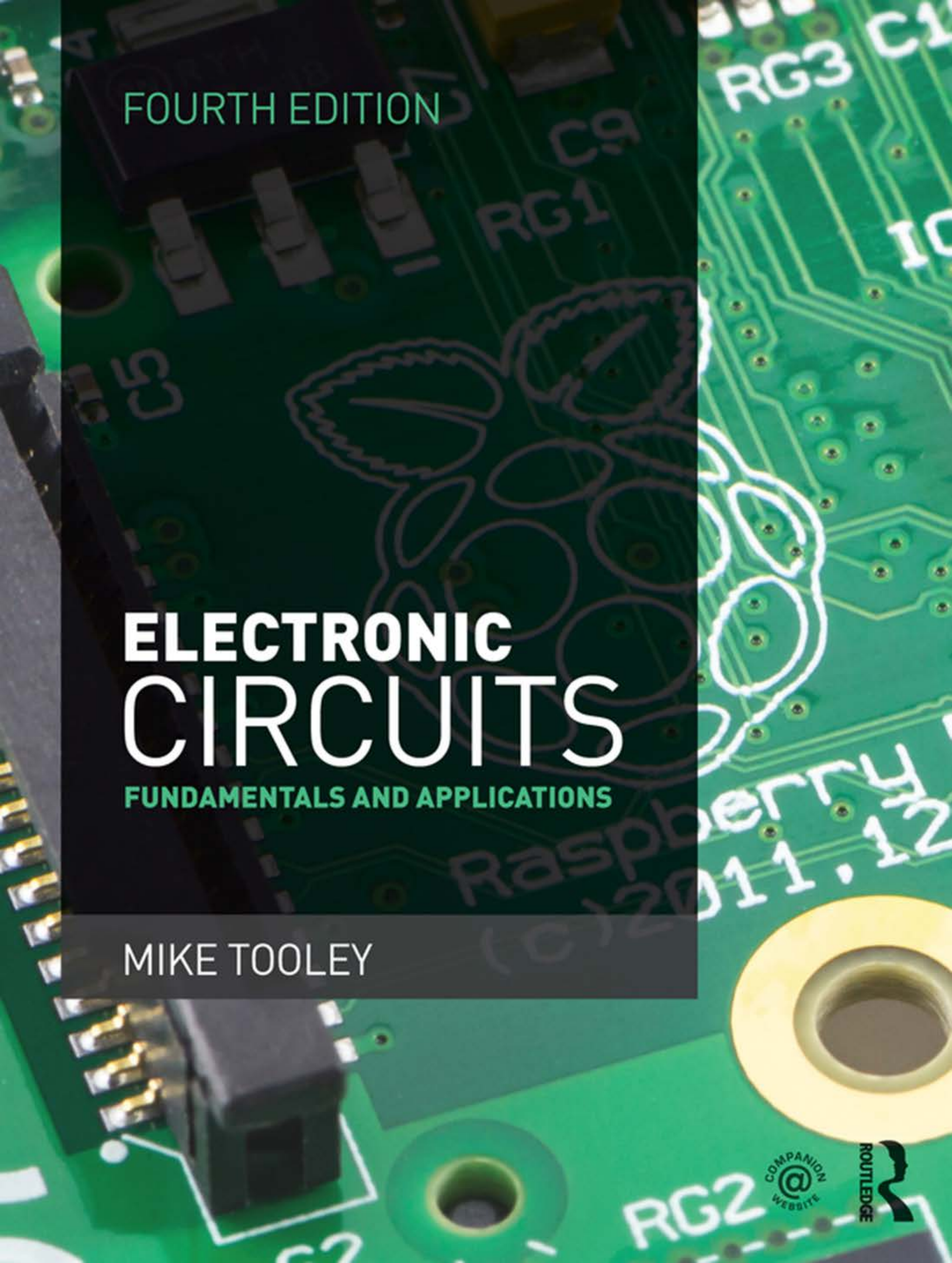

FOURTH EDITION

ELECTRONIC CIRCUITS

FUNDAMENTALS AND APPLICATIONS

MIKE TOOLEY

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Electronic Circuits

Electronics explained in one volume, using both theoretical and practical applications.

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Mike Tooley has over 30 years' experience of teaching electrical principles, electronics and avionics to engineers and technicians, previously as Head of Department of Engineering and Vice Principal at Brooklands College in Surrey, UK, and currently works as a consultant and freelance technical author.

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Fundamentals and applications

Fourth edition

Mike Tooley

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Contents

Note that there is an additional chapter and extra resources on the companion website for this title. Visit www.key2electronics.com for more information.

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Preface

This is the book that I wish I had when I first started exploring electronics over half a century ago. In those days, transistors were only just making their debut and integrated circuits were completely unknown. Of course, since then much has changed but, despite all of the changes, the world of electronics remains a fascinating one. And, unlike most other advanced technological disciplines, electronics is still something that you can 'do' at home with limited resources and with a minimal outlay. A soldering iron, a multi-meter and a handful of components are all you need to get started. Except, of course, for some ideas to get you started – and that's exactly where this book comes in!

