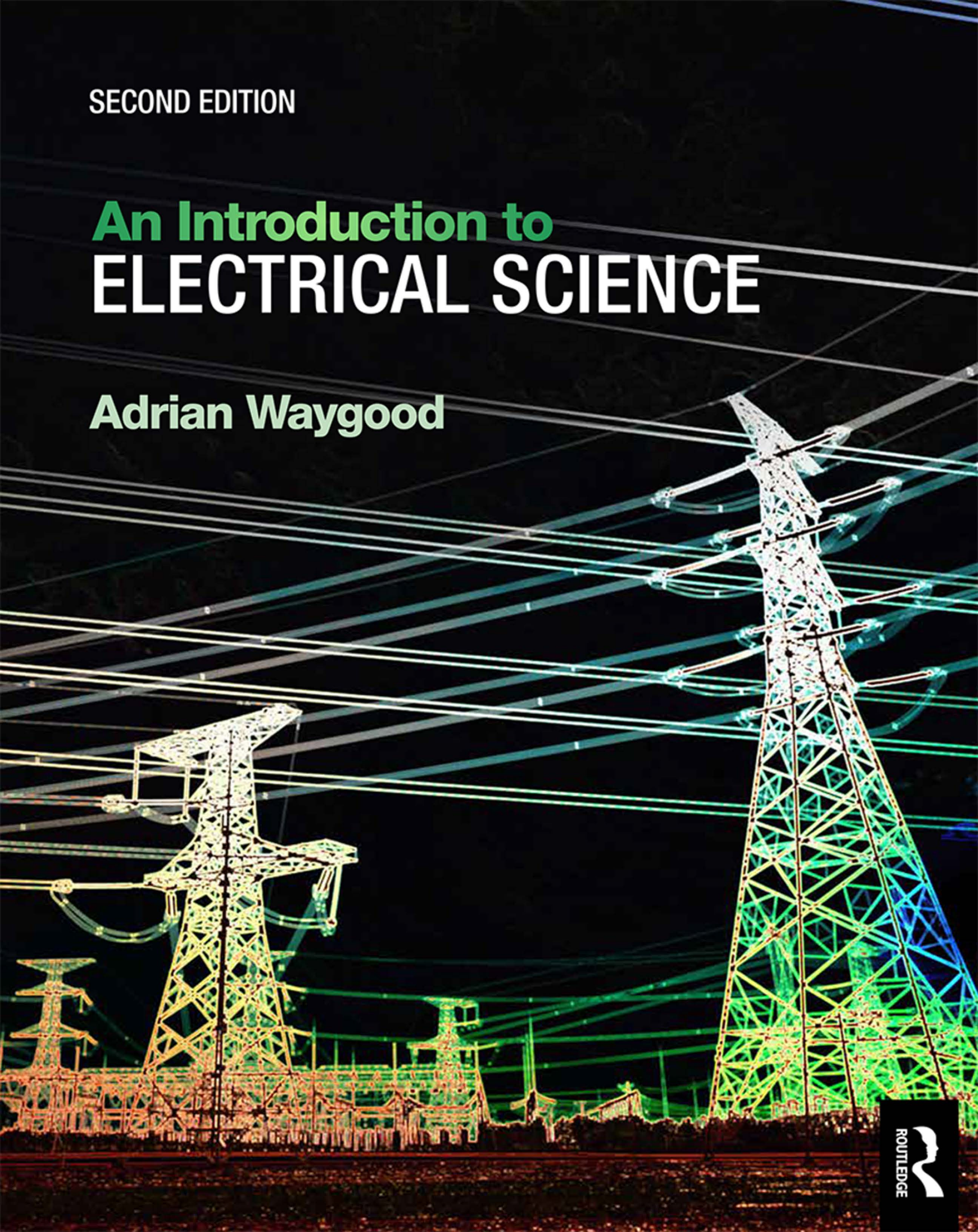
SECOND EDITION

An Introduction to ELECTRICAL SCIENCE

Adrian Waygood



ROUTLEDGE

An Introduction to Electrical Science

Second Edition

Heavily updated and expanded, this second edition of Adrian Waygood's textbook provides an indispensable introduction to the science behind electrical engineering.

