherently difficult and a conscious effort is needed to achieve a wide spectrum of learning and experience. This is particularly the case in middle life when the tendency is too often to continue to develop the expertise of early academic training.

And so we are led to the idea of professional retraining. To acquire this by a definite break in the money-making rhythm of middle life is exceedingly difficult and one looks for less drastic means. One way of proved value is by maintaining close contact with appropriate reference books and in the expanding electronics field the *Electronics Engineer's Reference Book* is an excellent example.

PREFACE

Since the earlier editions of this reference book were published, the first in 1958, the second in 1959 and the third in 1967, new techniques have emerged, many new electronic devices have been developed and the application of electronic equipment has rapidly extended over ever widening fields. This phenomenal rate of development, which continues, has been rightly described as startling even in a world which has become accustomed to a rapid rate of technological advancement.

In this situation no reference book can be complete or entirely up-to-date. The aim in publishing this fourth edition has been to present within the scope of a single volume of practical size as much as possible of the latest knowledge and techniques to provide a work of reference which will be of value to the electronics engineer and his fellows in other engineering disciplines wishing to assess effectively and quickly the potentialities of electronic solutions to their problems; and also to the scientist, the student, the educational profession, management personnel and the reader with a general interest in electronics and their applications.

This edition has been entirely rewritten. A bibliography has been included which gives reference to nationally and internationally recognised authoritative literature on the various subjects. The editor is indebted to the 61 writers for their contributions and for their ready cooperation in fitting their work into the format of the new edition. All are specialists in their own fields. Their qualifications and activities are given in the List of Contributors.

The arrangement of the Reference Book has been revised to give a more logical grouping and sequence of its 27 sections which broadly follow the general order of: basics, materials and components, devices, circuits, measurements and applications.

The application of electronics is now so vast, there being few areas in our everyday lives where electronic devices are not used in one form or another, such that it is impracticable in a single-volume reference book of this size to include them all. The main applications, including the very wide field of telecommunications embracing colour television and broadcasting generally, are however described in some detail in the last 13 sections, numbers 15 to 27.

As in the case of the companion volumes, the new editions of the *Civil Engineer's*, the *Electrical Engineer's* and the *Mechanical Engineer's Reference Books*, the Publishers have seized the opportunity provided by the complete revision of this fourth edition of the *Electronics Engineer's Reference Book* to issue the work in a new and modernised format giving a more pleasing and clear appearance making the text more easily assimilable and more direct in reference. The index has been simplified and made more easily usable.

L.W.T.

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The production of this reference book would have been impossible without the good will, help and cooperation of the electronics industry, the users of electronic equipment and members of the educational profession. Bare acknowledgements are very inadequate but the editor wishes to thank the following firms and organisations which so readily made available information and illustrations and permitted members of their specialist staffs to write contributions:

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L.W.T.

CONTENTS

12 MICROELECTRONICS

Techniques for Microelectronics — Thin-Film Circuits — Thick-Film Circuits — Hybrid Circuits — Microwave Integrated Circuits

13 BASIC ELECTRONIC CIRCUITS

Valve Amplifying Circuits — Bipolar-Transistor Amplifying Circuits — Field-Effect Transistor Amplifying Circuits — Wideband Amplifiers — Tuned Amplifiers — Detectors and Discriminators — Oscillators — Frequency Changers — Sawtooth Generators — Pulse Generators — Pulse-Shaping Circuits — Digital Techniques — Rectifiers and Power Supplies

14 ELECTRONIC INSTRUMENTATION AND MEASUREMENTS

Cathode-Ray Oscilloscopes — Vectorscopes — Angalogue Voltmeters — Digital Voltmeters — Thermocouples and Thermo-electric Effects — The Electron Microscope — Noise and Sound Measurement — Acoustic Measurements

15 TELECOMMUNICATIONS

Noise and Communication Theory — Modulation Theory and Systems — Broadcasting Frequency Bands and Propagation Characteristics — Broadcasting Transmitters — Sound Broadcasting — Black and White Television Broadcasting — Colour Television Systems —Television Standards Conversion — High Quality Sound Distribution for Television and Sound Broadcasting — Cable Television — Sound and Television Receivers — Communication Satellites — Optical Communication Using Lasers — Data Systems — Electronic Telephone Exchanges

16 SOUND AND VIDEO RECORDING

Sound Recording on Magnetic Tape — Videotape Recording — Television Film Recording

17 ELECTRONIC MUSIC

Electronic Organs — Radiophonic Sound and Music

18 RADAR SYSTEMS

Primary Radar — Secondary Surveillance Radar (SSR)

19 ELECTRONICS IN WEATHER FORECASTING

The Basic Data Set—Radiosondes — The Basic Data Set—Artificial Earth Satellites — Telecommunications — Computation Interpretation

20 RADIO ASTRONOMY

Early History — Radio-Telescopes — Radio Astronomy Receivers — Radar Astronomy — Solar System Radio Astronomy — Galactic Radio Astronomy — Extra-Galactic Radio Astronomy

21 ELECTRONICS IN SPACE EXPLORATION

Sounding Rocket Electronics — Near Earth Spacecraft — Deep Space Probes

22 ELECTRONIC AIDS IN EDUCATION

General — Types of Equipment

23 PUBLIC ADDRESS AND SOUND REINFORCEMENT SYSTEMS

Acoustic Feedback — 100 Volt Line Loudspeaker Distribution System — Codes of Practice and Recommendations for Sound Systems — Microphones — Loudspeakers — Controlled Time Delay Systems

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1 GENERAL INFORMATION

1 GENERAL INFORMATION

TERMINOLOGY

Electronics

Electronics may be defined as that branch of science and technology which deals with the study of the phenomena of *conduction* of electricity in a vacuum, in a gas, and in semiconductors, and with the utilisation of devices based on these phenomena. British Standard 204:1960–11029.

For other terminology and definitions in the field of electronics and associated subjects the reader is referred to the British Standards listed below.

BS 204:1960	*Glossary of terms used in telecommunication (including radio) and electronics.* Note: This standard is under progressive revision and is gradually being replaced by BS 4727 which is being issued in a number of separate parts.
BS 204:Supplement No. 1:1964	*Terms used in wired broadcast and broadcast relay.*
BS 204:Supplement No. 3:1966	*Colour television terms.*
BS 4727	*Glossary of electrotechnical, power, telecommunications, electronics, lighting and colour terms.*
Part 1	*Terms common to power, telecommunications and electronics.*
	Group 01:1971 Fundamental concepts.
	Group 02:1971 General technological terminology.
	Group 03:1971 Relay terminology.
	Group 04:1971 Measurement terminology.
	Group 05:1972 Semiconductor terminology.
	Group 06:1973 Electronic tube terminology.
Part 3	*Terms particular to telecommunications and electronics.*
	Group 01:1971 General telecommunication and electronics terminology.
	Group 02:1971 Telephony terminology.
	Group 03:1971 Telegraphy, including facsimile terminology.
	Group 04:1971 Broadcasting, radio and television terminology.
	Group 05:1971 Propagation and media terminology.
	Group 06:1971 Radio location and navigation terminology.
	Group 07:1971 Radiocommunication terminology.
Part 4	*Terms particular to lighting and colour.*
	Group 01:1971 Radiation and photometry.
	Group 02:1971 Vision and colour terminology.
	Group 03:1972 Lighting technology terminology.

Terminology for electronics reliability

Some terms recommended in the U.K. by the British Standards Institution (BSI) and internationally by the International Electrotechnical Commission (IEC) are given below. Full details are given in BS 4200 Part 2: 1967.

RELIABILITY

General definition The ability of an item to perform a required function under stated conditions for a stated period of time.
Note: The term reliability is also used as a reliability characteristic denoting a probability of success, or a success ratio.

Observed reliability—of non-repaired items For a stated period of time, the ratio of the number of items which performed their functions satisfactorily at the end of the period to the total number of items in the sample at the beginning of the period.

Observed reliability—of repaired item or items The ratio of the number of occasions on which an item or items performed their functions satisfactorily for a stated period of time to the total number of occasions the item or items were required to perform for the same period.

Assessed reliability The reliability of an item determined by a limiting value or values of the confidence interval associated with a stated confidence level, based on the same data as the observed reliability of nominally identical items.

Extrapolated reliability Extension by a defined extrapolation or interpolation of the observed or assessed reliability for durations and/or conditions different from those applying to the observed or assessed reliability.

Predicted reliability For the stated conditions of use, and taking into account the design of an item, the reliability computed from the observed, assessed or extrapolated reliabilities of its parts.

FAILURES

General definition The termination of the ability of an item to perform a required function.

Failure cause The circumstances during design, manufacture or use which have led to failure.

Failure mode The effect by which a failure is observed. For example, an open or shortcircuit condition, or a gain change.

Failure mechanism The physical, chemical or other process which results in failure.

Misuse failure Failure attributable to the application of stresses beyond the stated capabilities of the item.

Inherent weakness failure Failure attributable to weakness inherent in the item itself when subjected to stresses within the stated capabilities of the item.

Primary failure Failure of an item, not caused either directly or indirectly by the failure of another item.

Secondary failure Failure of an item, caused either directly or indirectly by the failure of another item.

Wear-out failure Failure whose probability of occurrence increases with the passage of time and which occurs as a result of processes which are the characteristic of the population.

Sudden failure Failure that *could not* be anticipated by prior examination or monitoring.

Gradual failure Failure that *could* be anticipated by prior examination or monitoring.

Partial failure Failure resulting from deviations in characteristic(s) beyond specified limits but *not such* as to cause complete lack of the required function.

Complete failure Failure resulting from deviations in characteristic(s) beyond specified limits *such* as to cause complete lack of the required function.

Intermittent failure Failure of an item for a limited period of time, following which the item recovers its ability to perform its required function without being subjected to any external corrective action.

Catastrophic failure Failure which is both sudden and complete.

Degradation failure Failure which is both gradual and partial.

Note: In time such a failure may develop into a complete failure.

Early failure period That possible early period, beginning at a stated time and during which the failure rate decreases rapidly in comparison with that of the subsequent period.

Constant failure rate period That possible period during which the failures occur at an approximately uniform rate.

Wear-out failure period That possible period during which the failure rate increases rapidly in comparison with the preceding period.

Observed failure rate For a stated period in the life of an item, the ratio of the total number of failures in a sample to the cumulative observed time on that sample. The observed failure rate is to be associated with particular, and stated time intervals (or summation of intervals) in the life of the items, and with stated conditions.

Observed mean life The mean value of the lengths of observed times to failure of all items in a sample under stated conditions.

Observed mean time to failure (MTTF) For a stated period in the life of an item, the ratio of the cumulative time for a sample to the total number of failures in the sample during the period, under stated conditions.

Observed mean time between failures (MTBF) For a stated period in the life of an item, the mean value of the length of time between consecutive failures, computed as the ratio of the cumulative observed time to the number of failures under stated conditions.

Terminology for computer systems

Peripheral equipment (or 'Peripherals') The various items of equipment which are connected to a computer to make up any particular system.

Central data processing system The assembly of equipment—including computers and peripherals—which form the electronic 'heart' of the complete scheme.

Computer store (or memory) A vital part of a computer used to retain (or remember) operating data and instructions during computation processes.

Disc file store One particular peripheral device used as an additional electronic memory for retaining data and operating instructions within the system.

Software A recognised name for computer programmes—the information having been prepared by 'programmers' and punched on to paper tape.

Tape reader The device to convert the information on the paper tape into electrical input signals to the computer.

Display 'back-up' The waveform generation and processing equipment connected between the display indicator units and the computer system.

'On-line' operation The mode of operation in which the computing system is directly connected to the plant or process which is to be controlled.

'Off-line' operation The mode of operation in which the computing system provides data to permit control or processing operations to be carried out but is *not* directly connected to the plant or process which is being controlled.

'Real-time' operation The mode of operation where the computing system is required to provide data to control and/or monitor events at the instant they occur.

Interface equipment Equipment interposed between two other equipments (or systems) to ensure compatibility of operation.

Terminology for integrated (micro-) circuits

Digital (integrated) circuit A circuit which operates with digital variables at the input(s) and output(s) and which is characterised by the inter-relationships between the states of the digital variables at the input and output terminals.

Note: The digital variable may be voltage, or current, or impedance, etc.

Binary (digital) circuit A digital circuit in which the digital variable at each input or output terminal may take one of only two states.

Note: The pairs of ranges of values of the digital variable may, however, be different at different terminals.

Combinatorial (digital) circuit A digital circuit in which for each possible combination of the states of the digital variable at the input(s), there is one, and only one, combination of the states of the digital variable at the output(s).

Sequential (digital) circuit A digital circuit in which there exists at least one combination of the states of the digital variable at the input(s) for which there is more than one corresponding combination of the states of the digital variables at the output(s).

Note: These combinations at the outputs are determined by the previous electrical history (including internal memory, delay, etc.).

Monostable (binary digital) circuit A sequential circuit which has one stable state and which requires an appropriate excitation to remain in another defined state during a determined time interval.

Note 1: This time interval may be independent of the duration of the excitation.

Note 2: The stable state has an unlimited duration when no excitation is applied.

Bistable (binary digital) circuit A sequential circuit which has two internal states both of which are stable and which requires an appropriate excitation when in either state to cause a transition to the other state.

Multistable (binary digital) circuit A sequential circuit which has more than two internal states each of which is stable and which requires an appropriate excitation when in any state to cause a transition to another state.

Delay (binary digital) circuit A sequential circuit for which the changes in the states of the digital variable at the output(s) are delayed for a determined time with regard to the respective changes in the states of the digital variable at the input(s).

Note: The delay may or may not be the same for changes of the digital variable to each state.

Gate A network having one or more inputs which opens or closes a channel according to the combination of stimuli applied to the input(s).

Positive—AND gate (Negative—OR gate) A binary digital gate whose output is in the High state if, and only if all its inputs are in the High state.

Positive—OR gate (Negative—AND gate) A binary digital gate whose output is in the Low state if, and only if all its inputs are in the Low state.

Positive—NAND gate (Negative—NOR gate) A binary digital gate whose output is in the Low state if, and only if all its inputs are in the High state.

Positive—NOR gate (Negative—NAND gate) A binary digital gate whose output is in the High state if, and only if all its inputs are in the Low state.

Analogue integrated circuit A circuit for which a continuous relationship (either linear or non-linear) exists between its input(s) and output(s).

Terminology for microelectronics

Microelectronics The concept of the construction and use of highly miniaturised electronic circuits.

Micro-circuit A micro-electronic device, having a high equivalent circuit-element and/or component density which is considered as a single unit.

Note: A micro-circuit may be a micro-assembly or an integrated (micro-) circuit.

Integrated (micro-) circuit A micro-circuit in which a number of circuit elements are inseparably associated and electrically interconnected such that for the purposes of specification and testing, commerce and maintenance, it is considered indivisible.

Note 1: For this definition, a circuit element does not include envelope or external connection and is not specified or sold as a separate item.

Note 2: Where no misunderstanding is possible, the term Integrated Micro-circuit may be abbreviated to Integrated Circuit.

Note 3: Further qualifying adjectives may be used to describe the technique used in the manufacture of a specific micro-circuit.

Examples of the use of qualifying adjectives:

Semiconductor monolithic integrated circuit
Semiconductor multi-chip integrated circuit
Thin film integrated circuit
Thick film integrated circuit
Hybrid integrated circuit.

Micro-assembly A micro-circuit in which the various components and/or integrated micro-circuits are constructed separately and can be tested before being assembled and packaged.

Note 1: For this definition it is assumed that a component has external connections and possibly an envelope as well and that it can also be specified and sold as a separate item.

Note 2: Further qualifying adjectives may be used to describe the form of the components and/or the assembly technique used in the construction of the specified micro-assembly.

Examples of the use of qualifying adjectives:

Semiconductor multi-chip micro-assembly
Discrete component micro-assembly.

UNITS

International unit system

The International System of Units (SI) is the modern form of the metric system agreed at an international conference in 1960. It has been adopted by the International Standards Organisation (ISO) and the International Electrotechnical Commission (IEC) and its use is recommended wherever the metric system is applied. It is now being adopted throughout most of the world and is likely to remain the primary world system of units of measurement for a very long time. The indications are that SI Units will supersede the units of existing metric systems and all systems based on Imperial Units.

SI Units and the rules for their application are contained in *ISO Resolution* R1000 (1969) and an informatory document *SI-Le Systeme International d'Unités*, published by the Bureau International des Poids et Mesures (BIPM). An abridged version of the former is given in British Standards Institution (BSI) publication PD 5686 *The use of SI Units* (1969) and BS 3763 *International System* (*SI*) *Units*; BSI (1964) incorporates information from the BIPM document.

The adoption of SI presents less of a problem to the electronics engineer and the electrical engineer than to those concerned with other engineering disciplines as all the practical electrical units were long ago incorporated in the metre-kilogram-second (MKS) unit system and these remain unaffected in SI.

The SI was developed from the metric system as a fully coherent set of units for science, technology and engineering. A coherent system has the property that corresponding equations between quantities and between numerical values have exactly the same form, because the relations between units do not involve numerical conversion factors. In constructing a coherent unit system, the starting point is the selection and definition of a minimum set of independent 'base' units. From these, 'derived' units are obtained by forming products or quotients in various combinations, again without numerical factors. Thus the base units of length (metre), time (second) and mass (kilogramme) yield the SI units of velocity (metre/second), force (kilogramme–metre/second-squared) and so on. As a result there is, for any given physical quantity, only one SI unit with no alternatives and with no numerical conversion factors. A single SI unit (joule = kilogramme metre-squared/second-squared) serves for energy of any kind, whether it be kinetic, potential, thermal, electrical, chemical . . ., thus unifying the usage in all branches of science and technology.

The SI has seven base units, and two supplementary units of angle. Certain important derived units have special names and can themselves be employed in combination to form alternative names for further derivations.

Each physical quantity has a quantity-symbol (e.g., *m* for mass) that represents it in equations, and a unit-symbol (e.g., kg for kilogramme) to indicate its SI unit of measure.

