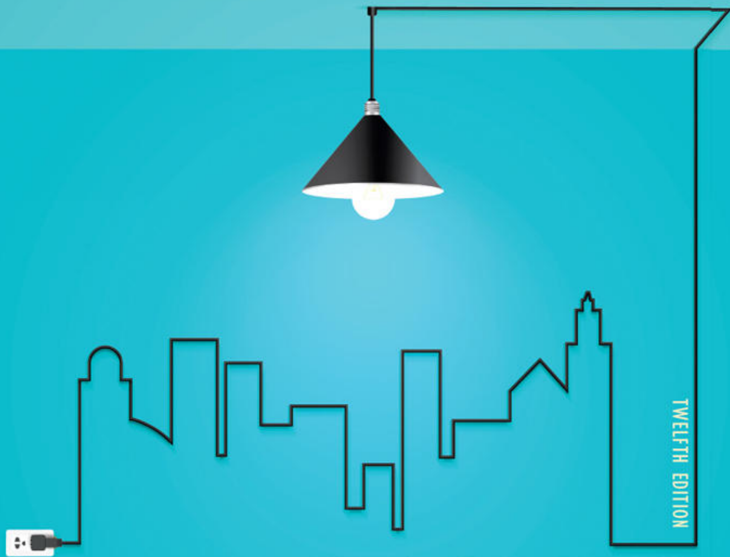

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ELECTRICAL & ELECTRONIC TECHNOLOGY

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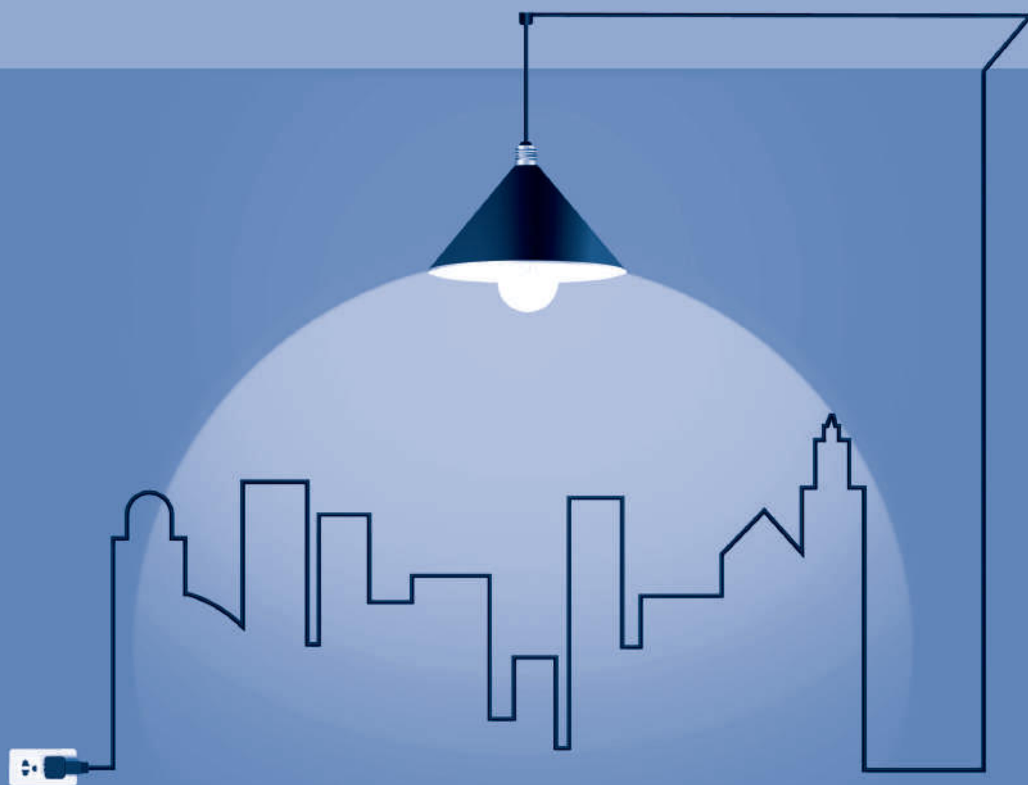