While fully matched to the electrical science requirements of the 2330 levels 2 and 3 Certificates in Electrotechnical Technology from City & Guilds (Electrical Installation), the main purpose of this book is to develop an easy understanding of the how and why within each topic. It is aimed at those starting careers in electricity and electronics, as well as any hobbyists, with an array of new material to reflect changes in the industry.

New chapters include:

- Electrical drawings
- Practical resistors
- Measuring instruments
- Basic motor action
- Practical capacitors
- Basic transformer theory
- The electricity supply industry
- … and more

The author details the historical context of each main principle and offers a wealth of examples, images and diagrams, all whilst maintaining his signature conversational and accessible style. There is also a companion website, with interactive multiple choice quizzes for each chapter and more, at www.routledge.com/cw/waygood

Adrian Waygood is a retired lecturer and instructional designer, having had a career in the armed forces, technical institutes and the defence industry in the UK, Canada and the Middle East. These include the Royal Navy, the Royal Navy of Oman, the Northern Alberta and British Columbia Institutes of Technology, the Higher Colleges of Technology (United Arab Emirates) and British Aerospace. He has also managed government trades apprenticeship programmes in Canada, and has consulted on instructional-design methodology at technical-teacher training colleges in India and Indonesia. He holds a Higher National Certificate in Electrical and Electronics Engineering, together with a Master's Degree in Education Technology.

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An Introduction to Electrical Science

Second Edition

Adrian Waygood

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Dedication

To my brother, John Brian Waygood, 1936–2017.
'*Ying tong iddle I po!*'

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Foreword

I *love* science. I'm an avid reader of books about science and technology, and would rather watch television programs about them than anything else. Physics, astronomy, cosmology, paleontology, earth sciences, wildlife, how things work, and the world we live in – nothing interests me more. And so much of it, delivered through channels like the BBC, Smithsonian, and National Geographic, is very well done. Today the media has the technology to produce educational programs that are not only informative and educational, but also captivating and easy to follow. I expect many young people will develop an interest, and even choose a career, in science and technology because of this exposure. Watching these programs, I think how lucky science teachers are today to have these tools to awaken interest in, and love of, science in their students.

As wonderful as video media is at delivering an overview of science topics, it does not lend itself well to the in-depth study necessary for anyone who chooses to make science and technology his or her career. For that, printed materials are still indispensable. And learners can often find written text less appealing than what they have been exposed to through video and animation. Writers and publishers of science textbooks must produce materials that cater to students who have been conditioned to a sophisticated, interesting, and captivating learning experience.

I am honoured to have been asked to provide a short foreword to Adrian Waygood's newly revised book on electrical science. I know him well and worked closely with him in the Electrical Programs at the Northern Alberta Institute of Technology – NAIT. Adrian was a very effective instructor, popular with his students and highly respected by his colleagues. Through his career he has accumulated a broad experience in technical training with the Royal Navy, with the Royal Navy of Oman, in Canadian colleges, and in several countries in the Middle East.

I expect students will find this textbook on electrical science to be an excellent experience. The presentation is interesting, and the conversational nature of the writing is engaging and encourages reading on. Topics are presented and developed in a logical and easy-to-follow sequence. The author strives to ensure no 'holes' are left in the concepts, and no assumptions made about prior knowledge. The basics of each topic are presented rather than assumed – no lazy presentation here.

Concepts and conventions are made much more interesting and understandable through explanations of their history, development of thought, and evolution of the science. The author is meticulous about the correct use of terminology and scientific accuracy and, where custom or convention tend to create confusion, he provides explanation.

Adrian believes, as do I, that it is not sufficient to skim over the definitions and equations with a simple goal of passing an exam. What is important is a fundamental and thorough understanding of the basics of the science. With that, the learner is armed with the ability to build on his or her knowledge and understanding, and to exercise critical thinking in problem solving.

This is a thorough and comprehensive, yet engaging and easy to understand, introduction to electrical science and circuit fundamentals. It is an excellent resource for anyone preparing for a career in electrical trades, technology, or engineering as well as being an appropriate choice for anyone simply interested in learning for learning's sake.

Greg Collins
Chair (Retired)
Electrical Engineering Technology
Northern Alberta Institute of Technology – NAIT
Edmonton, Alberta, Canada

Introduction

The first edition of this book was published in 2013 followed, two years later, by its companion book, *Electrical Science for Technicians*.

Since then, I have revised and expanded *An Introduction to Electrical Science* primarily in order to incorporate topics that, for reasons of space, had to be omitted from the first edition.