BASE UNITS

Definitions of the seven base units have been laid down in the following terms. The quantity-symbol is given in italics, the unit-symbol (and its abbreviation) in roman type.
Length: *l*; metre (m). The length equal to 1 650 763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels $2p_{10}$ and $5d_5$ of the krypton-86 atom.
Mass: *m*; kilogramme (kg). The mass of the international prototype kilogramme (a block of platinum preserved at the International Bureau of Weights and Measures at Sèvres).
Time: *t*; second (s). The duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium-133 atom.
Electric current: *i*; ampere (A). The current which, maintained in two straight parallel conductors of infinite length, of negligible circular cross-section and 1 m apart in vacuum, produces a force equal to 2×10^{-7} newton per metre of length.
Thermodynamic temperature: *T*; kelvin (K). The fraction 1/273.16 of the thermodynamic (absolute) temperature of the triple point of water.
Luminous intensity: *I*; candela (cd). The luminous intensity in the perpendicular direction of a surface of 1/600 000 m^2 of a black body at the temperature of freezing platinum under a pressure of 101 325 newtons per square metre.
Amount of substance: *Q*; mole (mol). The amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kg of carbon-12. The elementary entity must be specified and may be an atom, a molecule, an ion, an electron, etc., or a specified group of such entities.

SUPPLEMENTARY ANGULAR UNITS

Plane angle: α, β . . .; radian (rad). The plane angle between two radii of a circle which cut off on the circumference an arc of length equal to the radius.
Solid angle: Ω; steradian (sr). The solid angle which, having its vertex at the centre of a sphere, cuts off an area of the surface of the sphere equal to a square having sides equal to the radius.
Force: The base SI unit of electric current is in terms of force in newtons (N). A force of 1 N is that which endows unit mass (1 kg) with unit acceleration (1 m/s^2). The newton is thus not only a coherent unit; it is also devoid of any association with gravitational effects.

TEMPERATURE

The base SI unit of thermodynamic temperature is referred to a point of 'absolute zero' at which bodies possess zero thermal energy. For practical convenience, two points on the Kelvin temperature scale, namely 273.15 K and 373.15 K, are used to define the Celsius (or Centigrade) scale (0 °C and 100 °C). Thus in terms of temperature *intervals*, 1 K = 1 °C; but in terms of temperature *levels*, a Celsius temperature θ corresponds to a Kelvin temperature (θ + 273.15) K.

DERIVED UNITS

Nine of the more important SI derived units with their definitions are given

Quantity	*Unit Name*	*Unit Symbol*
Force	newton	N
Energy	joule	J
Power	watt	W
Electric charge	coulomb	C
Electric potential difference and EMF	volt	V
Electric resistance	ohm	Ω
Electric capacitance	farad	F
Electric inductance	henry	H
Magnetic flux	weber	Wb

Newton That force which gives to a mass of 1 kilogram an acceleration of 1 metre per second squared.

Joule The work done when the point of application of 1 newton is displaced a distance of 1 metre in the direction of the force.

Watt The power which gives rise to the production of energy at the rate of 1 joule per second.

Coulomb The quantity of electricity transported in 1 second by a current of 1 ampere.

Volt The difference of electric potential between two points of a conducting wire carrying a constant current of 1 ampere, when the power dissipated between these points is equal to 1 watt.

Ohm The electric resistance between two points of a conductor when a constant difference of potential of 1 volt, applied between these two points, produces in this conductor a current of 1 ampere, this conductor not being the source of any electromotive force.

Farad The capacitance of a capacitor between the plates of which there appears a difference of potential of 1 volt when it is charged by a quantity of electricity equal to 1 coulomb.

Henry The inductance of a closed circuit in which an electromotive force of 1 volt is produced when the electric current in the circuit varies uniformly at a rate of 1 ampere per second.

Weber The magnet flux which, linking a circuit of one turn, produces in it an electromotive force of 1 volt as it is reduced to zero at a uniform rate in 1 second.

Some of the simpler derived units are expressed in terms of the seven basic and two supplementary units directly. Examples are listed in *Table 1.1*.

Table 1.1 DIRECTLY DERIVED UNITS

Quantity	*Unit-name*	*Unit-symbol*
Area	square metre	m^2
Volume	cubic metre	m^3
Mass density	kilogramme per cubic metre	kg/m^3
Linear velocity	metre per second	m/s
Linear acceleration	metre per second square	m/s^2
Angular velocity	radian per second	rad/s
Angular acceleration	radian per second squared	rad/s^2
Force	kilogramme metre per second squared	$kg\ m/s^2$
Magnetic field strength	ampere per metre	A/m
Concentration	mole per cubic metre	mol/m^3
Luminance	candela per square metre	cd/m^2

Units in common use, particularly those for which a statement in base units would be lengthy or complicated, have been given special shortened names. Those that are named from scientists and engineers have an initial capital letter: all others are in small letters.

Table 1.2 NAMED DERIVED UNITS

Quantity	*Unit-name*	*Unit-symbol*	*Derivation*
Force	newton	N	kg m/s^2
Pressure	pascal	Pa	N/m^2
Power	watt	W	J/s
Energy	joule	J	N m, W s
Electric charge	coulomb	C	A s
Electric flux	coulomb	C	A s
Magnetic flux	weber	Wb	V s
Magnetic flux density	tesla	T	Wb/m^2
Electric potential	volt	V	J/C, W/A
Resistance	ohm	Ω	V/A
Conductance	siemens	S	A/V
Capacitance	farad	F	A s/V, C/V
Inductance	henry	H	V s/A, Wb/A
Luminous flux	lumen	lm	cd sr
Illuminance	lux	lx	lm/m^2
Frequency	hertz	Hz	1/s

The named derived units are used to form further derivations. Examples are:

Table 1.3 FURTHER DERIVED UNITS

Quantity	*Unit-name*	*Unit-symbol*
Torque	newton metre	N m
Dynamic viscosity	pascal second	Pa s
Surface tension	newton per metre	N/m
Power density	watt per square metre	W/m^2
Energy density	joule per cubic metre	J/m^3
Heat capacity	joule per kelvin	J/K
Specific heat capacity	joule per kilogramme kelvin	J/(kg K)
Thermal conductivity	watt per metre kelvin	W/(m K)
Electric field strength	volt per metre	V/m
Magnetic field strength	ampere per metre	A/m
Electric flux density	coulomb per square metre	C/m^2
Current density	ampere per square metre	A/m^2
Resistivity	ohm metre	Ω m
Permittivity	farad per metre	F/m
Permeability	henry per metre	H/m

Names of SI units and the corresponding EMU and ESU CGS units are given in *Table 1.4.*

Table 1.4

Quantity	*Symbol*	*SI*	*EMU & ESU*
Length	l	metre (m)	centimetre (cm)
Time	t	second (s)	second
Mass	m	kilogram (kg)	gram (g)
Force	F	newton (N)	dyne (dyn)
Frequency	f, ν	hertz (Hz)	hertz
Energy	E, W.	joule (J)	erg (erg)
Power	P	watt (W)	erg/sec. (erg/s)
Pressure	p	newton/metre^2 (N/m^2)	dyne/centimetre^2 (dyne/cm^2)
Electric charge	Q	coulomb (C)	coulomb (C)
Electric potential	V	volt (V)	volt
Electric current	I	ampere (A)	ampere
Magnetic flux	Φ	weber (Wb)	maxwell (Mx)
Magnetic induction	B	tesla (T)	gauss (G)
Magnetic field strength	H	ampere turn/metre (At/m)	oersted (Oe)
Magneto-motive force	F_m	ampere turn (At)	gilbert (Gb)
Resistance	R	ohm (Ω)	ohm
Inductance	L	henry (H)	henry
Conductance	G	mho (Ω^{-1}) (siemens)	mho
Capacitance	C	farad (F)	farad

GRAVITATIONAL AND ABSOLUTE SYSTEMS

There may be some difficulty in understanding the difference between SI and the Metric Technical System of units which has been used principally in Europe. The main difference is that while mass is expressed in kg in both systems, weight (representing a force) is expressed as kgf, a gravitational unit, in the MKSA system and as N in SI. An absolute unit of force differs from a gravitational unit of force because it induces unit acceleration in a unit mass whereas a gravitational unit imparts gravitational acceleration to a unit mass.

A comparison of the more commonly known systems and SI is shown in *Table 1.5.*

Table 1.5 COMMONLY USED UNITS OF MEASUREMENT

	SI (absolute)	*FPS (gravitational)*	*FPS (absolute)*	*cgs (absolute)*	*Metric technical units (gravitational)*
Length	metre (m)	ft	ft	cm	metre
Force	newton (N)	lbf	poundal (pdl)	dyne	kgf
Mass	kg	lb or slug	lb	gram	kg
Time	s	sec	sec	sec	sec
Temperature	°C K	°F	°F °R	°C K	°C K

Table 1.5—*continued* COMMONLY USED UNITS OF MEASUREMENT

		SI (absolute)	*FPS (gravitational)*	*FPS (absolute)*	*cgs (absolute)*	*Metric technical units (gravitational)*
Energy	mech.	joule*	ft lbf	ft pdl	dyne cm = erg	kgf m
	heat		Btu	Btu	calorie	k cal.
Power	mech.	watt	hp	hp watt	erg's	metric hp
	elec.		watt			watt
Electric current		amp	amp	amp	amp	amp
Pressure		N/m^2	lbf/ft^2	pdl/ft^2	dyne/cm^2	kgf/cm^2

* 1 joule = 1 newton metre or 1 watt second.

EXPRESSING MAGNITUDES OF SI UNITS

To express magnitudes of a unit, decimal multiples and submultiples are formed using the prefixes shown in *Table 1.6*. This method of expressing magnitudes ensures complete adherence to a decimal system.

Table 1.6 THE INTERNATIONALLY AGREED MULTIPLES AND SUBMULTIPLES

Factor by which the unit is multiplied		*Prefix*	*Symbol*	*Common everyday examples*
One million million (billion)	10^{12}	tera	T	
One thousand million	10^{9}	giga	G	gigahertz (GHz)
One million	10^{6}	mega	M	megawatt (MW)
One thousand	10^{3}	kilo	k	kilometre (km)
One hundred	10^{2}	hecto*	h	
Ten	10^{1}	deca*	da	decagramme (dag)
UNITY	1			
One tenth	10^{-1}	deci*	d	decimetre (dm)
One hundredth	10^{-2}	centi*	c	centimetre (cm)
One thousandth	10^{-3}	milli	m	milligramme (mg)
One millionth	10^{-6}	micro	μ	microsecond (μs)
One thousand millionth	10^{-9}	nano	n	nanosecond (ns)
One million millionth	10^{-12}	pico	p	picofarad (pF)
One thousand million millionth	10^{-15}	femto	f	
One million million millionth	10^{-18}	atto	a	

* To be avoided wherever possible.

AUXILIARY UNITS

Certain auxiliary units may be adopted where they have application in special fields. Some are acceptable on a temporary basis, pending a more widespread adoption of the SI system. *Table 1.7* lists some of these.

Table 1.7 AUXILIARY UNITS

Quantity	*Unit-symbol*	*SI equivalent*
Day	d	86 400 s
Hour	h	3 600 s
Minute (time)	min	60 s
Degree (angle)		$\pi/180$ rad
Minute (angle)	′	$\pi/10\,800$ rad
Second (angle)	″	$\pi/648\,000$ rad
Are	a	1 $\mathrm{dam}^2 = 10^2\ \mathrm{m}^2$
Hectare	ha	1 $\mathrm{hm}^2 = 10^4\ \mathrm{m}^2$
Barn	b	100 $\mathrm{fm}^2 = 10^{-28}\ \mathrm{m}^2$
Standard atmosphere	atm	101 325 Pa
Bar	bar	0.1 MPa = 10^5 Pa
Litre	l	1 $\mathrm{dm}^3 = 10^{-3}\ \mathrm{m}^3$
Tonne	t	10^3 kg = 1 Mg
Atomic mass unit	u	$1.660\,53 \times 10^{-27}$ kg
Angström	Å	0.1 nm = 10^{-10} m
Electron-volt	eV	$1.602\,19 \times 10^{-19}$ J
Curie	Ci	$3.7 \times 10^{10}\ \mathrm{s}^{-1}$
Röntgen	R	2.58×10^{-4} C/kg

NUCLEAR ENGINEERING

It has been the practice to use special units with their individual names for evaluating and comparing results. These units are usually formed by multiplying a unit from the cgs or SI system by a number which matches a value derived from the result of some natural phenomenon. The adoption of SI both nationally and internationally has created the opportunity to examine the practice of using special units in the nuclear industry, with the object of eliminating as many as possible and using the pure system instead.

As an aid to this, ISO draft Recommendations 838 and 839 have been published, giving a list of quantities with special names, the SI unit and the alternative cgs unit. It is expected that as SI is increasingly adopted and absorbed, those units based on cgs will go out of use. The values of these special units illustrate the fact that a change from them to SI would not be as revolutionary as might be supposed. Examples of these values together with the SI units which replace them are shown in *Table 1.8*.

Table 1.8 NUCLEAR ENGINEERING

Special unit			*SI Replacement*
Name		*Value*	
Angström	(Å)	10^{-10} m	m
Barn	(b)	$10^{-28}\ \mathrm{m}^2$	m^2
Curie	(Ci)	$3.7 \times 10^{10}\ \mathrm{s}^{-1}$	s^{-1}
Electron-volt	(eV)	$(1.602\,10 \pm 0.000\,07) \times 10^{-19}$ J	J
Röntgen	(R)	2.58×10^{-4} C/kg	C/kg

UNIVERSAL CONSTANTS IN SI UNITS

Table 1.9

The digits in parentheses following each quoted value represent the standard deviation error in the final digits of the quoted value as computed on the criterion of internal consistency. The unified scale of atomic weights is used throughout (^{12}C = 12). C = coulomb; G = gauss; Hz = hertz; J = joule; N = newton; T = tesla; u = unified nuclidic mass unit; W = watt; Wb = weber. For result multiply the numerical value by the SI unit.

Constant	*Symbol*	*Numerical value*	*SI unit*
Speed of light in vacuum	c	2.997 925(1)	10^{8} m/s^{-1}
Gravitational constant	G	6.670(5)*	10^{-11} N m^{2}/kg^{-2}
Elementary charge	e	1.602 10(2)	10^{-19} C
Avogadro constant	N_A	6.022 52(9)	10^{26} kmol^{-1}
Mass unit	u	1.660 43(2)	10^{-27} kg
Electron rest mass	m_e	9.109 08(13)	10^{-31} kg
		5.485 97(3)	10^{-4} u
Proton rest mass	m_p	1.672 52(3)	10^{-27} kg
		1.007 276 63(8)	u
Neutron rest mass	m_n	1.67 482(3)	10^{-27} kg
		1.008 665 4(4)	u
Faraday constant	F	9.648 70(5)	10^{4} C mol^{-1}
Planck constant	h	6.625 59(16)	10^{-34} J s
	$h/2\pi$	1.054 494(25)	10^{-34} J s
Fine-structure constant	α	7.297 20(3)	10^{-3}
	$1/\alpha$	137.038 8(6)	
Charge-to-mass ratio for electron	e/m_e	1.758 796(6)	10^{11} C kg^{-1}
Quantum of magnetic flux	hc/e	4.135 56(4)	10^{-11} Wb
Rydberg constant	R_∞	1.097 373 1(1)	10^{7} m^{-1}
Bohr radius	a_0	5.291 67(2)	10^{-11} m
Compton wavelength of electron	h/m_ec	2.426 21(2)	10^{-12} m
	$\lambda c/2\pi$	3.861 44(3)	10^{-13} m
Electron radius	$e^2/m_ec^2 = r_e$	2.817 77(4)	10^{-15} m
Thomsen cross section	$8\eta r_e^2/3$	6.651 6(2)	10^{-29} m^{2}
Compton wavelength of proton	$\lambda c,p$	1.321 398(13)	10^{-15} m
	$\lambda c,p/2\pi$	2.103 07(2)	10^{-16} m
Gyromagnetic ratio of proton	γ	2.675 192(7)	10^{8} rad s^{-1} T^{-1}
	$\gamma/2\pi$	4.257 70(1)	10^{7} Hz T^{-1}
(Uncorrected for diamagnetism H$_2$O)	γ'	2.675 123(7)	10^{8} rad s^{-1} T^{-1}
	$\gamma'/2\pi$	4.257 59(1)	10^{7} Hz T^{-1}
Bohr magneton	μB	9.273 2(2)	10^{-24} J T^{-1}
Nuclear magneton	μN	5.050 50(13)	10^{-27} J T^{-1}
Proton moment	μ_p	1.410 49(4)	10^{-26} J T^{-1}
	$\mu_p/\mu N$	2.792 76(2)	

* The universal gravitational constant is not, and cannot in our present state of knowledge, be expressed in terms of other fundamental constants. The value given here is a direct determination by P. R. Heyl and P. Chrzanowski, *J. Res. Natl. Bur. Std.* (*U.S.*) 29, 1 (1942).

The above values are extracts from *Review of Modern Physics* Vol. 37 No. 4 October 1965 published by the American Institute of Physics.

Table 1.9—*continued*

The digits in parentheses following each quoted value represent the standard deviation error in the final digits of the quoted value as computed on the criterion of internal consistency. The unified scale of atomic weights is used throughout ($^{12}C = 12$). C = coulomb; G = gauss; Hz = hertz; J = joule; N = newton; T = tesla; u = unified nuclidic mass unit; W = watt; Wb = weber. For result multiply the numerical value by the SI unit.