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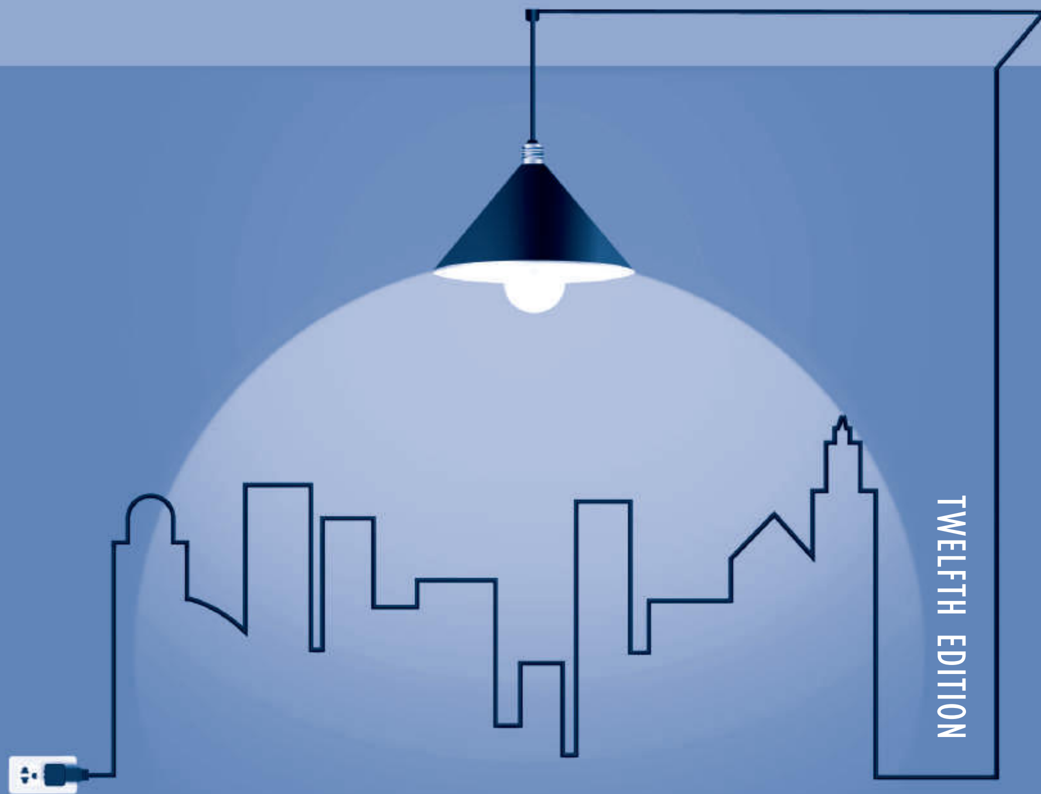

TWELFTH EDITION

HUGHES
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EDWARD HUGHES

REVISED BY JOHN HILEY, KEITH BROWN & IAN McKENZIE SMITH

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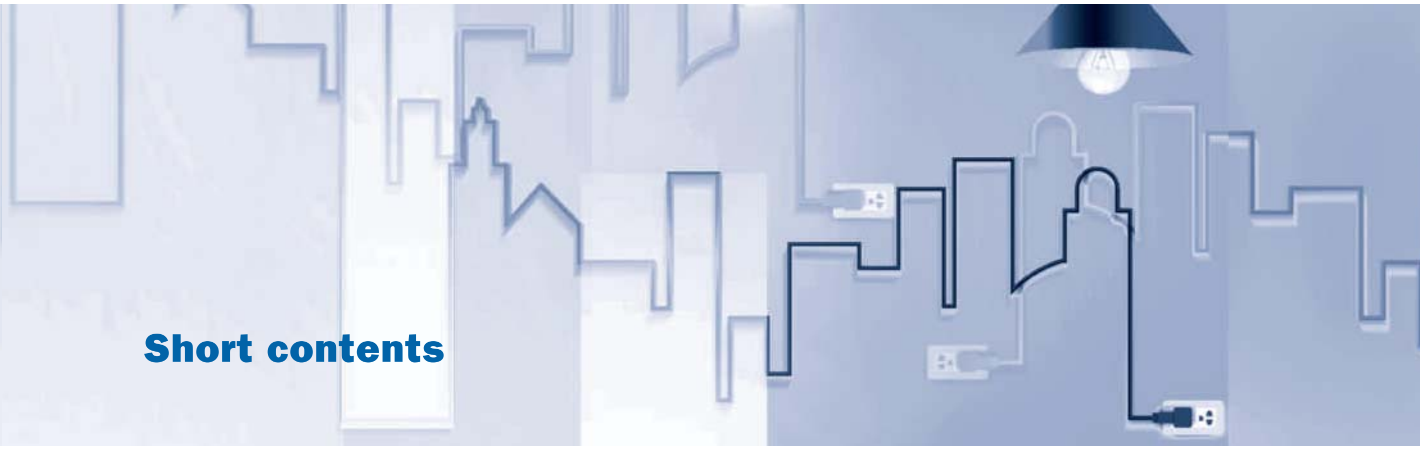