The book has been designed to help you understand how electronic circuits work. It will provide you with the basic underpinning knowledge necessary to appreciate the operation of a wide range of electronic circuits, including amplifiers, logic circuits, power supplies and oscillators.

The book is ideal for people who are studying electronics for the first time at any level, including a wide range of school and college courses. It is equally well suited to those who may be returning to study or who may be studying independently as well as those who may need a quick refresher. The book has 19 chapters, each dealing with a particular topic, and ten appendices containing useful information. The approach is topic-based rather than syllabus-based and each major topic looks at a particular application of electronics. The relevant theory is introduced on a progressive basis and delivered in manageable chunks.

In order to give you an appreciation of the solution of simple numerical problems related to the operation of basic circuits, worked examples have been liberally included within the text. In addition, a number of problems can be found at the end of each chapter and solutions are provided at the end of the book. You can use these end-of-chapter problems to check your understanding and also to give you some experience of the 'short answer' questions used in most in-course assessments. For good measure, we have included 80 revision problems in Appendix 2.

At the end of the book you will find 22 sample coursework assignments. These should give you plenty of 'food for thought' as well as offering you some scope for further experimentation. It is not envisaged that you should complete all of these assignments, and a carefully chosen selection will normally suffice. If you are following a formal course, your teacher or lecturer will explain how these should be tackled and how they can contribute to your course assessment.

While the book assumes no previous knowledge of electronics, you need to be able to manipulate basic formulae and understand some simple trigonometry in order to follow the numerical examples. A study of mathematics to GCSE level (or equivalent) will normally be adequate to satisfy this requirement. However, for those who may need a refresher or have had previous problems with mathematics, Appendix 8 will provide you with the underpinning mathematical knowledge required.

In the later chapters of the book, a number of representative circuits (with component values) have been included together with sufficient information to allow you to adapt and modify the circuits for your own use. These circuits can be used to form the basis of your own practical investigations or they can be combined together in more complex circuits.

This latest edition brings the book up to date with coverage of several important new topics, including the use of digital storage and sound card oscilloscopes, HDL/VHDL modelling of large-scale logic systems and a completely new chapter devoted to the Raspberry Pi.

Finally, you can learn a great deal from building, testing and modifying simple circuits. To do this you will need access to a few basic tools and some minimal testing equipment. Your first purchase should be a simple multi-range meter, either digital or analogue. This instrument will allow you to measure the voltages and currents present so that you can compare them with the predicted values. If you are attending a formal course of instruction and have access to an electronics laboratory, do make full use of it!

A note for teachers and lecturers

The book is ideal for students following formal courses (e.g. GCSE, AS-, A-level, BTEC, City & Guilds, etc.) in schools, sixth-form colleges and further/higher education colleges. It is equally well suited for use as a text that can support distance or flexible learning and for those who may need a 'refresher' before studying electronics at a higher level.

While the book assumes little previous knowledge, students need to be able to manipulate basic formulae and understand some simple trigonometry to follow the numerical examples. A study of mathematics to GCSE level (or beyond) will normally be adequate to satisfy this requirement. However, an appendix has been added specifically to support students who may have difficulty with mathematics. Students will require a scientific calculator in order to tackle the end-of-chapter problems as well as the revision problems that appear at the end of the book.

We have also included 22 sample coursework assignments. These are open-ended and can be modified or extended to suit the requirements of the particular awarding body. The assignments have been divided into those that are broadly at Level 2 and those that are at Level 3. In order to give reasonable coverage of the subject, students should normally be expected to complete four or five of these assignments.

Teachers can differentiate students' work by mixing assignments from the two levels. In order to challenge students, minimal information should be given to students at the start of each assignment. The aim should be to give students 'food for thought' and encourage them to develop their own solutions and interpretation of the topic.

Where this text is to be used to support formal teaching it is suggested that the chapters should be followed broadly in the order that they appear, with the notable exception of Chapter 13. Topics from this chapter should be introduced at an early stage in order to support formal lab work. Assuming a notional delivery time of 4.5 hours per week, the material contained in this book (together with supporting laboratory exercises and assignments) will require approximately two academic terms (i.e. 24 weeks) to deliver, in which the total of 90 hours of study time should be divided equally into theory (supported by problem solving) and practical (laboratory and assignment work). The recommended four or five assignments will require about 25–30 hours of student work to complete.

When developing a teaching programme it is, of course, essential to check that you fully comply with the requirements of the awarding body concerning assessment and that the syllabus coverage is adequate.

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A word about safety

When working on electronic circuits, personal safety (both yours and that of those around you) should be paramount in everything you do. Hazards can exist within many circuits – even those that, on the face of it, may appear to be totally safe. Inadvertent misconnection of a supply, incorrect earthing, reverse connection of a high-value electrolytic capacitor and incorrect component substitution can all result in serious hazards to personal safety as a consequence of fire, explosion or the generation of toxic fumes.