Constant	*Symbol*	*Numerical value*	*SI unit*
(Uncorrected for diamagnetism in H_2O sample)		2.792 68(2)	
Gas constant	R_0	8.314 34(35)	J deg^{-1} mol^{-1}
Boltzmann constant	k	1.380 54(6)	10^{-23} J deg^{-1}
First radiation constant ($2\eta hc^2$)	c_1	3.741 50(9)	10^{-16} W/m^2
Second radiation constant (hc/k)	c_2	1.438 79(6)	10^{-2} m/deg
Stefan-Boltzmann constant	σ	5.669 7(10)	10^{-8} W m^{-2} deg^{-4}

METRIC TO IMPERIAL CONVERSION FACTORS

Table 1.10

SI units	*British units*
SPACE AND TIME	
Length:	
1 μm (micron)	= 39.37 × 10^{-6} in
1 mm	= 0.039 370 1 in
1 cm	= 0.393 701 in
1 m	= 3.280 84 ft
1 m	= 1.093 61 yd
1 km	= 0.621 371 mile
Area:	
1 mm^2	= 1.550 × 10^{-3} in^2
1 cm^2	= 0.155 0 in^2
1 m^2	= 10.763 9 ft^2
1 m^2	= 1.195 99 yd
1 ha	= 2.471 05 acre
Volume:	
1 mm^3	= 61.023 7 × 10^{-6} in^3
1 cm^3	= 61.023 7 × 10^{-3} in^3
1 m^3	= 35.314 7 ft^3
1 m^3	= 1.307 95 yd^3
Capacity:	
10^6 m^3	= 219.969 × 10^6 gal
1 m^3	= 219.969 gal
1 litre (l)	= 0.219 969 gal = 1.759 80 pint

Table 1.10—*continued*

SI units	*British units*
Capacity flow:	
10^3/m^3/s	= 791.9 × 10^6 gal/h
1 m^3/s	= 13.20 × 10^3 gal/min
1 litre/s	= 13.20 gal/min
1 m^3/kW h	= 219.969 gal/kW h
1 m^3/s	= 35.314 7 ft^3/s (cusecs)
1 litre/s	= 0.588 58 × 10^{-3} ft^3/min (cfm)
Velocity:	
1 m/s	= 3.280 84 ft/s = 2.236 94 mile
1 km/h	= 0.621 371 mile/h
Acceleration:	
1 m/s^2	= 3.280 84 ft/s^2
MECHANICS	
Mass:	
1 g	= 0.035 274 oz
1 kg	= 2.204 62 lb
1 t	= 0.984 207 ton = 19.684 1 cwt
Mass flow:	
1 kg/s	= 2.204 62 lb/s = 7.936 64 klb/h
Mass density:	
1 kg/m^3	= 0.062 428 lb/ft^3
1 kg/litre	= 10.022 119 lb/gal
Mass per unit length:	
1 kg/m	= 0.671 969 lb/ft = 2.015 91 lb/yd
Mass per unit area:	
1 kg/m^2	= 0.204 816 lb/ft^2
Specific volume:	
1 m^3/kg	= 16.018 5 ft^3/lb
1 litre/tonne	= 0.223 495 gal/ton
Momentum:	
1 kg m/s	= 7.233 01 lbft/s
Angular momentum:	
1 kg m^2/s	= 23.730 4 lbft^2/s
Moment of inertia:	
1 kg m^2	= 23.730 4 lbft^2
Force:	
1 N	= 0.224 809 lbf
Weight (force) per unit length:	
1 N/m	= 0.068 521 8 lbf/ft = 0.205 566 lbf/yd
Moment of force (or torque):	
1 Nm	= 0.737 562 lbf/ft
Weight (force) per unit area:	
1 N/m^2	= 0.020 885 lbf/ft^2
Pressure:	
1 N/m^2	= 1.450 38 × 10^{-4} lbf/in^2
1 bar	= 14.5038 lbf/in^2
1 bar	= 0.986 923 atmosphere
1 mbar	= 0.401 463 in H_2O
	= 0.029 53 in Hg

Table 1.10—*continued*

SI units	*British units*
Stress:	
1 N/mm^2	= 6.474 90 × 10^{-2} tonf/in^2
1 MN/m^2	= 6.474 90 × 10^{-2} tonf/in^2
1 hbar	= 0.647 490 tonf/in^2
Second moment of area:	
1 cm^4	= 0.024 025 in^4
Section modulus:	
1 m^3	= 61 023.7 in^3
1 cm^3	= 0.061 023 7 in^3
Kinematic viscosity:	
1 m^2/s	= 10.762 75 ft^2/s = 10^6 cSt
1 cSt	= 0.038 75 ft^2/h
Energy, work:	
1 J	= 0.737 562 ft lbf
1 MJ	= 0.372 5 hph
1 MJ	= 0.277 78 kW h
Power:	
1 W	= 0.737 562 ft lbf/s
1 kW	= 1.341 hp = 737.562 ft lbf/s
Fluid mass:	
(Ordinary) 1 kg/s	= 2.204 62 lb/s = 793 6.64 lb/h
(Velocity) 1 kg/m^2 s	= 0.204 815 lb/ft^{2}s
HEAT	
Temperature:	
(Interval) 1 °K	= 9/5 deg R (Rankine)
1 °C	= 9/5 deg F
(Coefficient) 1 °R^{-1}	= 1 deg F^{-1} = 5/9 deg C
1 °C^{-1}	= 5/9 deg F^{-1}
Quantity of heat:	
1 J	= 9.478 17 × 10^{-4} Btu
1 J	= 0.238 846 cal
1 kJ	= 947.817 Btu
1 GJ	= 947.817 × 10^3 Btu
1 kJ	= 526.565 CHU
1 GJ	= 526.565 × 10^3 CHU
1 GJ	= 9.478 17 therm
Heat flow rate:	
1 W(J/s)	= 3.412 14 Btu/h
1 W/m^2	= 0.316 998 Btu/ft^2 h
Thermal conductivity:	
1 W/m °C	= 6.933 47 Btu in/ft^2 h °F
Coefficient and heat transfer:	
1 W/m^2 °C	= 0.176 110 Btu/ft^2 h °F
Heat capacity:	
1 J/°C	= 0.526 57 × 10^{-3} Btu/°R
Specific heat capacity:	
1 J/g °C	= 0.238 846 Btu/lb °F
1 kJ/kg °C	= 0.238 846 Btu/lb °F
Entropy:	
1 J/K	= 0.526 57 × 10^{-3} Btu/°R

Table 1.10—*continued*

SI units	*British units*
Specific Entropy:	
1 J/kg °C	= 0.238 846 × 10^{-3} Btu/lb °F
1 J/kg °K	= 0.238 846 × 10^{-3} Btu/lb °R
Specific energy/Specific latent heat:	
1 J/g	= 0.429 923 Btu/lb
1 J/kg	= 0.429 923 × 10^{-3} Btu/lb
Calorific value:	
1 kJ/kg	= 0.429 923 Btu/lb
1 kJ/kg	= 0.773 861 4 CHU/lb
1 J/m^3	= 0.026 839 2 × 10^{-3} Btu/ft^3
1 kJ/m^3	= 0.026 839 2 Btu/ft^3
1 kg/litre	= 4.308 86 Btu/gal
1 kJ/kg	= 0.009 630 2 therm/ton
ELECTRICITY	
Permeability:	
1 H/m	= $10^7/4\,\Pi\,\mu o$
Magnetic flux density:	
1 tesla	= 10^4 gauss = 1 Wb/m^2
Conductivity:	
1 mho	= 1 reciprocal ohm
1 siemen	= 1 reciprocal ohm
Electric stress:	
1 kV/mm	= 25.4 kV/in
1 kV/m	= 0.025 4 kV/in

SYMBOLS AND ABBREVIATIONS

Table 1.11 QUANTITIES AND UNITS OF PERIODIC AND RELATED PHENOMENA
(Based on ISO recommendation R31)

Symbol	*Quantity*
T	periodic time
$\tau, (T)$	time constant of an exponentially varying quantity
f, ν	frequency
η	rotational frequency
ω	angular frequency
λ	wave length
$\sigma\,(\tilde{\nu})$	wave number
k	circular wave number
$\log e\,(A_1/A_2)$	natural logarithm of the ratio of two amplitudes
$10 \log_{10}(P_1/P_2)$	ten times the common logarithm of the ratio of two powers
δ	damping coefficient
Λ	logarithmic decrement
α	attenuation coefficient
β	phase coefficient
γ	propagation coefficient

Table 1.12 SYMBOLS FOR QUANTITIES AND UNITS OF ELECTRICITY AND MAGNETISM
(Based on ISO recommendation R31)

Symbol	*Quantity*
I	electric current
Q	electric charge, quantity of electricity
e	volume density of charge, charge density
σ	surface density of charge
$E, (K)$	electric field strength
V, ϕ	electric potential
$U, (V)$	potential difference, tension
E	electromotive force
D	displacement (rationalised displacement)
D'	non-rationalised displacement
ψ	electric flux, flux of displacement (flux of rationalised displacement)
ψ'	flux of non-rationalised displacement
C	capacitance
ϵ	permittivity
ϵ_0	permittivity of vacuum
ϵ'	non-rationalised permittivity
ϵ'_0	non-rationalised permittivity of vacuum
ϵ_r	relative permittivity
χ_e	electric susceptibility
χ'_e	non-rationalised electric susceptibility
P	electric polarisation
$p, (p_e)$	electric dipole moment
$J, (S)$	current density
$A, (\alpha)$	linear current density
H	magnetic field strength
H'	non-rationalised magnetic field strength
U_m	magnetic potential difference
F, F_m	magnetomotive force
B	magnetic flux density, magnetic induction
Φ	magnetic flux
A	magnetic vector potential
L	self inductance
M, L_{12}	mutual inductance
$k, (x, k)$	coupling coefficient
σ	leakage coefficient
μ	permeability
μ_0	permeability of vacuum
μ'	non-rationalised permeability
μ'_0	non-rationalised permeability of vacuum
μ_r	relative permeability
x, k	magnetic susceptibility
x', k'	non-rationalised magnetic susceptibility
m	electromagnetic moment (magnetic moment)
H_i, M	magnetisation
B_i, J	magnetic polarisation
J'	non-rationalised magnetic polarisation
ω	electromagnetic energy density
S	Poynting vector
c	velocity of propagation of electromagnetic waves in vacuo

Table 1.12—*continued*

Symbol	*Quantity*
R	resistance (to direct current)
G	conductance (to direct current)
e	resistivity
γ, σ	conductivity
R, R_m	reluctance
$A, (P)$	permeance
N	number of turns in winding
m	number of phases
p	number of pairs of poles
ϕ	phase displacement
Z	impedance (complex impedance)
$[Z]$	modulus of impedance (impedance)
X	reactance
R	resistance
Q	quality factor
Y	admittance (complex admittance)
$[Y]$	modulus of admittance (admittance)
B	susceptance
G	conductance
P	active power
$S, (P_s)$	apparent power
$Q, (P_q)$	reactive power

Table 1.13 SYMBOLS FOR QUANTITIES AND UNITS OF ACOUSTICS
(Based on ISO recommendation R31)

Symbol	*Quantity*
T	period, periodic time
f, ν	frequency, frequency interval
ω	angular frequency, circular frequency
λ	wavelength
k	circular wave number
ρ	density (mass density)
Ps	static pressure
p	(instantaneous) sound pressure
$\epsilon, (x)$	(instantaneous) sound particle displacement
u, v	(instantaneous) sound particle velocity
a	(instantaneous) sound particle acceleration
q, U	(instantaneous) volume velocity
c	velocity of sound
E	sound energy density
$P, (N, W)$	sound energy flux, sound power
I, J	sound intensity
$Z_s, (W)$	specific acoustic impedance
$Z_a, (Z)$	acoustic impedance
$Z_m, (w)$	mechanical impedance
$L_p, (L_N, L_w)$	sound power level
$L_p, (L)$	sound pressure level
δ	damping coefficient

Table 1.13—*continued*

Symbol	*Quantity*
Λ	logarithmic decrement
α	attenuation coefficient
β	phase coefficient
γ	propagation coefficient
δ	dissipation coefficient
r, τ	reflection coefficient
γ'	transmission coefficient
$\alpha, (\alpha_a)$	acoustic absorption coefficient
R	sound reduction index sound transmission loss
A	equivalent absorption area of a surface or object
T	reverberation time
$L_N, (\Lambda)$	loudness level
N	loudness

Table 1.14 SOME TECHNICAL ABBREVIATIONS AND SYMBOLS

Quantity	*Abbreviation*	*Symbol*
Alternating current	a.c.	
Ampere	A or amp	
Amplification factor		μ
Amplitude modulation	a.m.	
Angular velocity		ω
Audio frequency	a.f.	
Automatic frequency control	a.f.c	
Automatic gain control	a.g.c.	
Bandwidth		Δf
Beat frequency oscillator	b.f.o.	
British thermal unit	Btu	
Cathode-ray oscilloscope	c.r.o.	
Cathode-ray tube	c.r.t.	
Centigrade	C	
Centi-	c	
Centimetre	cm	
Square centimetre	cm^2 or sq cm	
Cubic centimetre	cm^3 or cu cm or c.c.	
Centimetre-gramme-second	c.g.s.	
Continuous wave	c.w.	
Coulomb	C	
Deci-	d	
Decibel	dB	
Direct current	d.c.	
Direction finding	d.f.	
Double sideband	d.s.b.	
Efficiency		η
Equivalent isotropic radiated power	e.i.r.p.	
Electromagnetic unit	e.m.u.	
Electromotive force instantaneous value	e.m.f.	E or V, e or v

Table 1.14—*continued*

Quantity	*Abbreviation*	*Symbol*
Electron volt	eV	
Electrostatic unit	e.s.u.	
Fahrenheit	F	
Farad	F	
Frequency	freq.	f
Frequency modulation	f.m.	
Gauss	G	
Giga-	G	
Gramme	g	
Henry	H	
Hertz	Hz	
High frequency	h.f.	
Independent sideband	i.s.b.	
Inductance-capacitance		L-C
Intermediate freq.	i.f.	
Kelvin	K	
Kilo-	k	
Knot	kn	
Length		l
Local oscillator	l.o.	
Logarithm, common		log or $\log_{10}$
Logarithm, natural		ln or $\log_e$
Low frequency	l.f.	
Low tension	l.t.	
Magnetomotive force	m.m.f.	F or M
Mass		m
Medium frequency	m.f.	
Mega-	M	
Metre	m	
Metre-kilogramme-second	m.k.s.	
Micro-	μ	
Micromicro	p	
Micron		μ
Milli-	m	
Modulated continuous wave	m.c.w.	
Nano-	n	
Neper	N	
Noise factor		N
Ohm		Ω
Peak to peak	p–p	
Phase modulation	p.m.	
Pico-	p	
Plan-position indication	PPI	
Potential difference	p.d.	V
Power factor	p.f.	
Pulse repetition frequency	p.r.f.	

Table 1.14—*continued*

Quantity	*Abbreviation*	*Symbol*
Radian	rad	
Radio frequency	r.f.	
Radio telephony	R/T	
Root mean square	r.m.s.	
Short-wave	s.w.	
Single sideband	s.s.b.	
Signal frequency	s.f.	
Standing wave ratio	s.w.r.	
Super-high frequency	s.h.f.	
Susceptance		*B*
Travelling-wave tube	t.w.t.	
Ultra-high frequency	u.h.f.	
Very high frequency	v.h.f.	
Very low frequency	v.l.f.	
Volt	V	
Voltage standing wave ratio	v.s.w.r.	
Watt	W	
Weber	Wb	
Wireless telegraphy	W/T	

MATHEMATICAL SIGNS AND SYMBOLS

Table 1.15 MATHEMATICAL SIGNS AND SYMBOLS FOR USE IN TECHNOLOGY
(Based on ISO recommendation R31)

Sign, symbol	*Quantity*
$=$	equal to
ǂ $\neq$	not equal to
$\equiv$	identically equal to
Λ	corresponds to
$\approx$	approximately equal to
$\rightarrow$	approaches
$\simeq$	asymptotically equal to
$\sim$	proportional to
∞	infinity
$<$	smaller than
$>$	larger than
$\leq$	smaller than or equal to
$\geq$ $\geqslant$ $\geqq$	larger than or equal to
$\ll$	much smaller than
$\gg$	much larger than
$+$	plus
$-$	minus
$\times$	multiplied by

Table 1.15—*continued*

Sign, symbol	*Quantity*
$\frac{a}{b}$ a/b	a divided by b
$\lvert a \rvert$	magnitude of a
a^n	a raised to the power n
$a^{\frac{1}{2}}$ $a^{1/2}$ $\sqrt{a}$ $\sqrt{a}$	square root of a
$a^{1/n}$ $a^{\frac{1}{n}}$ $\sqrt[n]{a}$ $\sqrt[n]{a}$	n'th root of a
$\bar{a}$ $\langle a \rangle$	mean value of a
$p!$	factorial p, $1 \times 2 \times 3 \times \ldots \times p$
$\binom{n}{p}$	binomial coefficient, $\frac{n(n-1)\ldots(n-p+1)}{1 \times 2 \times 3 \times \ldots \times p}$
Σ	sum
Π	product
$f(x)$ $f(x)$	function f (of f) of the variable x
$[f(x)]_a^b$ $f(x)/_a^b$	$f(b) - f(a)$
$\lim\limits_{x \to a} f(x)$; $\lim_{x \to a} f(x)$	the limit to which $f(x)$ tends as x approaches a
Δx	delta x = finite increment of x
δx	delta x = variation of x
$\frac{df}{dx}$; df/dx; $f'(x)$	differential coefficient of $f(x)$ with respect to x
$\frac{d^n f}{dx^n}$; $f^{(n)}(x)$	differential coefficient of order n of $f(x)$
$\frac{\partial f(x, y, \ldots)}{\partial x}$; $\left(\frac{\partial f}{\partial x}\right)_{y \ldots}$	partial differential coefficient of $f(x, y, \ldots)$ with respect to x, when $y, \ldots$ are held constant
df	the total differential of f
$\int f(x)dx$	indefinite integral of $f(x)$ with respect to x
${}_a\!\int^b f(x)dx$; $\int_a^b f(x)dx$	definite integral of $f(x)$ from $x = a$ to $x = b$
e	base of natural logarithms
e^x; $\exp x$	e raised to the power x
$\log_a x$	logarithm to the base a of x
$\ln x$; $\log_e x$	natural logarithm (Napierian logarithm) of x
$\lg x$; $\log x$; $\log_{10} x$	common (Briggsian) logarithm of x
$\mathrm{lb}\, x$; $\log_2 x$	binary logarithm of x
$\sin x$	sine of x
$\cos x$	cosine of x
$\tan x$; $\mathrm{tg}\, x$	tangent of x
$\cot x$; $\mathrm{ctg}\, x$	cotangent of x
$\sec x$	secant of x
$\mathrm{cosec}\, x$	cosecant of x
$\arcsin x$	arc sine of x
$\arccos x$	arc cosine of x
$\arctan x$, $\mathrm{arctg}\, x$	arc tangent of x
$\mathrm{arccot}\, x$, $\mathrm{arcctg}\, x$	arc cotangent of x
$\mathrm{arcsec}\, x$	arc secant of x
$\mathrm{arccosec}\, x$	arc cosecant of x
$\sinh x$	hyperbolic sine of x
$\cosh x$	hyperbolic cosine of x
$\tanh x$	hyperbolic tangent of x
$\coth x$	hyperbolic cotangent of x