Another change that has had to be accommodated in this new edition is the proposal by the **International Committee for Weights and Measures** (**CIPM**) to change the formal definitions of the SI Base Units, in particular the **ampere**, whose present definition dates back to 1946. The proposed changes are the result of the ability we now have to apply *exact* values to the speed of light together with a further four scientific constants. One of these constants is the 'elementary charge', i.e. the amount of electric charge on an individual electron. This, coupled with the fact that scientists are now able to count the passage of individual electrons, means that the definition of the ampere will be completely changed from its present dependence on the electromagnetic attraction/repulsion between a pair of current-carrying conductors, to the rate of flow of elementary particles.

Unfortunately, at the time of completing the manuscript for this book (January 2018), these changes have yet to be implemented or even finalised. In fact, the changes have already been postponed once, and are now unlikely to be introduced until 2019. However, it is felt that, as the new definitions are imminent, the changes should be brought to my readers' attention, so I have incorporated what we know about the proposals before this book goes to print.

Now, a note on how you should use this book. You will find that each chapter starts with a list of desired learning outcomes, or '**objective statements**'. These guide you as to *what you should endeavour to learn from each chapter*. These statements specify what you *must* know when you have read the chapter, as opposed to what is *nice* to know. By adding a question mark at the end of each objective statement, they become **test items**. For example, an objective statement might state, '*... list the three effects of an electric current*'. After completing the chapter, you should then ask yourself, '***Can I** ... list the three effects of an electric current?*' If you can, then you have *achieved that particular objective, and you can move on to the next*.

I would like to thank my publishers for their support during the preparation of this book, and to my good friend and former colleague, Greg Collins, for writing the Foreword to this revised edition.

Finally, thank you for purchasing this book; I hope you enjoy reading it and find it useful. You are invited to visit my blog site at www.professorelectron.com.

Adrian Waygood, MEd (Tech)
(January 2018)

Online resources

There is also a companion website for this book featuring multiple choice questions, further written questions and an extra chapter on electrical measuring instruments. The website can be accessed via the following link: www.routledge.com/cw/waygood

Chapter 1

SI system of measurements

Objectives

On completion of this chapter, you should be able to

1 explain the term 'SI base units'.
2 list the seven SI base units.
3 explain the term 'SI derived units'.
4 explain the relationship between SI 'base' and 'derived' units.
5 recognise SI prefixes.
6 apply correct SI symbols.
7 use correct SI prefixes.
8 apply SI conventions when writing SI units.
9 be aware of changes to SI base units scheduled for 2019.

Introduction

In 1948, the **General Conference of Weights and Measures** (**CGPM**) charged an international committee, the CIPM*, to *'study the establishment of a complete set of rules for (metric) units of measurement'*.

***CIPM** (**Comité international des poid et mesures**) is an International Committee for Weights and Measurements comprising eighteen individuals, each from a different member state, whose principal task is to promote world-wide uniformity in units of measurement. The Committee achieves this either by direct action, or by submitting proposals to the General Conference on Weights and Measures.

The outcome of this study was a rational system of metric units termed '**SI**'.

The abbreviation **SI** stands for *Système Internationale d'Unités* and this system of measurements has been adopted internationally by the scientific and engineering communities, as well as by businesses for the purpose of international trade. Whereas *most* countries now use SI exclusively, *some* countries – most notably the United States and, to a lesser extent, the United Kingdom – still make wide use of non-metric units, especially for day-to-day use.

Earlier versions of the metric system include the '**cgsA**' ('centimetre, gram, second, ampere') and the '**mksA**' ('metre, kilogram, second, ampere') systems. SI is largely based on the 'mksA' system.

SI comprises *two* classes of units:

- base units
- derived units.

Base units

There are *seven* **base units** from which *all* other SI units are derived. These are shown in Table 1.1.

Table 1.1

Quantity	SI unit	SI symbol
length	metre	m
mass*	kilogram	kg
time	second	s
electric current	ampere	A
temperature	kelvin	K
luminous intensity	candela	cd
amount of substance	mole	mol

* The kilogram is a little confusing because it is the only base unit with a prefix (kilo). It has been suggested that the name 'kilogram' should be replaced (to remove the prefix 'kilo') as the unit for mass, but this is likely to cause more confusion than necessary.