Potential hazards can usually be easily recognized and it is well worth making yourself familiar with them, but perhaps the most important point to make is that electricity acts very quickly and you should always think carefully before working on circuits where mains or high voltages (i.e. those over 50 V or so) are present. Failure to observe this simple precaution can result in the very real risk of electric shock.

Voltages in many items of electronic equipment, including all items which derive their power from the a.c. mains supply, are at a level which can cause sufficient current flow in the body to disrupt normal operation of the heart. The threshold will be even lower for anyone with a defective heart. Bodily contact with mains or high-voltage circuits can thus be lethal. The most critical path for electric current within the body (i.e. the one that is most likely to stop the heart) is that which exists from one hand to the other. The hand-to-foot path is also dangerous, but somewhat less so than the hand-to-hand path.

So, before you start to work on an item of electronic equipment, it is essential not only to switch off, but to disconnect the equipment at the mains by removing the mains plug. If you have to make measurements or carry out adjustments on an item of working (or 'live') equipment, a useful precaution is that of using one hand only to perform the adjustment or to make the measurement. Your 'spare' hand should be placed safely away from contact with anything metal (including the chassis of the equipment which may, or may not, be earthed).

The severity of electric shock depends upon several factors, including the magnitude of the current, whether it is alternating or direct current, and its precise path through the body. The magnitude of the current depends upon the voltage which is applied and the resistance of the body. The electrical energy developed in the body will depend upon the time for which the current flows. The duration of contact is also crucial in determining the eventual physiological effects of the shock. As a rough guide, and assuming that the voltage applied is from the 250 V, 50 Hz a.c. mains supply, the following effects are typical:

Current	**Physiological effect**
Less than 1 mA	Not usually noticeable
1 mA to 2 mA	Threshold of perception (a slight tingle may be felt)
2 mA to 4 mA	Mild shock (effects of current flow are felt)
4 mA to 10 mA	Serious shock (shock is felt as pain)
10 mA to 20 mA	Motor nerve paralysis may occur (unable to let go)
20 mA to 50 mA	Respiratory control inhibited (breathing may stop)
More than 50 mA	Ventricular fibrillation of heart muscle (heart failure)

It is important to note that the figures are quoted as a guide – there have been cases of lethal shocks resulting from contact with much lower voltages and at relatively small values of current. The upshot of all this is simply that any potential in excess of 50 V should be considered dangerous. Lesser potentials may, under unusual circumstances, also be dangerous. As such, it is wise to get into the habit of treating all electrical and electronic circuits with great care.

Mike Tooley
August 2014

CHAPTER 1

Electrical fundamentals

Chapter summary

This chapter has been designed to provide you with the background knowledge required to help you understand the concepts introduced in the later chapters. If you have studied electrical science, electrical principles or electronics beyond school level then you will already be familiar with many of these concepts. If, on the other hand, you are returning to study or are a newcomer to electronics or electrical technology this chapter will help you get up to speed.

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Fundamental units

You will already know that the units that we now use to describe such things as length, mass and time are standardized within the International System of Units. This SI system is based upon the seven **fundamental units** (see Table 1.1).

Derived units

All other units are derived from these seven fundamental units. These **derived units** generally have their own names and those commonly encountered in electrical circuits are summarized in Table 1.2 together with the corresponding physical quantities.

If you find the exponent notation shown in Table 1.2 a little confusing, just remember that V^{-1} is simply 1/V, s^{-1} is 1/s, m^{-2} is $1/m^{-2}$, and so on.

Example 1.1

The unit of flux density (the Tesla) is defined as the magnetic flux per unit area. Express this in terms of the fundamental units.

Solution

The SI unit of flux is the Weber (Wb). Area is directly proportional to length squared and, expressed in terms of the fundamental SI units, this is square metres (m^2). Dividing the flux (Wb) by the area (m^2) gives Wb/m^2 or $Wb\ m^{-2}$. Hence, in terms of the fundamental SI units, the Tesla is expressed in $Wb\ m^{-2}$.

Table 1.1 SI units

Quantity	Unit	Abbreviation
Current	ampere	A
Length	metre	m
Luminous intensity	candela	cd
Mass	kilogram	kg
Temperature	Kelvin	K
Time	second	s
Matter	mol	mol

(Note that 0 K is equal to –273 °C and an **interval** of 1 K is the same as an **interval of 1 °C.**)

Table 1.2 Electrical quantities

Quantity	Derived unit	Abbreviation	Equivalent (in terms of fundamental units)
Capacitance	Farad	F	$\mathrm{A\ s\ V^{-1}}$
Charge	Coulomb	C	A s
Energy	Joule	J	N m
Force	Newton	N	$\mathrm{kg\ m\ s^{-1}}$
Frequency	Hertz	Hz	$\mathrm{s^{-1}}$
Illuminance	Lux	lx	$\mathrm{lm\ m^{-2}}$
Inductance	Henry	H	$\mathrm{V\ s\ A^{-1}}$
Luminous flux	Lumen	lm	cd sr
Magnetic flux	Weber	Wb	V s
Potential	Volt	V	$\mathrm{W\ A^{-1}}$
Power	Watt	W	$\mathrm{J\ s^{-1}}$
Resistance	Ohm	Ω	$\mathrm{V\ A^{-1}}$

Example 1.2

The unit of electrical potential, the volt (V), is defined as the difference in potential between two points in a conductor which, when carrying a current of one amp (A), dissipates a power of one watt (W). Express the volt (V) in terms of joules (J) and coulombs (C).