Table 1.15—*continued*

Sign, symbol	*Quantity*
sech x	hyperbolic secant of x
cosech x	hyperbolic cosecant of x
arsinh x	inverse hyperbolic sine of x
arcosh x	inverse hyperbolic cosine of x
artanh x	inverse hyperbolic tangent of x
arcoth x	inverse hyperbolic cotangent of x
arsech x	inverse hyperbolic secant of x
arcosech x	inverse hyperbolic cosecant of x
i, j	imaginary unity, $1^2 = -1$
$Re\, z$	real part of z
$Im\, z$	imaginary part of z
$\lvert z \rvert$	modulus of z
arg z	argument of z
z^*	conjugate of x, complex conjugate of z
$\tilde{\mathrm{A}}$	transpose of matrix A
A^*	complex conjugate matrix of matrix A
$\mathrm{A}^\dagger$	Hermitian conjugate matrix of matrix A
Aa	vector
$\lvert \mathbf{A} \rvert$, A	magnitude of vector
$\mathbf{A} \cdot \mathbf{B}$	scalar product
$\mathbf{A} \times \mathbf{B}, \mathbf{A} \wedge \mathbf{B}$	vector product
V	differential vector operator
Vϕ, grad ϕ	gradient of ϕ
V $\cdot A$, div **A**	divergence of **A**
V $\times$ **A**, V $\wedge$**A** curl **A**, rot **A**	curl of **A**
V$^2\phi$, $\wedge\phi$	Laplacion of ϕ

MATHEMATICAL FORMULAE

Algebraic and Trigonometric Formulæ

$\sin^2 A + \cos^2 A = \sin A \operatorname{cosec} A = 1$ $\qquad$ $1 + \tan^2 A = \sec^2 A.$

$\sin A = \dfrac{\cos A}{\cot A} = \dfrac{1}{\operatorname{cosec} A} - \sqrt{1 - \cos^2 A}.$ $\qquad$ $1 + \cot^2 A = \operatorname{cosec}^2 A.$

$\cos A = \dfrac{\sin A}{\tan A} = \dfrac{1}{\sec A} = \sqrt{1 - \sin^2 A.}$ $\qquad$ $1 - \sin A = \operatorname{coversin} A.$

$\text{tangent}\, A = \dfrac{\sin A}{\cos A} = \dfrac{1}{\cot A};$ $\qquad$ $\tan \theta/2 = t;$ $\qquad$ $\sin \theta = \dfrac{2t}{1 + t^2};$ $\qquad$ $\cos \theta = \dfrac{1 - t^2}{1 + t^2}$

$\text{cotangent}\, A = \dfrac{1}{\tan A},$ $\qquad$ $\text{secant}\, A = \dfrac{1}{\cos A},$ $\qquad$ $\text{cosecant}\, A = \dfrac{1}{\sin A}$

$\sin(A \pm B) = \sin A \cos B \pm \cos A \sin B;$ $\qquad$ $\tan(A \pm B) = \dfrac{\tan A \pm \tan B}{1 \pm \tan A \tan B};$

$\cos(A \pm B) = \cos A \cos B \pm \sin A \sin B$ $\qquad$ $\sinh u = (e^u - e^{-u}) \div 2;$

$\cosh u = \dfrac{e^u + e^{-u}}{2};$ $\qquad$ $\tanh u = \dfrac{e^u - e^{-u}}{e^u + e^{-u}}.$ $\cot(A \pm B) = \dfrac{\cot A \cot B \pm 1}{\cot B \pm \cot A};$

$\cosh^2 u - \sinh^2 u = 1;$ $\qquad$ $\sin A + \sin B = 2 \sin \tfrac{1}{2}(A + B) \cos \tfrac{1}{2}(A - B);$

$\sin^2 A - \sin^2 B = \sin(A + B)\sin(A - B)$; $\tan A \pm \tan B = \dfrac{\sin(A \pm B)}{\cos A \cos B}$.

$\sin A - \sin B = 2\cos\frac{1}{2}(A + B)\sin\frac{1}{2}(A - B)$; $e^{i\theta} = \cos\theta + i\sin\theta$;

$\cos A + \cos B = 2\cos\frac{1}{2}(A + B)\cos\frac{1}{2}(A - B)$; $e^{i\theta} = \cos\theta - i\sin\theta$;

$\cos B - \cos A = 2\sin\frac{1}{2}(A + B)\sin\frac{1}{2}(A - B)$. versine $A = 1 - \cos A$ $\cos\theta = \dfrac{e^{i\theta} + e^{-i\theta}}{2}$

$\sin\theta = \dfrac{e^{i\theta} - e^{-i\theta}}{2i}, i = \sqrt{-1}, e^{in\theta} = \cos n\theta + i\sin n\theta\,(\cos\theta + i\sin\theta)^n = \cos n\theta + i\sin n\theta$;

$\cot A \pm \cot B = \dfrac{\sin(B \pm A)}{\sin A \sin B}$ $\sin 2A = 2\sin A\cos A$; $\cos 2A = \cos^2 A - \sin^2 A$;

$\cos^2 A - \sin^2 B = \cos(A + B)\cos(A - B)$; $\tan 2A = \dfrac{2\tan A}{1 - \tan^2 A}$ $\sin\frac{1}{2}A = \sqrt{\dfrac{1 - \cos A}{2}}$,

$\cos\frac{1}{2}A = \pm\sqrt{\dfrac{1 + \cos A}{2}}$; $\tan\frac{1}{2}A = \dfrac{\sin A}{1 + \cos A}$; $\sin^2 A = \dfrac{1 - \cos 2A}{2}$; $\cos^2 A = \dfrac{1 + \cos 2A}{2}$;

$\tan^2 A = \dfrac{1 - \cos 2A}{1 + \cos 2A}$; $\dfrac{\sin A \pm \sin B}{\cos A + \cos B} = \tan\frac{1}{2}(A \pm B)$; $\dfrac{\sin A \pm \sin B}{\cos B - \cos A} = \cot\frac{1}{2}(A \pm B)$.

Angle	*0*	*30°*	*45°*	*60°*	*90°*	*180°*	*270°*	*360°*
Radians	0	$\pi/6$	$\pi/4$	$\pi/3$	$\pi/2$	π	$3\pi/2$	2π
Sine	0	$\frac{1}{2}$	$\frac{1}{2}\sqrt{2}$	$\frac{1}{2}\sqrt{3}$	1	0	-1	0
Cosine	1	$\frac{1}{2}\sqrt{3}$	$\frac{1}{2}\sqrt{2}$	$\frac{1}{2}$	0	-1	0	1
Tangent	0	$\frac{1}{3}\sqrt{3}$	1	$\sqrt{3}$	∞	0	∞	0

APPROXIMATIONS FOR SMALL ANGLES

$\sin\theta \simeq (\theta - \theta^3/6\ldots)$; $\tan\theta \simeq (\theta + \theta^3/3\ldots)$; $\cos\theta \simeq (1 - \theta^2/2\ldots)$ θ in radians; $\sin 14\frac{1}{2}° = \frac{1}{4}$; $\sin 19\frac{1}{2}° = \frac{1}{3}$.

QUADRATIC EQUATION

If $ax^2 + bx + c = 0$, then $x = \dfrac{-b \pm \sqrt{b^2 - 4ac}}{2a}$

TO FIND THE SUM OF ANY NUMBER OF TERMS IN AN ARITHMETICAL PROGRESSION

$T_n = a + (n - 1)d$; $S = n(a + l)/2 = n|2a + (n - 1)d|/2$.
where a = first term; l = last term; n = number of terms; T_n = nth term; S = sum; d = common difference.

TO FIND THE SUM OF ANY NUMBER OF TERMS IN A GEOMETRICAL PROGRESSION

Let r = common ratio, then $T_n = ar^{n-1}$; $S = \dfrac{a(r^n - 1)}{r - 1} = \dfrac{a(1 - r^n)}{1 - r}$.

COMBINATIONS AND PERMUTATIONS

$$_nC_r = \frac{n!}{r!\,(n - r)!} = {}_nC_{n-r}.$$

The number of permutations of n things r at a time is ${}_nP_r$.

$$
\begin{aligned}
{}_nP_n &= n(n-1)(n-2) \text{———} 3 \,.\, 2 \,.\, 1 = n! \\
{}_nP_r &= n(n-1)(n-2) \text{———} (n-r+1).
\end{aligned}
$$

BINOMIAL THEOREM

$$(1 \pm x)^n = 1 \pm nx + \frac{n(n-1)}{1 \,.\, 2} x^2 \pm \frac{n(n-1)(n-2)}{1 \,.\, 2 \,.\, 3} x^3 + \ldots$$

MACLAURIN'S THEOREM

$$f(x) = f(o) + xf'(o) \frac{x^2}{1 \,.\, 2} f''(o) + \ldots$$

PROPERTIES OF 'e'

$$e = 1 + 1 + \frac{1}{2!} + \frac{1}{3!} \ldots = 2.718\,28; \; e^x = 1 + x + \frac{x^2}{2!} + \frac{x}{3!} + \ldots$$

$$\log_{10} e = 0.434\,29, \; \log_e 10 = 2.302\,59, \; e^{i\theta} = \cos\theta + i \sin\theta, \; (i^2 = -1)$$

$$e^u = \cosh u + \sinh u.$$

Derivatives and Integrals

y	$\dfrac{dy}{dx}$	$\int y dx$
x^n	nx^{n-1}	$x^{n+1}/n + 1$
$1/x = x^{-1}$		$\log_e x$
$\sin \omega x$	$\omega \cos \omega x$	$-\cos \omega x/\omega$
$\cos \omega x$	$-\omega \sin \omega x$	$\sin \omega x/\omega$
$\tan \omega x$	$\omega \sec^2 \omega x$	$-\log \cos \omega x/\omega$
$\tan x$	$\sec^2 x$	$-\log \cos x$ or $\log \sec x$
$\cot x$	$-\mathrm{cosec}^2\, x$	$\log \sin x$
$\sec x$	$\tan x \sec x = \sin x/\cos^2 x$	$\log_e (\sec x + \tan x)$
$\mathrm{cosec}\, x$	$-\cot x\, \mathrm{cosec}\, x = -\dfrac{\cos x}{\sin^2 x}$	$\log_e (\mathrm{cosec}\, x - \cot x)$
$\sin^{-1} \left(\dfrac{x}{a}\right)$	$\dfrac{1}{\sqrt{a^2 - x^2}}$	$x \sin^{-1} \dfrac{x}{a} + \sqrt{a^2 - x^2}$
$\cos^{-1} \left(\dfrac{x}{a}\right)$	$\dfrac{1}{-\sqrt{a^2 - x^2}}$	$x \cos^{-1} \dfrac{x}{a} - \sqrt{a^2 - x^2}$
$\left(\dfrac{x}{a}\right)$	$\dfrac{a}{a^2 + x^2}$	$x \tan^{-1} \dfrac{x}{a} - a \log_e \sqrt{a^2 + z^2}$
e^x	e^x	e^x
e^{ax}	ae^{ax}	e^{ax}/a
$\log_e x$	$1/x$	$x(\log_e x - 1)$
$\log_a x$	$\dfrac{1}{x} \log_a e$	$x \log_a \dfrac{x}{e}$

$$\int \frac{dx}{x^2+a^2} = \frac{1}{a}\tan^{-1}\frac{x}{a}, \qquad \int \frac{xdx}{ax^2+b} = \frac{1}{2a}\log_e(ax^2+b)$$

$$\int\sqrt{x^2 \pm a^2}\,dx = \tfrac{1}{2}\left[x\sqrt{x^2 \pm a^2} \pm a^2 \log_e\left(x+\sqrt{x^2 \pm a^2}\right)\right]$$

$$\int\sqrt{a^2-x^2}\,dx = \tfrac{1}{2}\left(x\sqrt{a^2-x^2} + a^2\sin^{-1}\left(\frac{x}{a}\right)\right)$$

$$\int\frac{dx}{\sqrt{x^2 \pm a^2}} = \log_e\left(x+\sqrt{x^2 \pm a^2}\right). \qquad \int\frac{dx}{\sqrt{a^2-x^2}} = \sin^{-1}\frac{x}{a}$$

$$\int x\sqrt{x^2 \pm a^2}\,dx = \tfrac{1}{3}\sqrt{(x^2 \pm a^2)^3}. \qquad \int x\sqrt{a^2-x^2}\,dx = -\tfrac{1}{3}\sqrt{(a^2-x^2)^3}$$

$$\int\frac{xdx}{\sqrt{a^2-x^2}} = -\sqrt{a^2-x^2}. \qquad \int\frac{dx}{\sqrt{2ax-x^2}} = \cos^{-1}\frac{a-x}{a}$$

$$\int \sin^2 xdx = \tfrac{1}{2}(x - \sin x\cos x) = \tfrac{1}{2}x - \tfrac{1}{4}\sin 2x. \qquad \int \cos^2 xdx = \tfrac{1}{2}(x + \sin x\cos x) = \tfrac{1}{2}x + \tfrac{1}{4}\sin 2x.$$

If $y = f(u)$, $u = \phi(x)$ then $\dfrac{dy}{dx} = \dfrac{dy}{du}\,\dfrac{du}{dx}$

If y is a product, uv, then $\dfrac{dy}{dx} = v\dfrac{du}{dx} + u\dfrac{dv}{dx}$.

If y is a quotient, $\dfrac{u}{v}$, then $\dfrac{dy}{dx} = \left(v\dfrac{du}{dx} - u\dfrac{dv}{dx}\right)\Big/v^2$.

$$\int u\frac{dv}{dx}\,dx = [uv] - \int v\frac{du}{dx}\,dx.$$

$\oint$ integral round a curve.

$$\oint a\cos\theta\, ds = 0$$

Trigonometric solution of triangles

RIGHT-ANGLED TRIANGLES (RIGHT ANGLE AT C)

$$\sin A = \frac{a}{c}. \quad \cos B = \frac{a}{c}. \quad b = \sqrt{c^2-a^2} = \sqrt{(c+a)(c-a)}$$

$$\text{Area} = \frac{a}{2}\sqrt{c^2-a^2} = \frac{ab}{2} = \frac{a^2\cot A}{2} = \frac{b^2\tan A}{2}. \quad \tan A = \frac{a}{b}.$$

$$B = 90^\circ - A,\ b = a\cot A,\ c = \frac{a}{\sin A}\ c = \sqrt{a^2+b^2}. \quad \text{covers}\,A = \frac{b-a}{b}$$

$$a = c\sin A,\ b = c\cos A,\ \text{Area} = \frac{c^2\sin A\cos A}{2}, \quad \text{covers}\,A = \frac{c-b}{c}$$

TRIANGLES

$$\sin\tfrac{1}{2}A = \sqrt{\frac{(s-b)(s-c)}{bc}};\ \cos\tfrac{1}{2}A = \frac{s(s-a)}{bc};\ s = \frac{a+b+c}{2}$$

$$\tan\tfrac{1}{2}A = \sqrt{\frac{(s-b)(s-c)}{s(s-a)}},\ \text{similar values for Angles } B \text{ and } C$$

$$\text{Area} = \sqrt{s(s-a)(s-b)(s-c)} = \tfrac{1}{2}ab\sin C = \frac{a^2\sin B\sin C}{2\sin A}$$

$$b = \frac{a\sin B}{\sin A};\quad c = \frac{a\sin C}{\sin A} = \frac{a\sin(A+B)}{\sin A} = \sqrt{a^2+b^2-2ab\cos C}$$

$$\tan A = \frac{a\sin C}{b-a\cos C};\quad \tan\tfrac{1}{2}(A-B) = \frac{a-b}{a+b}\cot\tfrac{1}{2}C$$

$$a^2 = b^2+c^2-2bc\cos A;\ b^2 = a^2+c^2-2ac\cos B;\ c^2 = a^2+b^2-2ab\cos C$$

Fourier transforms

Among other applications, these are used for converting from the time domain to the frequency domain.