An Introduction to Electrical Science, Waygood, ISBN 9780815391821, 2019. © Taylor & Francis

Derived units

Those SI units which are *not* base units are called **derived units**.

Derived units are formed by combining base units – for example, the **'volt'** is defined as *'the potential difference between two points such that the energy used in conveying a charge of one coulomb from one point to the other is one joule'*.

So the **volt** is defined in terms of the **coulomb** and the **joule**. The **coulomb** (see page 5), in turn, is defined in terms of the **ampere** and the **second** (both base units). The **joule** is defined in terms of the **newton** and the **metre** (a base unit). Finally, the **newton** is defined in terms of the **kilogram**, the **metre** and the **second** (all base units).

So, by 'deconstructing' the **volt**, we find that it is ultimately derived from a combination of each of the base units underlined in Figure 1.1 – i.e. the **ampere**, the **second**, the **kilogram** and the **metre**.

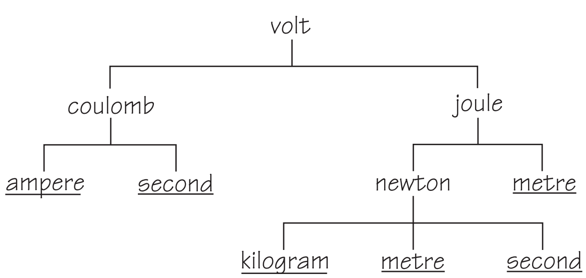

Figure 1.1

Most derived units have been given **special names** in honour of famous physicists whose research has contributed to our knowledge of the quantity concerned – for example, as we have learnt, the derived unit for potential difference is the **'volt'**, which is simply a special name given to a **'joule per coulomb'**, and is named after the Italian nobleman and professor of physics, Count Alessandro Volta (1745–1827).

Table 1.2 lists **SI derived units** with special names that you will meet in this text.

Table 1.2

Quantity	Symbol	SI unit	SI symbol
capacitance	C	farad	F
capacitive reactance	X_C	ohm	Ω
conductance	G	siemens	S
electric charge	Q	coulomb	C
force	F	newton	N
frequency	F	hertz	Hz
impedance	Z	ohm	Ω
inductance	L	henry	H
inductive reactance	X_L	ohm	Ω
potential difference	E, U, V	volt	V
power	P	watt	W
pressure	P	pascal	Pa
resistance	R	ohm	Ω
magnetic flux	Φ	weber*	Wb
magnetic flux density	B	tesla	T
magnetomotive force	H	ampere**	A
mutual inductance	M	henry***	H
self inductance	L	henry	H
work, energy	W	joule	J

Notes:
*The weber is pronounced 'vay-ber'.
**Often spoken as 'ampere turn'.
***The plural of 'henry' is 'henrys', not 'henries'.

Students often ask *why* some symbols for electrical (and other) quantities sometimes appear rather strange: '*I*' for current, '*U*' for potential difference, for example.

The answer is that much of the research into electricity was conducted by German, French, Italian, and other European physicists so, naturally, some of the symbols are based on those languages – rather than English.

The symbol for current, *I*, for example, is based on the French word *intensité*, from the expression '*l'intensité du courant électrique*'.

The origin of the symbol *U*, for potential difference, is less clear, but is thought to be based on the German word '*unterschied*', meaning 'difference'.

Non-SI metric units

Not all *metric* units are SI units, although many may be '*used alongside*' SI units. These include the commonly used units shown in Table 1.3.

Table 1.3

Quantity	Unit	Symbol
energy	watt hour	W·h
mass	tonne	t*
volume	litre	L or λ **
rotation	revolutions per second	r/s
temperature	degree Celsius***	ºC
time	minute (60 s); hour; day; year	min, h, d, a

Notes:
*The unit of mass, the *tonne*, is pronounced, or spoken, as 'metric ton'.
**Since a lower-case 'ell' (l) can be confused with the number 1, we shall use a capital 'ell' (L), in common with North American SI practice.
***The division intervals are identical for the both the *Celsius* and *kelvin* scales. However, 0ºC corresponds to 273.15 K, and 100ºC corresponds to 373.15 K.

Multiples and sub-multiples

Frequently, we have to deal with very large, or very small, quantities. For example, the resistance of insulation is measured in millions of ohms, while the resistance of a conductor is measured in thousandths of an ohm.