Short contents

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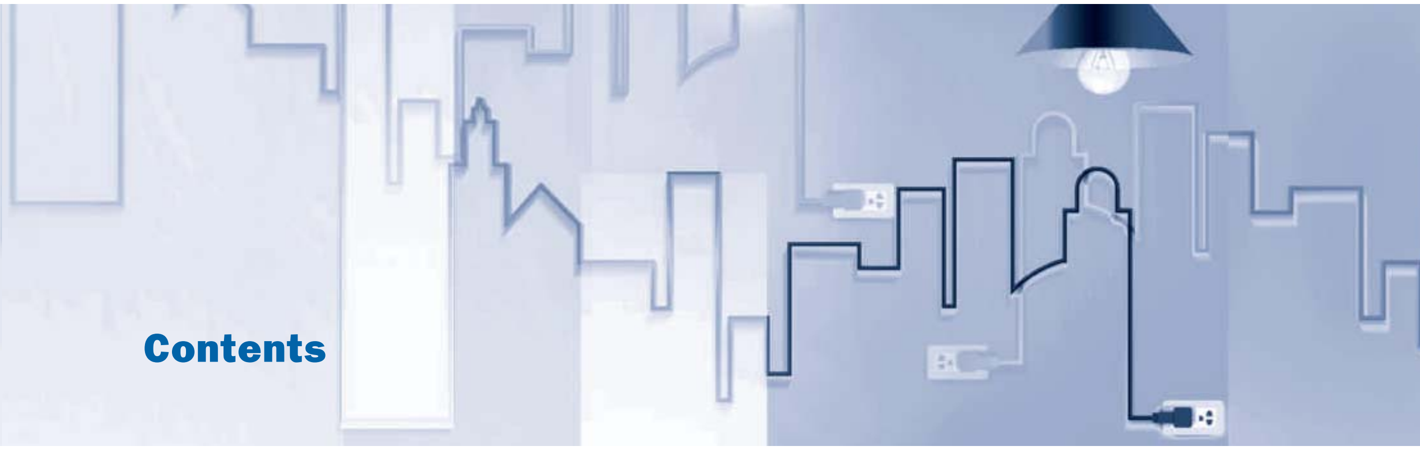

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Lecturer Resources

ON THE WEBSITE

For password-protected online resources tailored to support the use of this textbook in teaching, please visit **www.pearsoned.co.uk/hughes**

Preface to the Twelfth Edition

There are two main conclusions to be drawn from the Engineering UK 2015 report ‘The State of Engineering’. Firstly, that Britain is great at engineering: ‘*…its skilled engineers are world class and engineering makes a vital and valued contribution to the UK economy, and can help mitigate the grand global challenges of climate change, ageing populations, and supply of food, clean water and energy.*’ Secondly, that the UK, at all levels of education, does not have either the current capacity or the rate of growth needed to meet the forecast demand for skilled engineers by 2022. Engineering accounts for a quarter of UK’s turnover according to the report, and that the shortage skills could cost the UK economy up to £27bn a year if companies fail to hire 182,000 engineers annually until 2022. The conclusions are clear. Young people are needed by industry for the exciting jobs that await.

The same report also states: ‘*…that while 12 per cent of parents stated they would like their son to become an engineer, only 2 per cent said the same about their daughter.*’ By failing to inspire girls, we’re cutting ourselves off from an enormous pool of potential talent. Engineering is all about designing and building our future and we need to capture the imagination and attention of the young minds of both sexes, and show them that they can play a part in shaping the world. We hope this edition of *Hughes* plays its part in educating those electrical and electronic engineers of the future.

This edition represents something of a watershed in the life of *Hughes*. John Hiley is retiring after 15 years as co-author. He writes: ‘It has been a privilege to have been able to contribute to the continuing success of this textbook, one which has informed my whole career in Electrical and Electronic Engineering. I never stopped learning from it either as a student in the late 1960s (using the 4th edition), as an engineer in industry or latterly as a University Teacher. A new author will, of course, bring different expertise to the continued development of the textbook, and I’m sure that, in tandem with my co-author Keith, with whom it has been a great pleasure to collaborate since the 8th edition, the book will continue to inform long into the future. I wish it well.’

Once again, we acknowledge the support of our families during the course of preparation of this new edition, which is dedicated to them all: Wendy, Robin, Helen; Judy, Ben, Rachel and Megan.

John Hiley
Keith Brown
Heriot Watt University, Edinburgh
February 2016

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Preface to the First Edition

This volume covers the electrical engineering syllabuses of the Second and Third Year Courses for the Ordinary National Certificate in Electrical Engineering and of the First Year Course leading to a Degree of Engineering.

The rationalized M.K.S. system of units has been used throughout this book. The symbols, abbreviations and nomenclature are in accordance with the recommendations of the British Standards Institution, and, for the convenience of students, the symbols and abbreviations used in this book have been tabulated in the Appendix.