Basic formulae:

$$\int_{-\infty}^{\infty} U(f)\exp(j2\pi ft)df = u(t) \rightleftharpoons U(f) = \int_{-\infty}^{\infty} u(t)\exp(-j2\pi ft)dt.$$

Change of sign and complex conjugates:

$$u(-t) \rightleftharpoons U(-f),\ u^*(t) \rightleftharpoons U^*(-f).$$

Time and frequency shifts (τ and ϕ constant):

$$u(t-\tau) \rightleftharpoons U(f)\exp(-j2\pi f\tau),\ \exp(j2\pi\phi t)u(t) \rightleftharpoons U(f-\phi).$$

Scaling (T constant):

$$u(t/T) \rightleftharpoons TU(fT).$$

Products and convolutions:

$$u(t)\dagger v(t) \rightleftharpoons U(f)V(f),\ u(t)v(t) \rightleftharpoons U(f)\dagger V(f).$$

Differentiation:

$$u'(t) \rightleftharpoons j2\pi fU(f),\ -j2\pi tu(t) \rightleftharpoons U'(f),$$
$$\partial u(t,\alpha)/\partial\alpha \rightleftharpoons \partial U\text{-}f,\alpha)/\partial\alpha.$$

Integration ($U(0) = 0$, a and b real constants):

$$\int_{-\infty}^{t} u(\tau)d\tau \rightleftharpoons U(f)/j2\pi f,\ \int_{a}^{b} v(t,\alpha)d\alpha \rightleftharpoons \int_{a}^{b} V(f,\alpha)d\alpha.$$

Interchange of functions:

$$U(t) \rightleftharpoons u(-f).$$

Dirac delta functions:

$$\delta(t) \rightleftharpoons 1,\ \exp(j2\pi f_0 t) \rightleftharpoons \delta(f-f_0).$$

Rect(t) (unit length, unit amplitude pulse, centred on $t = 0$):

$$\text{rect}(t) \rightleftharpoons \sin\pi f/\pi f.$$

Gaussian distribution:

$$\exp(-\pi t^2) \rightleftharpoons \exp(-\pi f^2).$$

Repeated and impulse (delta function) sampled waveforms:

$$\sum_{-\infty}^{\infty} u(t-nT) \rightleftharpoons (1/T)\,U(f)\sum_{-\infty}^{\infty}\delta(f-n/T);$$
$$u(t)\sum_{-\infty}^{\infty}\delta(t-nT) \rightleftharpoons (1/T)\sum_{-\infty}^{\infty}U(f-n/T).$$

Parseval's lemma:

$$\int_{-\infty}^{\infty} u(t)v^*(t)dt = \int_{-\infty}^{\infty} U(f)V^*(f)df,\ \int_{-\infty}^{\infty}|u(t)|^2dt = \int_{-\infty}^{\infty}|U(\ )|^2d_j.$$

RELATION BETWEEN DECIBELS, CURRENT AND VOLTAGE RATIO, AND POWER RATIO

Table 1.16

$$\text{dB} = 10 \log \frac{P_1}{P_2} = 20 \log \frac{V_1}{V_2} = 20 \log \frac{I_1}{I_2}.$$

dB	I_1/I_2 *or* V_1/V_2	I_2/I_1 *or* V_2/V_1	P_1/P_2	P_2/P_1	*dB*	I_1/I_2 *or* V_1/V_2	I_2/I_1 *or* V_2/V_1	P_1/P_2	P_2/P_1
0.1	1.012	.989	1.023	.977	15.0	5.62	.178	31·6	.031 6
0.2	1.023	.977	1.047	.955	15.5	5.96	.168	35·5	.028 2
0.3	1.035	.966	1.072	.933	16.0	6.31	.158	39.8	.025 1
0.4	1.047	.955	1.096	.912	16.5	6.68	.150	44.7	.022 4
0.5	1.059	.944	1.122	.891	17.0	7.08	.141	50.1	.020 0
0.6	1.072	.933	1.148	.871	17.5	7.50	.133	56.2	.017 8
0.7	1.084	.923	1.175	.851	18.0	7.94	.126	63.1	.015 8
0.8	1.096	.912	1.202	.832	18.5	8.41	.119	70.8	.014 1
0.9	1.109	.902	1.230	.813	19.0	8.91	.112	79.4	.012 6
1.0	1.122	.891	1.259	.794	19.5	9.44	.106	89.1	.011 2
1.1	1.135	.881	1.288	.776	20.0	10.00	.100 0	100	.010 0
1.2	1.148	.871	1.318	.759	20.5	10.59	.094 4	112	.008 91
1.3	1.162	.861	1.349	.741	21.0	11.22	.089 1	126	.007 94
1.4	1.175	.851	1.380	.724	21.5	11.88	.084 1	141	.007 08
1.5	1.188	.841	1.413	.708	22.0	12.59	.079 4	158	.006 31
1.6	1.202	.832	1.445	.692	22.5	13.34	.075 0	178	.005 62
1.7	1.216	.822	1·479	.676	23.0	14.13	.070 8	200	.005 01
1.8	1.230	.813	1.514	.661	23.5	14.96	.066 8	224	.004 47
1.9	1.245	.804	1.549	.645	24.0	15.85	.063 1	251	.003 98
2.0	1.259	.794	1.585	.631	24.5	16.79	.059 6	282	.003 55
2.5	1.334	.750	1.778	.562	25.0	17.78	.056 2	316	.003 16
3.0	1.413	.708	1.995	.501	25.5	18.84	.053 1	355	.002 82
3.5	1.496	.668	2.24	.447	26.0	19.95	.050 1	398	.002 51
4.0	1.585	.631	2.51	.398	26.5	21.1	.047 3	447	.002 24
4.5	1.679	.596	2.82	.355	27.0	22.4	.044 7	501	.002 00
5.0	1.778	.562	3.16	.316	27.5	23.7	.042 2	562	.001 78
5.5	1.884	.531	3.55	.282	28.0	25.1	.039 8	631	.001 58
6.0	1.995	.501	3.98	.251	28.5	26.6	.037 6	708	.001 41
6.5	2.11	.473	4.47	.224	29.0	28.2	.035 5	794	.001 26
7.0	2.24	.447	5.01	.200	29.5	29.8	.033 5	891	.001 12
7.5	2.37	.422	5.62	.178	30.0	31.6	.031 6	1 000	.001 00
8.0	2.51	.398	6.31	.158	31.0	35.5	.028 2	1 260	7.94×10^{-4}
8.5	2.66	.376	7.08	.141	32.0	39.8	.025 1	1 580	6.31×10^{-4}
9.0	2.82	.355	7.94	.126	33.0	44.7	.022 4	2 000	5.01×10^{-4}
9.5	2.98	.335	8.91	.112	34.0	50.1	.020 0	2 510	3.98×10^{-4}
10.0	3.16	.316	10.00	.100	35.0	56.2	.017 8		3.16×10^{-4}
10.5	3.35	.298	11.2	.089 1	36.0	63.1	.015 8	3 980	2.51×10^{-4}
11.0	3.55	.282	12.6	.079 4	37.0	70.8	.014 1	5 010	2.00×10^{-4}

Table 1.16—*continued*

dB	I_1/I_2 or V_1/V_2	I_2/I_1 or V_2/V_1	P_1/P_2	P_2/P_1	*dB*	I_1/I_2 or V_1/V_2	I_2/I_1 or V_2/V_1	P_1/P_2	P_2/P_1
11.5	3.76	.266	14.1	.070 8	38.0	79.4	.012 6	6 310	1.58×10^{-4}
12.0	3.98	.251	15.8	.063 1	39.0	89.1	.011 2	7 940	1.26×10^{-4}
12.5	4.22	.237	17.8	.056 2	40.0	100.0	.010 0	1.00×10^{4}	1.00×10^{-4}
13.0	4.47	.224	20.0	.050 1	50.0	316.0	.003 16	1.00×10^{5}	1.00×10^{-5}
13.5	4.73	.211	22.4	.044 7	60.0	1 000.0	.001 00	1.00×10^{6}	1.00×10^{-6}
14.0	5.01	.200	25.1	.039 8	70.0	3 160.0	.000 32	1.00×10^{7}	1.00×10^{-7}
14.5	5.31	.188	28.2	.035 5	80.0	10 000.0	.000 10	1.00×10^{8}	1.00×10^{-8}

METRIC AND DECIMAL EQUIVALENT OF FRACTIONS OF AN INCH

Table 1.17

Inches		*mm*	*Inches*		*mm*
$\frac{1}{64}$	*.016*	0.396	$\frac{33}{64}$	*.516*	13.096
$\frac{1}{32}$	*.031*	0.793	$\frac{17}{32}$	*.531*	13.492
$\frac{3}{64}$	*.047*	1.190	$\frac{35}{64}$	*.547*	13.890
$\frac{1}{16}$	*.063*	1.587	$\frac{9}{16}$	*.563*	14.287
$\frac{5}{64}$	*.078*	1.984	$\frac{37}{64}$	*.578*	14.683
$\frac{3}{32}$	*.094*	2.381	$\frac{19}{32}$	*.594*	15.080
$\frac{7}{64}$	*.109*	2.778	$\frac{39}{64}$	*.609*	15.477
$\frac{1}{8}$	*.125*	3.175	$\frac{5}{8}$	*.625*	15.875
$\frac{9}{64}$	*.141*	3.571	$\frac{41}{64}$	*.641*	16.271
$\frac{5}{32}$	*.156*	3.968	$\frac{21}{32}$	*.656*	16.667
$\frac{11}{64}$	*.172*	4.365	$\frac{43}{64}$	*.672*	17.064
$\frac{3}{16}$	*.188*	4.762	$\frac{11}{16}$	*.688*	17.462
$\frac{13}{64}$	*.203*	5.159	$\frac{45}{64}$	*.703*	17.858
$\frac{7}{32}$	*.219*	5.556	$\frac{23}{32}$	*.719*	18.255
$\frac{15}{64}$	*.234*	5.955	$\frac{47}{64}$	*.734*	18.652
$\frac{1}{4}$	*.25*	6.350	$\frac{3}{4}$	*.75*	19.050
$\frac{17}{64}$	*.266*	6.746	$\frac{49}{64}$	*.766*	19.446
$\frac{9}{32}$	*.281*	7.143	$\frac{25}{32}$	*.781*	19.842
$\frac{19}{64}$	*.297*	7.540	$\frac{51}{64}$	*.797*	20.239
$\frac{5}{16}$	*.313*	7.937	$\frac{13}{16}$	*.813*	20.637
$\frac{21}{64}$	*.328*	8.334	$\frac{53}{64}$	*.828*	21.033
$\frac{11}{32}$	*.344*	8.730	$\frac{27}{32}$	*.844*	21.429
$\frac{23}{64}$	*.359*	9.127	$\frac{55}{64}$	*.859*	21.827
$\frac{3}{8}$	*.375*	9.525	$\frac{7}{8}$	*.875*	22.225
$\frac{25}{64}$	*.391*	9.921	$\frac{57}{64}$	*.891*	22.621
$\frac{13}{32}$	*.406*	10.318	$\frac{29}{32}$	*.906*	23.017
$\frac{27}{64}$	*.422*	10.715	$\frac{59}{64}$	*.922*	23.414
$\frac{7}{16}$	*.438*	11.112	$\frac{15}{16}$	*.938*	23.812
$\frac{29}{64}$	*.453*	11.508	$\frac{61}{64}$	*.953*	24.208
$\frac{15}{32}$	*.469*	11.905	$\frac{31}{32}$	*.969*	24.604
$\frac{31}{64}$	*.484*	12.302	$\frac{63}{64}$	*.984*	25.002
$\frac{1}{2}$	*.5*	12.700			

GREEK ALPHABET AND SYMBOLS

alpha	Α	α	angles, coefficients, area
beta	Β	β	angles, coefficients
gamma	Γ	γ	specific gravity
delta	Δ	δ	density, increment, finite difference operator
epsilon	Ε	ϵ	napierian logarithm, linear strain, permittivity, error, small quantity
zeta	Ζ	ζ	co-ordinates, coefficients, (Cap) impedance
eta	Η	η	magnetic field strength, efficiency
theta	Θ	θ	angular displacement, time
iota	Ι	ι	inertia
kappa	Κ	κ	bulk modulus, magnetic susceptibility
lambda	Λ	λ	permeance, conductivity, wavelength
mu	Μ	μ	bending moment, coefficient of friction, permeability
nu	Ν	ν	kinematic viscosity, frequency, reluctivity
xi	Ξ	ξ	output coefficient
omicron	Ο	ο	
pi	Π	π	circumference ÷ diameter
rho	Ρ	ρ	specific resistance
sigma	Σ	σ	(Cap) summation, radar cross section, standard deviation
tau	Τ	τ	time constant, pulse length
upsilon	Υ	υ	
phi	Φ	φ	flux, phase
chi	Χ	χ	(Cap) Reactance
psi	Ψ	ψ	angles
omega	Ω	ω	angular velocity, ohms

2 HISTORY OF ELECTRONICS

HISTORY OF ELECTRONICS 2

2 HISTORY OF ELECTRONICS

In 1897 Sir J. J. Thomson confirmed the existence of the electron as a negative charge of electricity; the word *electronic* was probably coined about this time and was certainly used by Professor J. A. (later, Sir Ambrose) Fleming in 1902. The expression *electronics*, however, found no great favour in Britain for many years. It began to appear about 1940 as an import from the U.S.A. but did not come into general acceptance until after World War II.

As everything in the known universe is electronic in character, the expression is not a felicitous one to apply to a section of electrical science, in which context it has had to acquire a special meaning. The definition of *electronics* (see Section 1) in practice needs considerable qualification; for instance, a Martian observer, with no background of common usage to draw upon, would be perplexed to find that magnetohydrodynamic (m.h.d.) power generation, radioactivity, fluorescent lamps and neon signs (all of which fulfil the criteria) are not generally regarded as electronic devices. He would also be confused to discover that the overwhelming majority of the components used in electronic engineering—resistors, capacitors, inductors, etc.—are wholly electrical devices.

ELECTRONICS IN THE NINETEENTH CENTURY

Although electronics is very much a twentieth-century activity, the fundamental building blocks, namely photoelectric, thermionic, semiconductor and gas discharge phenomena, were entirely nineteenth-century discoveries. They were, however, during that period, mainly scientific curiosities, having few applications outside of the laboratory, and it has been the role of the present century to develop them into commercial devices, equipments and systems.

Photoelectricity

Probably the earliest electronic device on record (although not recognised as such at the time) was the photovoltaic cell produced by Becquerel in 1839. The discovery of the photoconductive behaviour of selenium occurred in 1861 but did not receive much attention until 1873 when Willoughby-Smith read a paper to the IEE on the subject. The first practical application came in 1878 when Dr. Graham Alexander Bell and Sumner Tainter used a selenium cell in their Photophone (telephony via light waves). Hertz was the first to observe the photoemissive effect (1887) and confirmation was provided by Wiedemann and Ebert. Hallwachs and also Elster and Geitel studied the effect intensively; in 1890 the last-mentioned co-workers produced the prototype of the modern photoemissive tube.

Thermionics

The first step towards the thermionic valve came in 1873 when Guthrie noted that a heated metal ball, when placed near a charged electroscope, discharged it. In 1880 Elster and Geitel enclosed a lamp filament and a metal plate in a vacuum and found that a tiny current flowed from filament to plate across the vacuum. In the early 1880s both

Edison and Professor J. A. Fleming (who was at that time doing research work for Edison) were investigating the premature blackening of the glass envelopes of the Edison lamps. In an experimental version a metal plate having an external connection had been inserted into the lamp; Edison and Fleming both noted that when the plate was given a positive potential with respect to the filament a direct current flowed across the vacuum and through the external circuit; when the polarity was reversed, no current flowed. Neither man investigated the phenomenon at the time, although it was recorded and passed into history as the Edison Effect. The diode which they had unwittingly manufactured remained unrecognised as such for another 20 years.

Gas discharges

From the 1850s onward the behaviour of high voltage electricity through gases was the subject of considerable research, following Plucker's discovery that when such a voltage was connected between two separated electrodes in a near-evacuated glass cylinder a purple glow could be seen on the wall of the tube. Hittorf, Goldstein and Sir William Crookes investigated further—the latter with the familiar Crookes tube with its *Maltese Cross* electrode—and established that the glow was produced by the impact of invisible rays upon the glass and that these rays travelled from the negative electrode to the positive. Crookes believed that these *kathode rays* as they were called were negatively charged particles; this was confirmed by Hallwachs and (in 1897) by Sir. J. J. Thomson. The particles were termed *electrons.*

Research now divided. Tesla and others concentrated on experiments with gases to obtain a maximum overall glow for lighting purposes (the modern fluorescent lamp is one outcome), while some researchers studied the rays themselves, finding that they could cause certain materials to fluoresce. In 1897 Braun developed a much improved cathode-ray tube in which a mica screen coated with phosphors was mounted on the end wall; in 1902 he added deflection coils (Fleming had shown that the beam could be moved by varying the current through such coils) and thus produced the forerunner of the modern oscilloscope. To this, Wehnelt contributed two notable improvements, namely, a cylindrical control grid and also an oxide-coated filament to provide a copious supply of electrons. By so doing the cathode-ray tube was converted into a thermionic device—the first with a practical application.

X-rays

An off-shoot of the work on cathode rays was the discovery of X-rays by Professor Röntgen in 1895. These electromagnetic waves have a wavelength (10^{-1} nm to 10^{-3} nm), much shorter than that of visible light. X-rays are generated by focusing high-velocity electrons emitted from a cathode on to a target (anode) which is commonly of tungsten or rhenium.

The penetrating effect of X-rays and their ability to activate a photographic emulsion have been used in medical diagnosis since the early days; more recently these same properties have been used for non-destructive testing of materials (castings, weldings, etc.). All X-rays have an ionising effect and are biologically destructive; these properties are used in medical therapy and for sterilisation.

With the availability of particle accelerators and radio-active sources of high energy particles, the use of conventional X-ray tubes for therapy has now declined.

Semiconductors

In 1874 Braun discovered the semiconductor effect in some metallic sulphides, notably lead sulphide and iron sulphide. The first application of this effect was made fortuitously by Professor D. E. Hughes in 1878–79. Hughes discovered a means of generating electromagnetic waves (although he knew nothing of Clerk Maxwell's work) and devised various detectors, most of which were re-invented many years after. One of these was an iron needle in contact with a globule of mercury; in this, almost certainly, an oxide film on the mercury provided genuine rectification. Although Hughes anticipated Hertz in the generation of radio waves by five years and others by 10 years in the means of detecting them, he was discouraged from publishing and so his achievements went unrecognised for many years.