Solution

In terms of the derived units:

$$\text{Volts} = \frac{\text{Watts}}{\text{Amperes}} = \frac{\text{Joules/seconds}}{\text{Amperes}}$$

$$= \frac{\text{Joules}}{\text{Amperes} \times \text{seconds}} = \frac{\text{Joules}}{\text{Coulombs}}$$

Note that: watts = joules/seconds and also that amperes × seconds = coulombs

Alternatively, in terms of the symbols used to denote the units:

$$V = \frac{W}{A} = \frac{J/s}{A} = \frac{J}{A\ s} = \frac{J}{C} = JC^{-1}$$

Hence, one volt is equivalent to one joule per coulomb.

Measuring angles

You might think it strange to be concerned with angles in electrical circuits. The reason is simply that, in analogue and a.c. circuits, signals are based on repetitive waves (often sinusoidal in shape). We can refer to a point on such a wave in one of two basic ways, either in terms of the time from the start of the cycle or in terms of the angle (a cycle starts at 0° and finishes as 360° (see Fig. 1.1)). In practice, it is often more convenient to use angles rather than time; however, the two methods of measurement are interchangeable and it's important to be able to work in either of these units.

In electrical circuits, angles are measured in either degrees or radians (both of which are strictly dimensionless units). You will doubtless already be familiar with angular measure in degrees where one complete circular revolution is equivalent to an angular change of 360°. The alternative method of measuring angles, the **radian**, is defined somewhat differently. It is the angle subtended at the centre of a circle by an arc having length which is equal to the radius of the circle (see Fig. 1.2).

You may sometimes find that you need to convert from radians to degrees, and vice versa. A complete circular revolution is equivalent to a rotation of 360° or 2π radians (note that π is approximately equal to 3.142). Thus one radian is equivalent to $360/2\pi$ degrees (or approximately 57.3°). Try to remember the following rules that will help you to convert angles expressed in degrees to radians and vice versa:

- From degrees to radians, divide by 57.3.
- From radians to degrees, multiply by 57.3.

Example 1.3

Express a quarter of a cycle revolution in terms of:

(a) degrees;
(b) radians.

Solution

(a) There are 360° in one complete cycle (i.e. one full revolution). Hence there are (360/4)° or 90° in one-quarter of a cycle.

(b) There are 2π radians in one complete cycle. Thus there are $2\pi/4$ or $\pi/2$ radians in one-quarter of a cycle.

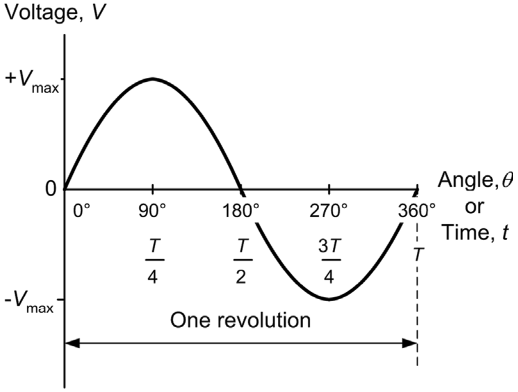

Figure 1.1 One cycle of a sine wave voltage

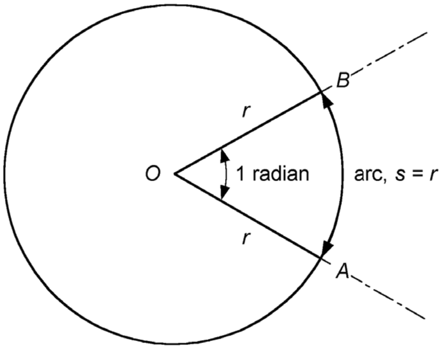

Figure 1.2 Definition of the radian

Example 1.4

Express an angle of 215° in radians.

Solution

To convert from degrees to radians, divide by 57.3. So 215° is equivalent to 215/57.3 = 3.75 radians.

Example 1.5

Express an angle of 2.5 radians in degrees.

Solution

To convert from radians to degrees, multiply by 57.3. Hence 2.5 radians is equivalent to 2.5 × 57.3 = 143.25°.