To avoid having to express very large or very small values in this way, we use, instead, **multiples** and **sub-multiples**. These are indicated by assigning a *prefix* to the SI unit. The more common are listed in Table 1.4.

Table 1.4

Multiplication factor	Power of ten	Prefix	Symbol
1 000 000 000 000 ×	10^{12}	tera	T
1 000 000 000 ×	10^{9}	giga	G
1 000 000 ×	10^{6}	mega	M
1 000 ×	10^{3}	kilo	k
0.001 ×	10^{-3}	milli	m
0.000 001 ×	10^{-6}	micro	m
0.000 000 000 001 ×	10^{-12}	pico	p

Examples
- 10 000 000 watts can be written as 10×10^{6} W, or as 10 MW
- 33 000 volts can be written as 33×10^{3} V, or as 33 kV
- 0.025 amperes can be written as 25×10^{-3} A, or as 25 mA

Note: the correct spelling for one-millionth of an ohm, is 'microhm', *not* 'microohm' or 'micro-ohm'.

Note that SI recommends using prefixes employed by the '**Engineering System**' – i.e. powers of ten which increase or decrease by a factor of *three*. Accordingly, units such as the 'centimetre', etc., should *not* be used when working in SI.

We *cannot* insert multiples or sub-multiples into equations. For example, we must *always* convert micro-watts, milliwatts, kilowatts, megawatts, etc., into **watts** whenever we insert that quantity into an equation.

To do this:

Table 1.5

to convert. . .	into. . .	multiply by. . .
picowatts	watts	$\times 10^{-12}$
microwatts	watts	$\times 10^{-6}$
milliwatts	watts	$\times 10^{-3}$
kilowatts	watts	$\times 10^{3}$
megawatts	watts	$\times 10^{6}$
gigawatts	watts	$\times 10^{9}$
terawatts	watts	$\times 10^{12}$

Although, in the above examples, we have used watts, this applies of course to *any* SI unit.

Multiplying expressions containing Indices

When *multiplying* expressions containing indices, the following rule applies:

$$(a\times10^{x})\times(b\times10^{y})=ab\times10^{(x+y)}$$

For example: Multiply 2 kilounits by 4 megaunits.

$$\left(2\times10^{3}\right)\times\left(4\times10^{6}\right)=\left(2\times4\right)\times10^{(3+6)}=8\times10^{9}\ \text{(Answer)}$$

Dividing expressions containing Indices

When *dividing* expressions containing indices, the following rule applies:

$$\frac{a\times10^{x}}{b\times10^{y}}=\frac{a}{b}\times10^{(x-y)}$$

For example: Divide 2 kilounits by 4 megaunits.

$$\frac{2\times10^{3}}{4\times10^{6}}=\frac{2}{4}\times10^{(3-6)}=0.5\times10^{-3}\ \text{(Answer)}$$

SI conventions

SI specifies *how* its units of measurement should be written. These rules, or **conventions**, apply to the units themselves, to their symbols and to their associated numerals.

You should be aware of the following conventions.

Rules for writing SI units

1 SI units and their symbols are never italicised:
e.g. ampere, not *ampere*
mV, not *mV*

2 When written in full, units are *never* capitalised:
e.g. watt, not Watt
ampere, not Ampere

3 SI symbols are written in lower-case, *unless they are named after someone*, in which case they are capitalised:
e.g. symbol for metre: m
symbol for ampere: A (after André-Marie Ampère)

4 SI symbols are symbols, not abbreviations, so are *not* punctuated with full stops (periods):
e.g. 230 V, not 230 V.
13 A, not 13 A.

5 There is no plural form of an SI symbol:
e.g. 500 kg, not 500 kgs
40 W, not 40 Ws

6 Numerals are always followed by the *symbol* for a unit:
e.g. 400 V, not 400 volts
10 kW, not 10 kilowatts

7 Written numbers are always followed by a written unit:
e.g. Twelve volts, not twelve V

8 A *space* is always placed between a number and the unit symbol:
e.g. 5000 W, not 5000W
275 kV, not 275kV

9 A hyphen *may* be used (optionally) between a number and the unit symbol, when the combination is used as an adjective:
e.g. 'A 66-kV power line' or 'A 66 kV power line'
'A 13-A socket' or 'A 13 A socket'

10 Compound derived unit symbols are separated by a point placed above the line:
e.g. SI unit for apparent power: V·A (volt ampere)
SI unit for resistivity: Ω·m (ohm metre)