In 1835 Munk had discovered that certain metallic powders changed in electrical conductivity when an electric spark occurred near them. Over the years the phenomenon was resurrected at intervals; by S. A. Varley in 1866; by Professor Calzecchi-Onesti in 1884 and by Branly in 1890. No great attention was paid to it until Professor Minchin and Professor (later Sir Oliver) Lodge independently suggested that the effect might be caused by electromagnetic waves emanating from the spark discharge. In 1894, Lodge took a tube of iron filings as used by Branly in his experiments and demonstrated that it could be used as a detector of Hertzian waves. Lodge called the device a coherer because, under the influence of the waves, the filings clung together and had to be tapped before the device could receive another wavetrain. (It was not a rectifier but a relay which shortcircuited on encountering radio-frequency signals.) The coherer became widely used in early wireless telegraphy but it is perhaps of interest to note that when, in 1901, Marconi received the first signals across the Atlantic he used an iron–mercury globule rectifier which had been re-invented in 1899 by Professor Tommasina. This detector was variously known as the *Castelli*, the *Solari* or the *Italian Navy* self-restoring coherer.

ELECTRONICS IN THE TWENTIETH CENTURY

Paradoxically, radio communication, from which electronics sprang, was not at the outset recognisably electronic in character. When, in 1895–96, Marconi developed the first practical system of wireless telegraphy, his apparatus, with the possible exception of the coherer, was basically electro-mechanical. Others soon produced rival systems; some, like Marconi's, were spark-derived, while others, a little later, employed arc or r.f. alternator methods and although both spark and arc fall within the specification of the official definition of electronics, they contained no elements which would be familiar to today's electronics engineers. All three approaches—spark, arc and r.f. alternator—entirely monopolised long-distance radio transmissions until the 1920s.

The birth of thermionic electronics occurred in 1904 when Fleming (then technical consultant to Marconi) found one of the old experimental Edison lamps in a cupboard and had the idea of trying it as a rectifier of radio signals. It worked. Fleming made an improved version which worked even better and then patented it on behalf of the Marconi Company.

Marconi was not unduly impressed. His magnetic detector, developed two years earlier, would do everything the diode could do, and was more robust (in fact, Fleming's valve never superseded it). Then in 1907 Dr. Lee de Forest announced the Audion, a valve with a third electrode (nicknamed the *grid-iron*, later abbreviated to *grid*). This valve, claimed its inventor, could amplify weak signals. The Marconi Company began litigation against de Forest, claiming that the Fleming diode was the master-invention and that the grid was merely an appendage; the initial verdict was for the Marconi Company, but this was overset in another court—and so it went on, with action and counter-action. Not until the 1920s was the issue settled, and then only by compromise; thus, in the early years, valve development was stultified because no one had a clear right to manufacture the triode.

At the outset, the principles of action of the triode were imperfectly understood; it was erratic in performance—and performance at best was poor. Gradually however, improvements were made, particularly in high vacuum techniques, and in 1913 came the great discovery that the triode could be made to oscillate. H. J. Round of the Marconi Company demonstrated valved radio telephony in that year but A. Meissner of Germany was the first to patent the valve oscillator, just a little ahead of several other workers.

World War I gave a tremendous impetus to valve development; by 1919 direction finding equipment and relatively low powered radio telephony transmitters were in considerable use by the armed services, while for reception the crystal detector (first used by Dunwoodie in 1906) was commonly used in conjunction with one or two stages of valve amplification, or superseded altogether by the triode detector. Higher transmitting powers were being achieved by connecting valves in parallel and in 1915 a 300-valve transmitter at Arlington, U.S.A., succeeded in spanning the Atlantic by radio-telephony. Progress was such that by 1919 a British transmitter did this using only three main valves.

Although it was not realised at the time, the end of the war was a turning point in electronics history. Hitherto, virtually the only applications of electronic devices had been in radio communication, but now an era of diversification was about to begin.

Radio communications

In November 1921 a newly-designed 100 kW valved transmitter at the Marconi station at Caernarvon established contact with Australia and in doing so relegated existing spark, arc and r.f. alternator systems to obsolescence. A further revolution came in 1924 with the experimental introduction of the Marconi–Franklin h.f. beam system, which, when fully developed, was to become the backbone of long distance point-to-point radio communication and remained so until the comparatively recent advent of satellite techniques. (One of Franklin's many inventions in connection with the beam system was the concentric feeder, which, as the coaxial cable, is ubiquitous today.)

The success of the h.f. system encouraged research into the even higher frequencies as potential message-carriers and this led in turn to the development of valves which would oscillate at these frequencies. World War II brought a vast acceleration in this and all other branches of electronics research and the knowledge thus gained was put to commercial usage in the post-war period—the klystron and travelling-wave-tube, for example, were key devices in opening world markets in v.h.f., u.h.f. and s.h.f. point-to-point multichannel links. Other new communication methods introduced include the ionospheric and tropospheric scatter systems, but by far the most significant innovation of recent years has been communication via satellite. Various factors combined to make this possible; the inventions of the transistor, the microcircuit and the printed board; the rocket techniques developed by Germany during the war and subsequently improved upon by the U.S.A. and the U.S.S.R. during the height of the 'cold war'—all these made possible the evolution of ultra light-weight compact equipments and provided the capability of putting the satellites into orbit.

On 10 July 1962 the Telstar satellite clearly demonstrated the advantages of the new approach and the subsequent introduction of geostationary satellites emancipated long-distance circuits from the vagaries of ionospheric reflection, provided multichannel working on a round-the-clock basis and have proved themselves to be economically viable.

While the electronics in the satellites are a hybrid of reasonably conventional thermionic (usually travelling wave tube) and solid-state microcircuit techniques, special wideband low-noise amplifiers are necessary at the earth terminals. At first, masers (Microwave Amplification by the Stimulated Emission of Radiation) were used but today the trend is towards parametric amplifiers. The maser concept was introduced by Townes in 1951, while the history of the parametric amplifier dates back to Lord Rayleigh (and even, perhaps, to Faraday). The modern approach to a practical device is due to the work of Suhl and Weiss in the late 1950s but workable *paramps* were first made by Uhler and others in 1958 and considerable development has taken place since. Even at room temperature the parametric amplifier has a low noise performance, but the use of refrigeration gives a noise figure comparable to that of a maser, but with a much greater bandwidth.

Sound broadcasting

In 1916 David Sarnoff of the American Marconi Company (later the Radio Corporation of America) put forward a plan for entertainment broadcasting, but this was shelved. After World War I, various radio companies developed new telephony transmitters, foreseeing a peacetime market for message-carrying by this means, and it became the custom for their engineers to relieve the monotony of reciting lists into a microphone (as a means of range testing) by playing the occasional gramophone record. To everyone's surprise, requests began to come in from amateurs (many of whom had been in signals units during the war), asking for more music. The demand grew, and in this fashion broadcasting began—a classic instance of serendipity.

Broadcasting to the general public began in the U.S.A. in 1920 (station KDKA) but in Britain, despite successful concerts from the Marconi Works at Chelmsford in 1920 (Melba and Melchior were among the artistes) the Post Office vetoed further transmissions on the grounds that they might interfere with legitimate services. Only after a petition by the amateur wireless societies was the embargo lifted and in January 1922 permission was granted to the Marconi Company to broadcast a concert for a halfhour once a week. On 14 February the Marconi station 2MT started broadcasting under these terms. A second permit followed and in May 1922, station 2LO at Marconi House, London, was brought into service. Its success, and that of 2MT, encouraged 23 other radio manufacturers to apply for permits—a circumstance that would clearly lead to chaos. As a solution a consortium of radio manufacturers was formed, named the British Broadcasting Company, which constituted a single broadcasting authority. This organisation took over responsibility for 2LO on 14 November 1922, after which other stations were quickly inaugurated in other parts of the country. As from 31 December 1926 the BBC was reconstituted to become a Corporation and the radio manufacturing companies ceased to be directly responsible for broadcasting in the U.K.

The impact of sound broadcasting was tremendous. Such was the public demand for receivers that two new sub-industries were created almost overnight; one catering for factory-built domestic receivers and the other for components for home construction. Aided by a spate of periodicals, home construction became a major British hobby; at first the simple crystal set was highly popular but was gradually superseded by battery-driven valve receivers. By the 1930s, the employment of mass production techniques in factory receivers had reduced costs to a figure competitive with home construction; circuits were becoming more complex (the supersonic heterodyne or *superhet* principle, invented by Armstrong in 1919 was coming into favour) and these factors, in conjunction with the arrival of the *all-mains* receiver, caused the wane of home construction. By this time, however, the domestic receiver and components industries had stabilised and sound broadcasting had become an integral part of everyday life.

The broadcasting boom gave great impetus to research, particularly in valve technology, and multi-electrode thermionic devices were rapidly introduced in the 1920s and 1930s. Applications other than for broadcasting soon became apparent and a hiving-off process began, which has continued to the present day. The gramophone industry for example, which had been dealt a severe blow by sound broadcasting, derived a new lease of life from electronic sound recording and reproduction and today is a major industry in its own right. Audio amplifier techniques were applied in the film industry, resulting in the *talking picture*. Public address techniques sprang from the same source. Another sub-industry, devoted to test equipment and instrumentation, was emerging; thermionic valve amplifiers were becoming more and more commonplace in general research laboratories and in advanced medical centres. Line communication systems were putting amplifiers to good use; in short, electronic devices were emerging from the confines of radio communication and were becoming ubiquitous tools.

On the transmission side of sound broadcasting, great strides were also being made. One important development was frequency modulation (f.m.). F.M. has its historical roots in 1902 but there was a long period of neglect until Westinghouse investigated it briefly in the 1920s. It is to Armstrong, however, that the credit must go, not only for its development but his years of perseverance to get the technique accepted in the U.S.A. It was not until 1950 that the BBC's first f.m. broadcasting station (at Wrotham Hill, Kent) was completed, after which a network of f.m. stations was provided throughout the U.K.

Television broadcasting

This also owes its inception to sound broadcasting although its concept goes back much earlier even than wireless telegraphy. As far back as 1847 practical systems of transmitting still pictures were in being and the wide attention given to the photoconductive properties of selenium in the 1870s brought renewed interest in trying to devise means of transmitting pictures having movement. Among the experimenters were Carey, Ayrton and Perry, de Paiva, Leblanc, Senlac and Nipkow; none succeeded but all made contributions to the state of the art. Indeed, Nipkow's ideas of 1884 would have worked, had he possessed thermionic amplifiers and a better photocell. The word *television* was coined by Perskyi in 1900.

In 1907 Professor Rosing, a Russian scientist, succeeded in transmitting images of geometrical shapes, but any attempt at movement produced picture break-up. Rosing's transmitter embodied mirror drum scanning (invented by Professor Weiller in 1889) and, at the receiver, electromagnetic scanning and a cathode-ray tube display.

A. A. Campbell Swinton in 1908 and again in 1911 drew up a remarkable blueprint for the future; his proposed system used a photomosaic form of camera picture tube at the transmitting end and a cathode-ray tube display at the receiver. As far as is known the equipment was never built, and the brilliant concept, upon which the television system of today is based, was all but forgotten. It was in 1911 also that it was first suggested (by A. Sinding-Larsen) that radio waves might be used as a carrier for picture impulses.

J. L. Baird in 1926 was the first to demonstrate true television pictures. His apparatus was essentially Nipkow's rotating disc system of 1884, with an improved photocell and the addition of amplifiers. In quick succession Baird also demonstrated Noctovision (televising in darkness), colour and stereoscopic television. The pictures were small, of low definition and had no entertainment value; nevertheless his successes encouraged many others to experiment with mechanical systems. In 1930 the BBC began experimental transmissions using the Baird apparatus.

In the U.S.A. in the 1920s two men began working (quite independently) on all-electronic scanning; Farnsworth on his 'Image Dissector' and Zworykin (a former pupil of Rosing) on his 'Iconoscope'. The practical difficulties in both devices were enormous and even by 1933, when Zworykin was able to demonstrate a 240-line picture, large-scale manufacture of his Iconoscope was still not possible. It was, however, the pattern for the future as it possessed the important feature of energy-storage between scans, which neither the Image Dissector nor the various mechanical systems had. Television owes a great debt to Zworykin, both for his camera tube and for the notable improvements he made to the cathode-ray tube.

In England in the early 1930s Baird in his laboratory had turned his attention to high-definition television, but still relied on mechanical scanning. However, by 1935 he faced strong competition from Marconi-EMI, for a brilliant Electric and Musical Industries team led by Shoenberg had developed the Emitron, a camera tube similar in principle to Zworykin's and this, allied to Marconi expertise in wideband modulation and v.h.f. transmission, provided a complete high-definition system.

In 1935 the Selsdon Committee recommended that the U.K. should have a high-definition service and by 1936 the BBC's first station was built at Alexandra Palace, London. A public trial of both the Baird and Marconi-EMI systems was arranged and the station began official programme service on 12 November 1936, each system taking its turn. By February 1937 the Marconi-EMI system was declared the better and thereafter carried the service exclusively. In September 1939 the Alexandra Palace station closed for the duration of the war; it did not reopen until 7 June 1946, after which the BBC pushed rapidly ahead with plans to provide television coverage throughout the U.K.

On 30 July 1954 the Independent Television Authority (now Independent Broadcasting Authority) was formed and on 22 September 1955 its London station came into service, to be followed by a U.K. network. In 1964 the BBC opened its second network, BBC2, operating a 625-lines at u.h.f. The IBA now also have a u.h.f. network. Colour television came into official service in Britain in the summer of 1967, using the PAL system, a German development of the American NTSC system which had been in public service in the U.S.A. since 1954.

Among the many important technical developments of recent years is the electronic field-store converter, first developed by the BBC in 1967 to permit the exchange of television programmes between countries using systems having different line standards and field frequencies. Another notable advance was the introduction of video recording on tape. The first audio tape recorder (operating with steel wire or ribbon) was exhibited by Poulsen at the Paris Exhibition of 1900 but remained virtually undeveloped for many years. The technique was resurrected in the 1920s. World War II saw further considerable developments, with magnetic oxide impregnated paper and plastic tapes coming into use. After the war—and particularly after the invention of the transistor—audio tape recorders for domestic and commercial purposes came into wide usage. The problem of recording video signals on tape is a much more difficult one and it was not until 1956 that a really satisfactory process was evolved (by the Ampex Corporation in the U.S.A.). Since then the process, with its facility of instant playback, has become general in television programme production, although film is also widely used.

Electronic navigational aids

Professor Elihu Thomson took out the first patent for directional reception of radio waves in 1899, but the basic principles of loop reception were known to Hertz. One of the most successful of the early direction-finding systems was that of Bellini and Tosi; just before World War I, H. J. Round developed a valved form of Bellini-Tosi equipment and this became the war's *secret weapon* (it was responsible for the battle of Jutland and the destruction of Zeppelins). Shipborne and airborne direction finders soon evolved.

Today, ships and aircraft carry a considerable complement of electronic navigational aids in addition to the normal communications equipment. A modern aircraft for example, may carry electronic instrumentation for automatic take-off and landing, in addition to automatic direction finders (radio compasses), radio altimeters, weather radar, doppler navigators and other devices. A military aircraft tends to be packed with electronics for communication, navigation, and offensive and defensive action.

Radar

This term did not come into use in the U.K. until well into the World War II period. Of American origin, it is an acronym (RAdio Detection And Ranging). The former British terms were RDF (Radio Direction Finding), or Radiolocation.

In 1888, Hertz found that radio waves could be reflected by objects in their path. Tesla, in 1900, suggested that this attribute could be used for detecting moving objects, while in 1904 Hülsmeyer patented a primitive form of radar. Marconi, in 1922, suggested means by which ultra-short radio waves could be used to detect ships but did no work on it at that time.

In 1924, Appleton and Barnett used similar techniques to those later employed for c.w. radar for their ionospheric sounding work and in 1925 Breit and Tuve developed a pulsed system for similar research. In Britain the first known proposal for a radar system came from Butement and Pollard in January 1931. Although their equipment produced short-range results the work was abandoned for lack of government support.

In 1935 Watson-Watt (later Sir Robert) suggested that radio waves might be used to detect aircraft at a distance and outlined a means of doing so. Intensive research began and by 1939 Britain possessed a defensive chain of highly secret RDF stations, while gun-laying and airborne equipments were also being developed. Contrary to popular belief, other countries, notably Germany, France and the U.S.A. possessed radar prior to the war but lacked Britain's highly developed control system. In 1941 the development of the resonant cavity magnetron by Boot and Randall gave the Allies a powerful new weapon in high-power centimetric radar. Later in the war the proximity fuse and radar-aligned guns successfully contained the German V1 flying bomb menace. Shipping and aircraft also made extensive use of radar for attack and defence.

In the post-war years highly complex radar installations have come into use as air traffic control aids at major airports. Shipborne radar is commonplace, while meteorological radar now fulfils a valuable role in weather forecasting. Speed-checking equipment, using radar principles, is used by many police forces.

Transistors

The semiconductor oscillator predates the discovery of the thermionic valve oscillator, for in 1909–11 Dr. Eccles in the course of his work on semiconductors produced an oscillating crystal. No significant further progress was made however until the 1920s when Scott-Taggart, Lossev and Podliasky were among those who revived interest in the matter.

The foundations of modern semiconductor techniques were laid by Planck's quantum theory of 1901 and by the papers of others over the years, particularly those of Schrödinger and Heisenberg in 1926–27. Shottky's work on semiconductor rectifier theory (1940) provided a further impetus. Meanwhile, however, Professor Lilienfeld, in 1930, had patented a semiconductor device similar to an insulated gate field-effect transistor. The device did not work, largely because of the inadequacy of the semiconductor material Lilienfeld had at his disposal. It was not until 1947 that Bardeen, Brattain and Shockley of Bell Telephone Laboratories produced the point-contact transistor (the word, a telescoping of *transfer resistor* was coined by Pierce, of Bell Telephones). In 1951 Shockley patented the junction transistor; in 1959 came another vital step when the planar technique was developed.

The subsequent years have seen monumental further improvements in the technology and performance of the transistor, which has now ousted the thermionic valve from most of its former applications in the lower power categories.