Electrical units and symbols

Table 1.3 shows the units and symbols that are commonly encountered in electrical circuits. It is important to get to know these units and also be able to recognize their abbreviations and symbols. You will meet all of these units later in this chapter.

Multiples and sub-multiples

Unfortunately, many of the derived units are either too large or too small for convenient everyday use but we can make life a little easier by using a standard range of multiples and sub-multiples (see Table 1.4).

Example 1.6

An indicator lamp requires a current of 0.075 A. Express this in mA.

Solution

You can express the current in mA (rather than in A) by simply moving the decimal point three places to the right. Hence 0.075 A is the same as 75 mA.

Example 1.7

A medium-wave radio transmitter operates on a frequency of 1,495 kHz. Express its frequency in MHz.

Solution

To express the frequency in MHz rather than kHz we need to move the decimal point three places to the left. Hence 1,495 kHz is equivalent to 1.495 MHz.

Example 1.8

Express the value of a 27,000 pF in μF.

Solution

To express the value in μF rather than pF we need to move the decimal point six places to the left. Hence 27,000 pF is equivalent to 0.027 μF (note that we have had to introduce an extra zero before the 2 and after the decimal point).

Table 1.3 Electrical units

Unit	Abbrev.	Symbol	Notes
Ampere	A	I	Unit of electric **current** (a current of 1 A flows when a charge of 1 C is transported in a time interval of 1 s)
Coulomb	C	Q	Unit of electric **charge** or quantity of electricity
Farad	F	C	Unit of **capacitance** (a capacitor has a capacitance of 1 F when a potential of 1 V across its plates produces a charge of 1 C)
Henry	H	L	Unit of **inductance** (an inductor has an inductance of 1 H when an applied current changing at 1 A/s produces a potential difference of 1 V across its terminals)
Hertz	Hz	f	Unit of **frequency** (a signal has a frequency of 1 Hz if one complete cycle occurs in an interval of 1 s)
Joule	J	W	Unit of **energy**
Ohm	Ω	R	Unit of **resistance**
Second	s	t	Unit of **time**
Siemen	S	G	Unit of **conductance** (the reciprocal of resistance)
Tesla	T	B	Unit of **magnetic flux density** (a flux density of 1 T is produced when a flux of 1 Wb is present over an area of 1 square metre)
Volt	V	V	Unit of electric **potential** (e.m.f. or p.d.)
Watt	W	P	Unit of **power** (equivalent to 1 J of energy consumed in 1 s)
Weber	Wb	ϕ	Unit of **magnetic flux**

Table 1.4 Multiples and sub-multiples

Prefix	Abbreviation	Multiplier
tera	T	10^{12} (= 1 000 000 000 000)
giga	G	10^{9} (= 1 000 000 000)
mega	M	10^{6} (= 1 000 000)
kilo	k	10^{3} (= 1 000)
(none)	(none)	10^{0} (= 1)
centi	c	10^{-2} (= 0.01)
milli	m	10^{-3} (= 0.001)
micro	μ	10^{-6} (= 0.000 001)
nano	n	10^{-9} (= 0.000 000 001)
pico	p	10^{-12} (= 0.000 000 000 001)

Exponent notation

Exponent notation (or **scientific notation**) is useful when dealing with either very small or very large quantities. It's well worth getting to grips with this notation as it will allow you to simplify quantities before using them in formulae.

Exponents are based on **powers of ten**. To express a number in exponent notation the number is split into two parts. The first part is usually a number in the range 0.1 to 100 while the second part is a multiplier expressed as a power of ten.

For example, 251.7 can be expressed as 2.517 × 100, i.e. 2.517×10^2. It can also be expressed as 0.2517 × 1,000, i.e. 0.2517×10^3. In both cases the exponent is the same as the number of noughts in the multiplier (i.e. 2 in the first case and 3 in the second case). To summarize:

$$251.7 = 2.517 \times 10^2 = 0.2517 \times 10^3$$

As a further example, 0.01825 can be expressed as 1.825/100, i.e. 1.825×10^{-2}. It can also be expressed as 18.25/1,000, i.e. 18.25×10^{-3}. Again, the exponent is the same as the number of noughts but the minus sign is used to denote a fractional multiplier. To summarize:

$$0.01825 = 1.825 \times 10^{-2} = 18.25 \times 10^{-3}$$

Example 1.9

A current of 7.25 mA flows in a circuit. Express this current in amperes using exponent notation.

Solution

$1\text{ mA} = 1 \times 10^{-3}$ A thus $7.25\text{ mA} = 7.25 \times 10^{-3}$ A.

Example 1.10

A voltage of 3.75×10^{-6} V appears at the input of an amplifier. Express this voltage in (a) V and (b) mV, using exponent notation.

Solution

(a) 1×10^{-6} V = 1 μV so 3.75×10^{-6} V = 3.75 μV.
(b) There are 1,000 μV in 1 mV so we must divide the previous result by 1,000 in order to express the voltage in mV. So 3.75 μV = 0.00375 mV.