11 No space or hyphen is placed between an SI unit or symbol and its multiplier:
e.g. kilowatt, not kilo-watt or kilo watt
kW, not k-W or k W
Special case for ohms:
microhm, not microohm or micro-ohm
kilohm, not kiloohm or kilo-ohm

12 *Spaces*, not commas, are used as thousand separators with large numbers:
e.g. 11 000 V, not 11,000 V
15 000.000 075, not 15,000.000075
The space is *optional* for four digits: 1500 mW *or* 1 500 mW

13 Square and cubic measurements are written as exponents:
e.g. m^2 (square metres) not sq m.
e.g. m^3 (cubic metres) not cu m.

Proposed new definitions for SI base units

As this book was being prepared for publication, the International Committee of Weights and Measures (CIPM) was examining proposed changes to the formal definitions of these SI base units. These revisions are expected to come into force on 20 May 2019, assuming they are accepted following a final vote at the 26th General Conference on Weights and Measures scheduled to take place on 16 November 2018.

Under the proposed revisions, SI will retain the same seven base units.

Of these, the kilogram, ampere, kelvin, and mole will be redefined by choosing exact numerical values for the physical constants on which they will be based.

However, the metre, second, and candela are already defined by physical constants and it will only be necessary to rephrase their present definitions.

It is argued that the new definitions will improve the SI base units without changing the size of any SI units, thus ensuring continuity with present measurements.

Of particular interest to us is the proposed redefinition of the ampere, which will be discussed later in this chapter.

A draft of the Ninth SI Units Brochure is available online (www.bipm.org/utils/common/pdf/si-brochure-draft-2016.pdf), and may be downloaded as a pdf document.

Definitions of electrical SI units

ampere (symbol: **A**)

The **ampere** is defined as '*the constant current that, if maintained in two straight parallel conductors of infinite length and negligible cross-sectional area and placed one metre apart in a vacuum, would produce between them a force equal to* 2×10^{-7} *newtons per unit length'*.

> However… thanks to the development of new technology, allowing scientists to count the movement of *individual* elementary charges (electrons), from May 2019 this definition is likely to be redefined along the following lines:
>
> The **ampere** (symbol: **A**) is defined as *'a current in the direction of flow of* $1/(1.602\ 176\ 620\ 8 \times 10^{-19})$ *elementary charges per second'*.
>
> The approved wording of this definition was not available when this book was published. Visit my blog site (www.professorelectron.com) to read about the progress of this proposal.

coulomb (symbol: **C**)

The **coulomb** is defined as '*the charge transported through any cross-section of a conductor in one second by a constant current of one ampere'*.

volt (symbol: **V**)

The **volt** is defined as *'the potential difference between two points such that the energy used in conveying a charge of one coulomb from one point to the other is one joule'*.

joule (symbol: **J**)

The **joule** is defined as *'the work done when the point of application of a force of one newton is displaced one metre in the direction of that force'*.

ohm (symbol: **Ω**)

The **ohm** is defined as *'the electrical resistance between two points of a conductor, such that when a constant potential difference of one volt is applied between those points, a current of one ampere results'*.

newton (symbol: **N**)

The **newton** is defined as *'the force which, when applied to a mass of one kilogram, will give it an acceleration of one metre per second per second'*.

watt (symbol: **W**)

The **watt** is defined as *'the power resulting when one joule of energy is dissipated in one second'*.

farad (symbol: **F**)

The **farad** is defined as '*the capacitance of a capacitor, between the plates of which there appears a difference in potential of one volt, when it is charged to 1 coulomb.*

weber* (symbol: **Wb**)

The weber is defined as *'the magnetic flux that, linking a circuit of one turn, produces a potential difference of one volt when it is reduced to zero at a uniform rate in one second'*.
(*pronounced 'vay-ber')

tesla (symbol: **T**)

The **tesla** is defined as *'one weber of magnetic flux per square metre of circuit area'*.

henry (symbol: **H**)

The **henry** is defined as *'the self- or mutual-inductance of a closed loop if a current of one ampere gives rise to a magnetic flux of one weber'*.

Misconceptions

The metric system and the SI system are the same thing

The metric system existed long before the introduction of SI. Former versions of the metric system include the 'cgsA system' (whose base units included the centimetre, gram, second, and ampere), and the 'mksA system', which shared the same base units as SI.