Printed circuits and microcircuits

During World War II the need for lighter, more compact, equipments led to research into means of achieving these aims. One approach was to sub-miniaturise components, while retaining their conventional forms; another was to use thin film-techniques (in rudimentary form) to manufacture certain components, while a third was to replace the conventional wiring by printing metallised paths on to insulating boards. Both thin-film and printed board techniques continued in development after the war but the breakthrough came with the invention of the transistor, for the low voltages and currents associated with it permitted the use of resistors and capacitors of much smaller physical dimensions, suitable for wiring on to printed boards, and enabled such components to be encapsulated into modules.

In the 1950s the cold war and the consequent acceleration of guided missile and space vehicle programmes by the U.S.A. and the U.S.S.R. brought the concept of producing whole circuits in one tiny block. The two main approaches to this were the thin-film techniques and the integrated semiconductor method; the latter had the advantage that not only passive components could be formed but active ones (transistors and diodes) also. At first, the small size and light weight were the prime advantages but it was soon realised that well-made microcircuits were inherently far more reliable than conventional components because of the great reduction in the number of intercomponent connections.

When microcircuit techniques became available to commercial electronics, a new type of industry gradually evolved which owes much more to photolitho techniques than to conventional processes of manufacture. A further benefit accrued in that the processes are eminently suitable to mass production. Just as the transistor edged out the thermionic valve, so now is the large-scale integrated circuit approach taking over from discrete transistors and components in many areas.

Computers

The first computer was the *Difference Engine* designed by Charles Babbage in 1822. This was wholly mechanical and was never completed, but it did embody some of the features of the modern computer.

No further progress was made for over 100 years, and it was not until after World War II that the first automatic calculators (employing thermionic valves) appeared; one of these, ENIAC, embodied 18 000 valves (usually some failed every time the equipment was switched on). This computer was built at the Pennsylvania University in 1946–47.

The first computers to work under the control of a program stored in the computer itself were built at Cambridge and Manchester universities in 1949. Commercial development in the U.K. was begun by Ferranti and Elliott Brothers and other companies followed soon after. The first deliveries began in 1954. The innovations of transistors and printed circuits saw the introduction of a second generation of computers; the first British transistor-based machines began to appear in 1960. The third generation, now in production, embodies microcircuits, which provide even greater reliability and higher switching speeds.

Lasers

The laser was a logical extension of the development of the maser (Microwave Amplification by Stimulated Emission of Radiation), the 'L' standing for 'Light'. The theoretical possibility of producing coherent light was stated by Einstein in 1917 but little was done in this direction until Schawlaw and Townes suggested (in 1958) that an optical maser was theoretically possible. In 1960 Dr. Maiman demonstrated the first true laser; this used a ruby crystal and produced a pulsed output. Another laser, using trivalent uranium, was also described in that year by Sorkin and Stevenson.

In 1961 the first gas discharge laser (which provided continuous emission), was produced by Bennett, Herriott and Javan and in the following year several research laboratories in the U.S.A. announced the development of a continuous-wave laser which used gallium arsenide in semiconductor junction form.

All this work was done in the U.S.A. although several countries were soon producing lasers. Unlike the maser, the laser did not immediately find a significant application but was rather the outcome of scientific curiosity. However, applications were soon forthcoming and many others will doubtless follow; among the areas in which the device is already in use, or has potential applications, are communications, holography, radar, aviation, control systems and medical research and surgery.

Conclusion

In the preceding pages an outline has been given of some of the main stages in the development of electronics. Today, electronics is an essential part of the fabric of living, serving the community in such diverse applications as line communications, railway signalling, machine tool control, medical diagnosis, chemical analysis, traffic engineering, process control and, indeed, in almost every facet of modern life, each of which has a history in its own right.

3 GENERAL PHYSICAL BACKGROUND

GENERAL PHYSICAL
BACKGROUND 3

3 GENERAL PHYSICAL BACKGROUND

PHYSICAL QUANTITIES

Engineering physics

Engineering technology involves energy associated with physical materials. The object is to employ materials—solid and fluid—to convert, transport or radiate energy. A comprehensive all-embracing theory or process is quite impossible, for energy has many forms, and materials differ profoundly in their physical nature. Many separate technologies have been built up around specific engineering systems, and for materials in a bulk macroscopic form, or in microstructure, or in molecular, atomic and subatomic structure. Each technology applies only to its own forms of energy and material structure, i.e., to its specific technological system.

Energy

Like 'force' or 'time' or 'mass', energy is a unifying *concept* invented to explain systematically certain important physical phenomena. Appreciation of the meaning of the concept is largely intuitive, aided by a study of 'energetic' physical systems.

Mechanical force systems possess potential energy, and tend to positions of equilibrium in which the potential energy is a minimum. When the potential energy is reduced, work is done by the system as kinetic energy of motion; when the potential energy is increased, energy is taken in from outside the system, i.e., work is done on the system. Energy is associated with gravitational, chemical, thermal, magnetic and electric systems; it can be stored, transported, radiated and converted from one form to another. In these processes it is conserved, i.e., the total quantity does not change.

Energy almost defeats precise definition, but statements such as the following aid the intuitive grasp of the meaning:

ENERGY is the capacity for doing *work*, using the word 'work' in the widest sense of 'action'.

WORK is the measure of the change of energy *state*.

STATE is the measure of the energy condition of a *system*.

SYSTEM is the ordered arrangement of related physical entities or processes, or of their *model*.

MODEL is the pictorial diagram used to describe the system, or the mathematical statement set up to describe its *behaviour*.

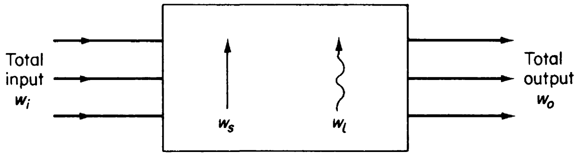

Figure 3.1 Energy balance

BEHAVIOUR is the verbal or mathematical description of the energy processes involved in changes of state. *Storage* occurs if the work done on a physical system is recoverable in the original form. *Conversion* takes place when related changes in state concern different forms of energy and if the action is reversible. *Dissipation* is an irreversible conversion into heat. *Transmission* and *radiation* are forms of energy transport in which there is a finite propagation time.

In a physical system, *Figure 3.1*, there will be identifiable energy inputs w_i and outputs w_o of any form. The system itself may store energy w_s and dissipate energy w_l. Then the conservation principle states that

$$w_i = w_s + w_l + w_o$$

Comparable statements can be made for energy changes Δw, and for energy rates $\Delta w/\Delta t = p$, i.e., the powers:

$$\Delta w_i = \Delta w_s + \Delta w_i + \Delta w_o \quad \text{and} \quad p_i = p_s + p_i + p_o$$

ELECTRICITY

Most of the observed electrical phenomena are explicable in terms of electric *charge* at rest, in motion and in acceleration. Static charges give rise to an *electric field* of force; charges in motion carry an electric field accompanied by a *magnetic field* of force; charges in acceleration develop a further field of *radiation.*

Modern physics has established the existence of elemental charges and their responsibility for observed phenomena. Modern physics is complex: it is customary to explain phenomena of engineering interest at a level adequate for a clear and reliable concept, based on the electrical nature of matter.

Molecules, atoms and electrons

Material substances, whether solid, liquid or gaseous, are conceived as composed of very large numbers of *molecules.* A molecule is the smallest portion of any substance which cannot be further subdivided without losing its characteristic material properties. In all states of matter molecules are in a state of rapid continuous motion. In a *solid* the molecules are relatively closely 'packed' and the molecules, although rapidly moving, maintain a fixed mean position. Attractive forces between molecules account for the tendency of the solid to retain its shape. In a *liquid* the molecules are less closely packed and there is a weaker cohesion between them, so that they can wander about with some freedom within the liquid, which consequently takes up the shape of the vessel in which it is contained. The molecules in a *gas* are still more mobile, and are relatively far apart. The cohesive force is very small, and the gas is enabled freely to contract and expand. The usual effect of heat is to increase the intensity and speed of molecular activity so that 'collisions' between molecules occur more often; the average spaces between the molecules increase, so that the substance attempts to expand, producing internal pressure if the expansion is resisted.

Molecules are capable of further subdivision, but the resulting particles, called *atoms,* no longer have the same properties as the molecules from which they came. An atom is the smallest portion of matter that can enter into chemical combination or be chemically separated, but it cannot generally maintain a separate existence except in the few special cases where a single atom forms a molecule. A molecule may consist of one, two or more (sometimes many more) atoms of various kinds. A substance whose molecules are composed entirely of atoms of the same kind is called an *element.* Where atoms of two or more kinds are present, the molecule is that of a chemical *compound.* At present 102 atoms are recognised, from combinations of which every conceivable substance is made.

As the simplest example, the atom of hydrogen has a mass of 1.63×10^{-27} kg and a molecule (H_2), containing two atoms, has twice this mass. In one gram of hydrogen there are about 3×10^{23} molecules with an order of size between 1 and 0.1 nm.

Electrons, as small particles of negative electricity having apparently almost negligible mass, were discovered by J. J. Thomson, on a basis of much previous work by many investigators, notably Crookes. The discovery brought to light two important facts: (1) that atoms, the units of which all matter is made, are themselves complex structures, and (2) that electricity is atomic in nature. The atoms of all substances are constructed from particles. Those of engineering interest are: *electrons*, *protons* and *neutrons*. Modern physics concerns itself also with *positrons*, *mesons*, *neutrinos* and many more. An *electron* is a minute particle of negative electricity which, when dissociated from the atom (as it can be) indicates a purely electrical, nearly mass-less nature. From whatever atom they are derived, all electrons are similar. The electron charge is $e = 1.6 \times 10^{-19}$ C, so that 1 C = 6.3×10^{18} electron charges. The apparent rest mass of an electron is 1/1850 of that of a hydrogen atom, amounting to $m = 9 \times 10^{-28}$ g. The meaning to be attached to the 'size' of an electron (a figure of the order of 10^{-13} cm) is vague. A *proton* is electrically the opposite of an electron, having an equal charge, but positive. Further, protons are associated with a mass the same as that of the hydrogen nucleus. A *neutron* is a chargeless mass, the same as that of the proton.

Atomic structure

The mass of an atom is almost entirely concentrated in a nucleus of protons and neutrons. The simplest atom, of hydrogen, comprises a nucleus with a single proton, together with one associated electron occupying a region formerly called the K-shell. Helium has a nucleus of two protons and two neutrons, with two electrons in the K-shell. In these cases, as in all normal atoms, the sum of the electron charges is numerically equal to the sum of the protons charges, and the atom is electrically balanced. The neon atom has a nucleus with 10 protons and 10 neutrons, with its 10 electrons in the K- and L-shells.

The *atomic weight* A is the total number of protons and neutrons in the nucleus. If there are Z protons there will be $A - Z$ neutrons: Z is the *atomic number*. The nuclear structure is not known, and the forces that keep the proton together against their mutual repulsion are conjectural.

A nucleus of atomic weight A and atomic number Z has a charge of $+Ze$ and is normally surrounded by Z electrons each of charge $-e$. Thus copper has 29 protons and 35 neutrons ($A = 64$, $Z = 29$) in its nucleus, electrically neutralised by 29 electrons in an enveloping cloud. The atomic numbers of the known elements range from 1 for hydrogen to 102 for nobelium, and from time to time the list is extended. This multiplicity can be simplified: within the natural sequence of elements there can be distinguished groups with similar chemical and physical properties. These are the *halogens* (F 9, Cl 17, Br 35, I 53); the *alkali metals* (Li 3, Na 11, K 19, Rb 37, Cs 55); the *copper* group (Cu 29, Ag 47, Au 79); the *alkaline earths* (Be 4, Mg 12, Ca 20, Sr 38, Ba 56, Ra 88); the *chromium* group (Cr 24, Mo 42, W 74, U 92); and the *rare gases* (He 2, Ne 10, A 18, Kr 36, Xe 54, Rn 86). In the foregoing the brackets contain the chemical symbols of the elements concerned followed by their atomic numbers. The difference between the atomic numbers of two adjacent elements within a group is always 8, 18 or 32. Now these three bear to one another a simple arithmetical relation: $8 = 2 \times 2 \times 2$, $18 = 2 \times 3 \times 3$ and $32 = 2 \times 4 \times 4$. Arrangement of the elements in order in a periodic table beginning with an alkali metal and ending with a rare gas shows a remarkable repetition of basic similarities. The periods are I, 1–2; II, 3–10, III, 11–18; IV, 19–36; V, 37–54, VI, 55–86; VII, 87–?.

An element is often found to be a mixture of atoms with the same chemical property but different atomic weights (*isotopes*). Again, because of the convertibility of mass and energy, the mass of an atom depends on the energy locked up in its compacted nucleus. Thus small divergences are found in the atomic weights which, on simple grounds, would be expected to form integral multiples of the atomic weight of hydrogen. The atomic weight of oxygen is arbitrarily taken as 16.0, so that the mass of the proton is 1.007 6 and that of the hydrogen atom is 1.008 1.

Atoms may be in various energy states. Thus the atoms in the filament of an incandescent lamp may emit light when excited, e.g., by the passage of an electric heating current, but will not do so when the heater current is switched off. Now heat energy is the kinetic energy of the atoms of the heated body. The more vigorous impact of atoms may not always shift the atom as a whole, but may shift an electron from one orbit to another of higher energy level within the atom. This position is not normally stable, and the electron gives up its momentarily-acquired potential energy by falling back into its original level, releasing the energy as a definite amount of light, the *light-quantum* or *photon*.

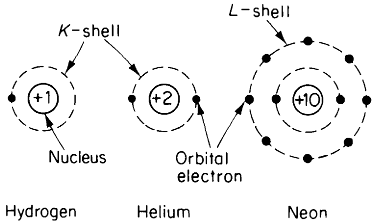

Figure 3.2 *Atomic structure. The nuclei are marked with their positive charges in terms of total electron charge. The term 'orbital' is becoming obsolete*

Electron: *mass* $m = 9 \times 10^{28}$ Y
charge $e = -1.6 \times 10^{-19}$ C
Proton: *mass* $= 1.63 \times 10^{-24}$ g
charge $= +1.6 \times 10^{-19}$ C
Neutron: mass as for proton; no charge

Among the electrons of an atom those of the outside peripheral shell are unique in that, on account of all the electron charges on the shells between them and the nucleus, they are the most loosely bound and most easily *removable*. In a variety of ways it is possible so to excite an atom that one of the outer electrons is torn away, leaving the atom *ionised* or converted for the time into an *ion* with an effective positive charge due to the unbalanced electrical state it has acquired. Ionisation may occur due to impact by other fast-moving particles, by irradiation with rays of suitable wavelength and by the application of intense electric fields.

The three 'structures' of *Figure 3.2* are based on the former 'planetary' concept, now modified in favour of a more complex idea derived from consideration of wave-mechanics. It is still true that, apart from its mass, the chemical and physical properties of an atom are given to it by the arrangement of the electron 'cloud' surrounding the nucleus.

Wave mechanics

The fundamental laws of optics can be explained without regard to the nature of light as an electromagnetic wave phenomenon, and photo-electricity emphasises its nature as a stream or ray of corpuscles. The phenomena of diffraction or interference can only be explained on the wave concept. *Wave mechanics* correlates the two apparently conflicting ideas into a wider concept of 'waves of matter'. Electrons, atoms and even molecules participate in this duality, in that their effects appear sometimes as corpuscular, sometimes as of a wave nature. Streams of electrons behave in a corpuscular fashion in photo-emission, but in certain circumstances show the diffraction effects familiar in wave action. Considerations of particle mechanics led de Broglie to write several theoretic papers (1922–6) on the parallelism between the dynamics of a particle and geometrical optics, and suggested that it was necessary to admit that classical dynamics could not interpret phenomena involving energy quanta. Wave mechanics was established by Schrödinger in 1926 on de Broglie's conceptions.

When electrons interact with matter they exhibit wave properties: in the free state they act like particles. Light has a similar duality, as already noted. The hypothesis of de Broglie is that a particle of mass m and velocity u has wave properties with a wavelength $\lambda = h/mu$, where h is the Planck constant, $h = 6.626 \times 10^{-34}$ J s. The mass m is relativistically affected by the velocity.

When electron waves are associated with an atom, only certain fixed-energy states are possible. The electron can be raised from one state to another if it is provided, by some external stimulus such as a photon, with the necessary energy-difference Δw in the form of an electromagnetic wave of wavelength $\lambda = hc/\Delta w$, where c is the velocity of free-space radiation (3×10^8 m/s). Similarly, if an electron falls from a state of higher to one of lower energy, it emits energy Δw as radiation. When electrons are raised in energy level, the atom is *excited*, but not ionised.

Electrons in atoms

Consider the hydrogen atom. Its single electron is not located at a fixed point, but can be anywhere in a region near the nucleus with some probability. The particular region is a kind of shell or cloud, of radius depending on the electron's energy state.

With a nucleus of atomic number Z, the Z electrons can have several possible configurations. There is a certain radial pattern of electron probability cloud distribution (or shell pattern). Each electron state gives rise to a cloud pattern, characterised by a definite energy level, and described by the series of quantum numbers n, l, m_l and m_s. The number $n(= 1, 2, 3 \ldots)$ is a measure of the energy level; $l(= 0, 1, 2 \ldots)$ is concerned with angular momentum; m_l is a measure of the component of angular momentum in the direction of an applied magnetic field; and m_s arises from the electron spin. It is customary to condense the nomenclature so that electron states corresponding to $l = 0$, 1, 2 and 3 are described by the letters s, p, d and f and a numerical prefix gives the value of n. Thus boron has 2 electrons at level 1 with $l = 0$, two at level 2 with $l = 0$, and one at level 3 with $l = 1$: this information is conveyed by the description $(1s)^2(2s)^2(2p)^1$.