Multiplication and division using exponents

Exponent notation really comes into its own when values have to be multiplied or divided. When multiplying two values expressed using exponents, you simply need to add the exponents. Here's an example:

$$(2 \times 10^2) \times (3 \times 10^6) = (2 \times 3) \times 10^{(2+6)} = 6 \times 10^8$$

Similarly, when dividing two values which are expressed using exponents, you only need to subtract the exponents. As an example:

$$(4 \times 10^6) \div (2 \times 10^4) = 4/2 \times 10^{(6-4)} = 2 \times 10^2$$

In either case it's important to remember to specify the units, multiples and sub-multiples in which you are working (e.g. A, kΩ, mV, μF, etc.).

Example 1.11

A current of 3 mA flows in a resistance of 33 kΩ. Determine the voltage dropped across the resistor.

Solution

Voltage is equal to current multiplied by resistance (see page 7). Thus:

$$V = I \times R = 3\text{ mA} \times 33\text{ k}\Omega$$

Expressing this using exponent notation gives:

$$V = (3 \times 10^{-3}) \times (33 \times 10^3)\text{ V}$$

Separating the exponents gives:

$$V = 3 \times 33 \times 10^{-3} \times 10^3\text{ V}$$

Thus $V = 99 \times 10^{(-3+3)} = 99 \times 10^0 = 99 \times 1 = 99$ V.

Example 1.12

A current of 45 μA flows in a circuit. What charge is transferred in a time interval of 20 ms?

Solution

Charge is equal to current multiplied by time (see the definition of the ampere on page 4). Thus:

$$Q = I\,t = 45\ \mu\text{A} \times 20\ \text{ms}$$

Expressing this in exponent notation gives:

$$Q = (45 \times 10^{-6}) \times (20 \times 10^{-3})\ \text{coulomb}$$

Separating the exponents gives:

$$Q = 45 \times 20 \times 10^{-6} \times 10^{-3}\ \text{coulomb}$$

Thus $Q = 900 \times 10^{(-6-3)} = 900 \times 10^{-9} = 900\ \text{nC}$

Example 1.13

A power of 300 mW is dissipated in a circuit when a voltage of 1,500 V is applied. Determine the current supplied to the circuit.

Solution

Current is equal to power divided by voltage (see page 9). Thus:

$$I = P\,/\,V = 300\ \text{mW}\,/\,1{,}500\ \text{V amperes}$$

Expressing this in exponent notation gives:

$$I = (300 \times 10^{-3})/(1.5 \times 10^{3})\ \text{A}$$

Separating the exponents gives:

$$I = (300/1.5) \times (10^{-3}/10^{3})\ \text{A}$$

$$I = 300/1.5 \times 10^{-3} \times 10^{-3}\ \text{A}$$

Thus, $I = 200 \times 10^{(-3-3)} = 200 \times 10^{-6} = 200\ \mu\text{A}$

Conductors and insulators

Electric current is the name given to the flow of **electrons** (or negative charge carriers). Electrons orbit around the nucleus of atoms just as the Earth orbits around the sun (see Fig. 1.3). Electrons are held in one or more **shells**, constrained to their orbital paths by virtue of a force of attraction towards the nucleus which contains an equal number of **protons** (positive charge carriers). Since like charges repel and unlike charges attract, negatively charged electrons are attracted to the positively charged nucleus. A similar principle can be demonstrated by observing the attraction between two permanent magnets; the two north poles of the magnets will repel each other, while a north and south pole will attract. In the same way, the unlike charges of the negative electron and the positive proton experience a force of mutual attraction.

The outer shell electrons of a **conductor** can be reasonably easily interchanged between adjacent atoms within the **lattice** of atoms of which the substance is composed. This makes it possible for the material to conduct electricity. Typical examples of conductors are metals such as copper, silver, iron and aluminium. By contrast, the outer-shell electrons of an **insulator** are firmly bound to their parent atoms and virtually no interchange of electrons is possible. Typical examples of insulators are plastics, rubber and ceramic materials.

Voltage and resistance

The ability of an energy source (e.g. a battery) to produce a current within a conductor may be expressed in terms of **electromotive force** (e.m.f.). Whenever an e.m.f. is applied to a circuit **a potential difference** (p.d.) exists. Both e.m.f. and p.d. are measured in volts (V). In many practical circuits there is only one e.m.f. present (the battery or supply) whereas a p.d. will be developed across each component present in the circuit.