The energy of an atom as a whole can vary according to the electron arrangement. The most stable state is that of minimum energy, and states of higher energy content are *excited*. By Pauli's *exclusion principle* the maximum possible number of electrons in states 1, 2, 3, 4 ... n are 2, 8, 18, 32 ... $2n^2$ respectively. Thus only 2 electrons can occupy the 1s state (or K-shell) and the remainder must, even for the normal minimum-energy condition, occupy other states. Hydrogen and helium, the first two elements, have respectively 1 and 2 electrons in the 1-quantum (K) shell; the next, lithium, has its third electron in the 2-quantum (L) shell. The passage from lithium to neon (*Figure 3.2*) results in the filling up of this shell to its full complement of 8 electrons. During the process, the electrons first enter the 2s subgroup, then fill the 2p subgroup until it has 6 electrons, the maximum allowable by the exclusion principle (see *Table 3.2*).

Very briefly, the effect of the electron-shell filling is as follows. Elements in the same chemical family have the same number of electrons in the subshell that is incompletely filled. The rare gases (He, Ne, A, Kr, Xe) have no uncompleted shells. Alkali metals (e.g., Na) have shells containing a single electron. The alkaline earths have two electrons

Table 3.1 ELEMENTS

Period	*Atomic Number*	*Name*	*Symbol*	*Atomic Weight*	*Period*	*Atomic Number*	*Name*	*Symbol*	*Atomic Weight*
I	1	Hydrogen	H	1.008	V	51	Antimony	Sb	121.8
	2	Helium	He	4.002		52	Tellurium	Te	127.6
						53	Iodine	I	126.9
II	3	Lithium	Li	6.94		54	Xenon	Xe	131.3
	4	Beryllium	Be	9.02					
	5	Boron	B	10.82	VI	55	Caesium	Cs	132.9
	6	Carbon	C	12.00		56	Barium	Ba	137.4
	7	Nitrogen	N	14.008		57	Lanthanum	La	138.9
	8	Oxygen	O	16.00		58	Cerium	Ce	140.1
	9	Fluorine	F	19.00		59	Praseodymium	Pr	140.9
	10	Neon	Ne	20.18		60	Neodymium	Na	144.3
						61	Promethium	Pm	147
III	11	Sodium	Na	22.99		62	Samarium	Sm	150.4
	12	Magnesium	Mg	24.32		63	Europium	Eu	152.0
	13	Aluminium	Al	26·97		64	Gadolinium	Gd	157.3
	14	Silicon	Si	28·06		65	Terbium	Tb	159.2
	15	Phosphorus	P	31.02		66	Dysprosium	Dy	162.5
	16	Sulphur	S	32.06		67	Holmium	Ho	163.5
	17	Chlorine	Cl	35.46		68	Erbium	Er	167.6
	18	Argon	A	39.94		69	Thulium	Tm	169.4
						70	Ytterbium	Yb	173.0
IV	19	Potassium	K	39.09		71	Lutecium	Lu	175.0
	20	Calcium	Ca	40.08		72	Hafnium	Hf	178.6
	21	Scandium	Sc	45.10		73	Tantalum	Ta	181.4
	22	Titanium	Ti	47.90		74	Tungsten	W	184.0
	23	Vanadium	V	50.95		75	Rhenium	Re	186.3
	24	Chromium	Cr	52.01		76	Osmium	Os	191.5
	25	Manganese	Mn	54.93		77	Iridium	Ir	193.1
	26	Iron	Fe	55.84		78	Platinum	Pt	195.2
	27	Cobalt	Co	58.94		79	Gold	Au	197.2
	28	Nickel	Ni	58.69		80	Mercury	Hg	200.6
	29	Copper	Cu	63.57		81	Thallium	Tl	204.4
	30	Zinc	Zn	65.38		82	Lead	Pb	207.2
	31	Gallium	Ga	69.72		83	Bismuth	Bi	209.0
	32	Germanium	Ge	72.60		84	Polonium	Po	210
	33	Arsenic	As	74.91		85	Astatine	At	211
	34	Selenium	Se	78.96		86	Radon	Rn	222
	35	Bromine	Br	79.91					
	36	Krypton	Kr	83.7	VII	87	Francium	Fr	223
						88	Radium	Ra	226.0
V	37	Rubidium	Rb	85.44		89	Actinium	Ac	227
	38	Strontium	Sr	87.63		90	Thorium	Th	232.1
	39	Yttrium	Y	88.92		91	Protoactinium	U_{x2}	234
	40	Zirconium	Zr	91.22		92	Uranium	U	238.1
	41	Niobium	Nb	92.91		93	Neptunium	Np	239
	42	Molybdenum	Mo	96.0		94	Plutonium	Pu	242
	43	Technetium	Tc	99		95	Americium	Am	243
	44	Ruthenium	Ru	101.7		96	Curium	Cm	243
	45	Rhodium	Rh	102.9		97	Berkelium	Bk	245
	46	Palladium	Pd	106.7		98	Californium	Cf	246
	47	Silver	Ag	107.9		99	Einsteinium	Es	247
	48	Cadmium	Cd	112.4		100	Fermium	Fm	256
	49	Indium	In	114.8		101	Mendelevium	Md	256
	50	Tin	Sn	118		102	Nobelium	No	—

Table 3.2 TYPICAL ATOMIC STRUCTURES

Element and Atomic Number		*Principal and Secondary Quantum Numbers*									
		1*s*	2*s*	2*p*	3*s*	3*p*	3*d*	4*s*	4*p*	4*d*	4*f*
H	1	1									
He	2	2									
Li	3	2	1								
C	6	2	2	2							
N	7	2	2	3							
Ne	10	2	2	6							
Na	11	2	2	6	1						
Al	13	2	2	6	2	1					
Si	14	2	2	6	2	2					
Cl	17	2	2	6	2	5					
A	18	2	2	6	2	6					
K	19	2	2	6	2	6		1			
Mn	25	2	2	6	2	6	5	2			
Fe	26	2	2	6	2	6	6	2			
Co	27	2	2	6	2	6	7	2			
Ni	28	2	2	6	2	6	8	2			
Cu	29	2	2	6	2	6	10	1			
Ge	32	2	2	6	2	6	10	2	2		
Se	34	2	2	6		6	10	2	4		
Kr	36	2	2	6		6	10	2	6		
		1	2	3	4*s*	4*p*	4*d*	4*f*	5*s*	5*p*	
Rb	37	2	8	18	2	6					
Xe	54	2	8	18	2	6	10		2	6	

in uncompleted shells. The good conductors (Ag, Cu, Au) have a single electron in the uppermost quantum state. An irregularity in the ordered sequence of filling (which holds consistently from H to A) begins at potassium (K) and continues to Ni, becoming again regular with Cu, and beginning a new irregularity with Rb.

Energy levels

The electron of a hydrogen atom, normally at level 1, can be raised to level 2 by endowing it with a particular quantity of energy most readily expressed as 10.2 eV. (1 eV = 1 electron-volt = 1.6×10^{-19} J is the energy acquired by a free electron falling through a potential difference of 1 V, which accelerates it and gives it kinetic energy.) The 10.2 V is the *first excitation potential* for the hydrogen atom. If the electron is given an energy of 13.6 eV it is freed from the atom, and 13.6 V is the *ionisation potential*. Other atoms have different potentials in accordance with their atomic arrangement.

Electrons in metals

An approximation to the behaviour of metals assumes that the atoms lose their valency electrons, which are free to wander in the ionic lattice of the material to form what is called an electron gas. The sharp energy-levels of the free atom are broadened into wide bands by the proximity of others. The potential within the metal is assumed to be smoothed out, and there is a sharp rise of potential at the surface that prevents the electrons from escaping: there is a potential-energy step at the surface that the electrons cannot normally overcome: it is of the order of 10 eV. If this is called W, then the energy of an electron wandering within the metal is $-W + \frac{1}{2}mu^2$.

The electrons are regarded as undergoing continual collisions on account of the thermal vibrations of the lattice, and on Fermi-Dirac statistical theory it is justifiable to treat the energy states (which are in accordance with Pauli's principle) as forming an energy-continuum. At very low temperatures the ordinary classical theory would suggest that electron energies spread over an almost zero range, but the exclusion principle makes this impossible and even at absolute zero of temperature the energies form a continuum, and physical properties will depend on how the electrons are distributed over the upper levels of this energy range.

Conductivity

The interaction of free electrons with the thermal vibrations of the ionic lattice (called 'collisions' for brevity) causes them to 'rebound' with a velocity of random direction but small compared with their average velocities as particles of an electron gas. Just as a difference of electric potential causes a drift in the general motion, so a difference of temperature between two parts of a metal carries energy from the hot region to the cold, accounting for thermal conduction and for its association with electrical conductivity. The free-electron theory, however, is inadequate to explain the dependence of conductivity on crystal axes in the metal.

At absolute zero of temperature (zero K = −273 °C) the atoms cease to vibrate, and free electrons can pass through the lattice with little hindrance. At temperatures over the range 0.3–10 K (and usually round about 5 K) the resistance of certain metals, e.g., Zn, Al, Sn, Hg and Cu, becomes substantially zero. This phenomenon, known as *superconductivity*, has not been satisfactorily explained.

Superconductivity is destroyed by moderate magnetic fields. It can also be destroyed if the current is large enough to produce at the surface the same critical value of magnetic field. It follows that during the superconductivity phase the current must be almost purely superficial, with a depth of penetration of the order of 10 μm.

Electron emission

A metal may be regarded as a potential 'well' of depth $-V$ relative to its surface, so that an electron in the lowest energy state has (at absolute zero temperature) the energy $W = Ve$ (of the order 10 eV): other electrons occupy levels up to a height ϵ^* (5–8 eV) from the bottom of the 'well'. Before an electron can escape from the surface it must be endowed with an energy not less than $\phi = W - \epsilon^*$, called the *work function*.

Emission occurs by *surface irradiation* (e.g., with light) of frequency ν if the energy quantum $h\nu$ of the radiation is at least equal to ϕ. The threshold of photo-electric emission is therefore with radiation at a frequency not less than $\nu = \phi/h$.

Emission takes place at *high temperatures* if, put simply, the kinetic energy of electron normal to the surface is great enough to jump the potential step W. This leads to an expression for the emission current i in terms of temperature T, a constant A and the thermionic work-function ϕ:

$$i = AT^2 \exp(-\phi/kT)$$

Electron emission is also the result of the application of a *high electric-field intensity* (of the order 1–10 GV/m) to a metal surface; also when the surface is bombarded with electrons or ions of sufficient kinetic energy, giving the effect of *secondary* emission.

Electrons in crystals

When atoms are brought together to form a crystal, their individual sharp and well-defined energy levels merge into energy *bands*. These bands may overlap, or there may be gaps in the energy levels available, depending on the lattice spacing and inter-atomic bonding. Conduction can take place only by electron migration into an empty or partly filled band: filled bands are not available. If an electron acquires a small amount of energy from the externally applied electric field, and can move into an available empty level, it can then contribute to the conduction process.

Insulators

In this case the 'distance' (or energy increase Δw in electron volts) is too large for moderate electric applied fields to endow electrons with sufficient energy, so the material remains an insulator. High temperatures, however, may result in sufficient thermal agitation to permit electrons to 'jump the gap'.

Semiconductors

Intrinsic semiconductors (i.e., materials between the good conductors and the good insulators) have a small spacing of about 1 eV between their permitted bands, which affords a low conductivity, strongly dependent on temperature and of the order of one-millionth that of a conductor.

Impurity semiconductors have their low conductivity provided by the presence of minute quantities of foreign atoms (e.g., 1 in 10^8) or by deformations in the crystal structure. The impurities 'donate' electrons of energy-level that can be raised into a conduction band (*n*-type); or they can attract an electron from a filled band to leave a 'hole', or electron deficiency, the movement of which corresponds to the movement of a positive charge (*p*-type).

Magnetism

Modern magnetic theory is very complex, with ramifications in several branches of physics. Magnetic phenomena are associated with moving charges. Electrons, considered as particles, are assumed to possess an axial spin, which gives them the effect of a minute current-turn or of a small permanent magnet, called a Bohr *magneton.* The gyroscopic effect of electron spin develops a precession when a magnetic field is applied. If the precession effect exceeds the spin effect, the external applied magnetic field produces less magnetisation than it would in free space, and the material of which the electron is a constituent part is *diamagnetic.* If the spin effect exceeds that due to precession, the material is *paramagnetic.* The spin effect may, in certain cases, be very large, and high magnetisations are produced by an external field: such materials are *ferromagnetic.*

An iron atom has, in the $n = 4$ shell (N), electrons that give it conductive properties. The K, L and N shells have equal numbers of electrons possessing opposite spin-directions, so cancelling. But shell M contains 9 electrons spinning in one direction and 5 in the other, leaving 4 net magnetons. Cobalt has 3, and nickel 2. In a solid metal, further cancellation occurs and the average number of unbalanced magnetons is: Fe, 2.2; Co, 1.7; Ni, 0.6.

In an iron crystal the magnetic axes of the atoms are aligned, unless upset by excessive thermal agitation. (At 770 °C for Fe, the Curie point, the directions become random and ferromagnetism is lost.) A single Fe crystal magnetises most easily along a cube edge of the structure. It does not exhibit spontaneous magnetisation like a permanent magnet, however, because a crystal is divided into a large number of *domains* in which the various magnetic directions of the atoms form closed paths. But if a crystal is exposed to an external applied magnetic field, (i) the electron spin axes remain initially unchanged, but those domains having axes in the favourable direction grow at the expense of the others (domain-wall displacement); and (ii) for higher field intensities the spin axes orientate into the direction of the applied field.

If wall movement makes a domain acquire more internal energy, then the movement will relax again when the external field is removed. But if wall-movement results in loss of energy, the movement is non-reversible—i.e., it needs external force to reverse it. This accounts for hysteresis and remanence phenomena.

The closed-circuit self-magnetisation of a domain gives it a mechanical strain. When the magnetisation directions of individual domains are changed by an external field, the strain directions alter too, so that an assembly of domains will tend to lengthen or shorten. Thus readjustments in the crystal lattice occur, with deformations (e.g., 20 parts in 10^6) in one direction. This is the phenomenon of *magnetostriction.*

The practical art of magnetics consists in control of magnetic properties by alloying, heat-treatment and mechanical working to produce variants of crystal structure and consequent magnetic characteristics.

Simplified electrical theories

In the following paragraphs, a discussion of electrical phenomena is given in terms adequate for the purpose of simple explanation.

Consider two charged bodies separated in air, *Figure 3.3.* Work must have been done in a physical sense to produce on one an excess and on the other a deficiency of electrons, so that the system is a repository of potential energy. (The work done in separating charges is measured by the product of the charges separated and the difference of electrical potential that results.) Observation of the system shows certain effects of interest: (1) there is a difference of electric potential between the bodies depending on the amount of charge and the geometry of the system; (2) there is a mechanical force of attraction between the bodies. These effects are deemed to be manifestations of the *electric field* between the bodies, described as a special state of space and depicted by *lines of force* which express in a pictorial way the strength and direction of the force effects. The lines stretch between positive and negative elements of charge through the medium (in this case, air) which separates the two charged bodies. The electric field is only a concept—for the lines have no real existence—used to calculate various effects produced when charges are separated by any method which results in excess and deficiency states of atoms by electron transfer. Electrons and

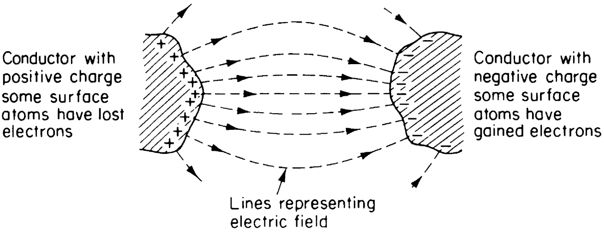

Figure 3.3 Charged conductors and their electric field

protons, or electrons and positively ionised atoms, attract each other, and the stability of the atom may be considered due to the balance of these attractions and dynamic forces such as electron spin. Electrons are repelled by electrons and protons by protons, these forces being summarised in the rules, formulated experimentally long before our present knowledge of atomic structure, that 'like charges repel and unlike charges attract one another'.

Conductors and insulators

In substances called *conductors*, the outer-shell electrons can be more or less freely interchanged between atoms. In copper, for example, the molecules are held together comparatively rigidly in the form of a 'lattice'—which gives the piece of copper its permanent shape—through the interstices of which outer electrons from the atoms can be interchanged within the confines of the surface of the piece, producing a random movement of free electrons called an 'electron atmosphere'. Such electrons are responsible for the phenomenon of electrical conductivity.

In other substances called *insulators* all the electrons are more or less firmly bound to their parent atoms so that little or no relative interchange of electron charges is possible. There is no marked line of demarcation between conductors and insulators, but the copper-group metals in the order silver, copper, gold, are outstanding in the series of conductors.

Conduction

Conduction is the name given to the movement of electrons, or ions, or both, giving rise to the phenomena described by the term *electric current*. The effects of a current include a redistribution of charges, heating of conductors, chemical changes in liquid solutions, magnetic effects, and many subsidiary phenomena.

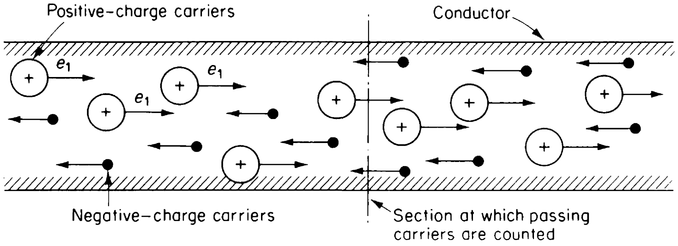

Figure 3.4 Electric current as the result of moving charges

If at some point on a conductor (*Figure 3.4*), n_1 carriers of electric charge (they can be water-drops, ions, dust particles, etc.) each with a positive charge e_1 arrive per second, and n_2 carriers (such as electrons) each with a negative charge e_2 arrive in the opposite direction per second, the total rate of passing of charge is $n_1e_1 + n_2e_2$, which is the charge per second or *current*. A study of conduction concerns the kind of carriers and their behaviour under given conditions. Since an electric field exerts mechanical forces on charges, the application of an electric field (i.e. a potential difference) between two points on a conductor will cause the movement of charges to occur, i.e., a current to flow, so long as the electric field is maintained.

The discontinuous particle nature of current flow is an observable factor. The current