The **conventional flow** of current in a circuit is from the point of more positive potential to the point of greatest negative potential (note that

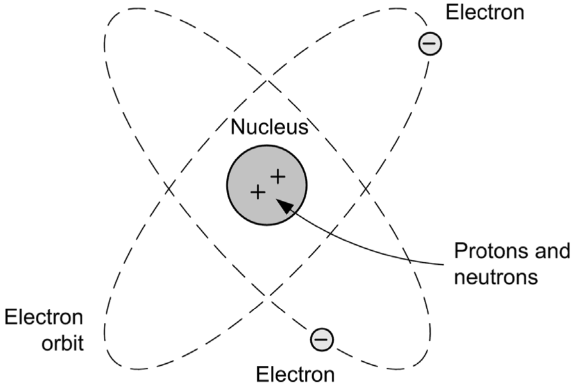

Figure 1.3 A single atom of helium (H_e) showing its two electrons in orbit around its nucleus

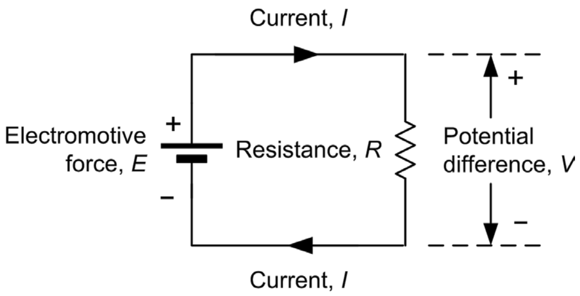

Figure 1.4 Simple circuit to illustrate the relationship between voltage (*V*), current (*I*) and resistance (*R*). Note that the direction of conventional current flow is from positive to negative

electrons move in the *opposite* direction!). **Direct current** results from the application of a direct e.m.f. (derived from batteries or a d.c. power supply). An essential characteristic of these supplies is that the applied e.m.f. does not change its polarity (even though its value might be subject to some fluctuation).

For any conductor, the current flowing is directly proportional to the e.m.f. applied. The current flowing will also be dependent on the physical dimensions (length and cross-sectional area) and material of which the conductor is composed.

The amount of current that will flow in a conductor when a given e.m.f. is applied is inversely proportional to its **resistance**. Resistance, therefore, may be thought of as an opposition to current flow; the higher the resistance the lower the current that will flow (assuming that the applied e.m.f. remains constant).

Ohm's Law

Provided that temperature does not vary, the ratio of p.d. across the ends of a conductor to the current flowing in the conductor is a constant. This relationship is known as Ohm's Law and it leads to the relationship:

$$V / I = \text{a constant} = R$$

where V is the potential difference (or voltage drop) in volts (V), I is the current in amperes (A), and R is the resistance in ohms (Ω) (see Fig. 1.4).

The formula may be arranged to make V, I or R the subject, as follows:

$$V = I \times R,\ I = V / R \text{ and } R = V / I$$

The triangle shown in Fig. 1.5 should help you remember these three important relationships. However, it's worth noting that, when performing calculations of currents, voltages and resistances in practical circuits it is seldom necessary to work with an accuracy of better than ±1% simply because component tolerances are usually greater than this. Furthermore, in calculations involving Ohm's Law, it can sometimes be convenient to work in units of kΩ and mA (or MΩ and μA) in which case potential differences will be expressed directly in V.

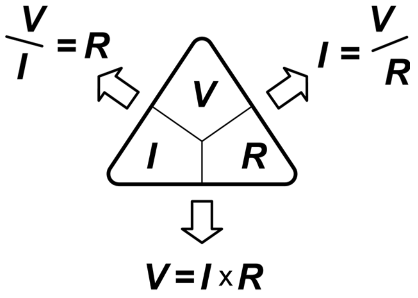

Figure 1.5 Triangle showing the relationship between *V*, *I* and *R*

Example 1.14

A 12 Ω resistor is connected to a 6 V battery. What current will flow in the resistor?

Solution

Here we must use $I = V / R$ (where $V = 6$ V and $R = 12$ Ω):

$$I = V / R = 6\text{ V} / 12\ \Omega = 0.5\text{ A (or 500 mA)}$$

Hence a current of 500 mA will flow in the resistor.

Example 1.15

A current of 100 mA flows in a 56 Ω resistor. What voltage drop (potential difference) will be developed across the resistor?

Solution

Here we must use $V = I \times R$ and ensure that we work in units of volts (V), amperes (A) and ohms (Ω).

$$V = I \times R = 0.1\ \text{A} \times 56\ \Omega = 5.6\ \text{V}$$

(Note that 100 mA is the same as 0.1 A.)

This calculation shows that a p.d. of 5.6 V will be developed across the resistor.

Example 1.16

A voltage drop of 15 V appears across a resistor in which a current of 1 mA flows. What is the value of the resistance?

Solution

$$R = V / I = 15\ \text{V} / 0.001\ \text{A} = 15{,}000\ \Omega = 15\ \text{k}\Omega$$

Note that it is often more convenient to work in units of mA and V, which will produce an answer directly in kΩ, i.e.

$$R = V / I = 15\ \text{V} / 1\ \text{mA} = 15\ \text{k}\Omega$$

Resistance and resistivity

The resistance of a metallic conductor is directly proportional to its length and inversely proportional to its area. The resistance is also directly proportional to its **resistivity** (or **specific resistance**). Resistivity is defined as the resistance measured between the opposite faces of a cube having sides of 1 cm.

The resistance, R, of a conductor is thus given by the formula:

$$R = \rho \times l / A$$

where R is the resistance (ft), ρ is the resistivity (Ωm), l is the length (m) and A is the area (m^2).

Table 1.5 shows the electrical properties of some common metals.

Example 1.17

A coil consists of an 8 m length of annealed copper wire having a cross-sectional area of 1 mm^2. Determine the resistance of the coil.

Solution

We will use the formula $R = \rho l / A$.

The value of ρ for annealed copper given in Table 1.5 is 1.724×10^{-8} Ωm. The length of the wire is 4 m while the area is 1 mm^2 or 1×10^{-6} m^2 (note that it is important to be consistent in using units of metres for length and square metres for area). Hence the resistance of the coil will be given by:

$$R = \frac{1.724 \times 10^{-8} \times 8}{1 \times 10^{-6}} = 13.724 \times 10^{(-8+6)}$$

Thus $R = 13.792 \times 10^{-2}$ or 0.13792 Ω.

Table 1.5 Properties of some common metals

Metal	Resistivity (at 20°C) (Ωm)	Relative conductivity (copper = 1)	Temperature coefficient of resistance (per °C)
Silver	1.626×10^{-8}	1.06	0.0041
Copper (annealed)	1.724×10^{-8}	1.00	0.0039
Copper (hard drawn)	1.777×10^{-8}	0.97	0.0039
Aluminium	2.803×10^{-8}	0.61	0.0040
Mild steel	1.38×10^{-7}	0.12	0.0045
Lead	2.14×10^{-7}	0.08	0.0040
Nickel	8.0×10^{-8}	0.22	0.0062

Example 1.18

A wire having a resistivity of $1.724 \times 10^{-8}\ \Omega$m, length 20 m and cross-sectional area 1 mm^2 carries a current of 5 A. Determine the voltage drop between the ends of the wire.

Solution

First we must find the resistance of the wire (as in Example 1.17):

$$R = \frac{\rho l}{A} = \frac{1.6 \times 10^{-8} \times 20}{1 \times 10^{-6}} = 32 \times 10^{-2} = 0.32\ \Omega$$

The voltage drop can now be calculated using Ohm's Law:

$V = I \times R = 5A \times 0.32\ \Omega = 1.6$ V

This calculation shows that a potential of 1.6 V will be dropped between the ends of the wire.

Energy and power

At first you may be a little confused about the difference between energy and power. Put simply, energy is the ability to do work while power is the rate at which work is done. In electrical circuits, energy is supplied by batteries or generators. It may also be stored in components such as capacitors and inductors. Electrical energy is converted into various other forms of energy by components such as resistors (producing heat), loudspeakers (producing sound energy) and light emitting diodes (producing light).

The unit of energy is the joule (J). Power is the rate of use of energy and it is measured in watts (W). A power of 1 W results from energy being used at the rate of 1 J per second. Thus:

$P = W / t$

where P is the power in watts (W), W is the energy in joules (J) and t is the time in seconds (s).

The power in a circuit is equivalent to the product of voltage and current. Hence:

$P = I \times V$

where P is the power in watts (W), I is the current in amperes (A) and V is the voltage in volts (V).

The formula may be arranged to make P, I or V the subject, as follows:

$P = I \times P$, $I = P / V$ and $V = P / I$

The triangle shown in Fig. 1.6 should help you remember these relationships.

The relationship, $P = I \times V$, may be combined with that which results from Ohm's Law ($V = I \times R$) to produce two further relationships. First, substituting for V gives:

$P = I \times (I \times R) = I^2 R$

Second, substituting for I gives:

$P = (V / R) \times V = V^2 / R$

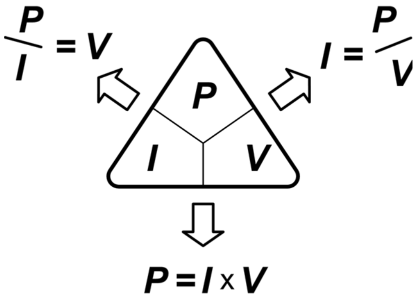

Figure 1.6 Triangle showing the relationship between P, I and V

Example 1.19

A current of 1.5 A is drawn from a 3 V battery. What power is supplied?

Solution

Here we must use $P = I \times V$ (where $I = 1.5$ A and $V = 3$ V).

$P = I \times V = 1.5\text{ A} \times 3\text{ V} = 4.5$ W

Hence a power of 4.5 W is supplied.

Example 1.20

A voltage drop of 4 V appears across a resistor of 100 Ω. What power is dissipated in the resistor?

Solution

Here we use $P = V^2 / R$ (where $V = 4$ V and $R = 100\ \Omega$).

$P = V^2 / R = (4\text{ V} \times 4\text{ V}) / 100\ \Omega = 0.16$ W

Hence the resistor dissipates a power of 0.16 W (or 160 mW).