It is impossible to acquire a thorough understanding of electrical principles without working out a large number of numerical problems, and, while doing this, students should make a habit of writing the solutions in an orderly manner, attaching the name of the unit wherever possible. When students tackle problems in examinations or in industry, it is important that they express their solutions in a way that is readily intelligible to others, and this facility can only be acquired by experience. Guidance in this respect is given by the 106 worked examples in the text, and the 670 problems afford ample opportunity for practice.

Most of the questions have been taken from examination papers; and for permission to reproduce these questions I am indebted to the University of London, the East Midland Educational Union, the Northern Counties Technical Examination Council, the Union of Educational Institutions and the Union of Lancashire and Cheshire Institutes.

I wish to express my thanks to Dr F. T. Chapman, C.B.E., M.I.E.E., and Mr E. F. Piper, A.M.I.E.E., for reading the manuscript and making valuable suggestions.

Edward Hughes
Hove
April 1959

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Figures

Figure 34.2 adapted from GB Seven Year Statement 2007, Chapter 2, figure 2.2, www.nationalgrid.com/uk/sys_07/print.asp?chap=2, National Grid 2011; Figure 34.3 adapted from Forecasting Demand, www.nationalgrid.com/NR/rdonlyres/1C4B1304-4631-8A84-3859FB8B4B38/17136/demand.pdf, National Grid 2011.

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Section one Electrical Principles

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Chapter one

International System of Measurement

Objectives

When you have studied this chapter, you should

- be familiar with the International System of Measurement
- be familiar with a variety of derived SI units
- be aware of the concepts of torque and turning moment
- be capable of analysing simple applications of the given SI units
- have an understanding of work, energy and power
- be capable of analysing simple applications involving work, energy and power
- have an understanding of efficiency and its relevance to energy and power
- be capable of analysing the efficiency of simple applications
- have an understanding of temperature and its units of measurement

Contents

Electrical technology is a subject which is closely related to the technologies of mechanics, heat, light and sound. For instance, we use electrical motors to drive machines such as cranes, we use electric heaters to keep us warm, we use electric lamp bulbs perhaps to read this book and we use electric radios to listen to our favourite music.

At this introductory stage, let us assume that we have some understanding of physics in general and, in particular, let us assume that we have some understanding of the basic mechanics which form part of any study of physics. It is not necessary to have an extensive knowledge, and in this chapter we shall review the significant items of which you should have an understanding. We shall use these to develop an appreciation of electrical technology.

In particular, we shall be looking at the concepts of work, energy and power since the underlying interest that we have in electricity is the delivery of energy to a point of application. Thus we drive an electric train yet the power source is in a generating station many kilometres away, or we listen to a voice on the phone speaking with someone possibly on the other side of the world. It is electricity which delivers the energy to make such things happen.

1.1 The International System

The International System of Units, known as SI in every language, was formally introduced in 1960 and has been accepted by most countries as their only legal system of measurement.

One of the SI's most important advantages over its predecessors is that it is a coherent system wherever possible. A system is coherent if the product or quotient of any two quantities is the unit of the resultant quantity. For example, unit area results when unit length is multiplied by unit length. Similarly, unit velocity results when unit length or distance is divided by unit time.

The SI is based on the measures of six physical quantities:

Mass
Length
Time
Electric current
Absolute temperature
Luminous intensity

All other units are derived units and are related to these base units by definition.

If we attempt to analyse relationships between one unit and another, this can be much more readily achieved by manipulating symbols, e.g. A for areas, W for energy and so on. As each quantity is introduced, its symbol will be highlighted as follows:

Energy Symbol: W

Capital letters are normally used to represent constant quantities – if they vary, the symbols can be made lower case, i.e. W indicates constant energy whereas w indicates a value of energy which is time varying.

The names of the SI units can be abbreviated for convenience. Thus the unit for energy – the joule – can be abbreviated to J. This will be highlighted as follows:

Energy Symbol: W Unit: **joule (J)**

Here the unit is given the appropriate unit abbreviation in brackets. These are only used after numbers, e.g. 16 J. By comparison, we might refer to a few joules of energy.

Now let us consider the six base quantities.

The *kilogram* is the mass of a platinum-iridium cylinder preserved at the International Bureau of Weights and Measures at Sèvres, near Paris, France.

Mass Symbol: m Unit: **kilogram (kg)**

It should be noted that the megagram is also known as the tonne (t).

The *metre* is the length equal to 1 650 763.73 wavelengths of the orange line in the spectrum of an internationally specified krypton discharge lamp.

Length Symbol: l Unit: **metre (m)**

Length and distance are effectively the same measurement, but we use the term distance to indicate a length of travel. In such instances, the symbol d may be used instead of l. In the measurement of length, the centimetre is additional to the normal multiple units.

The *second* is the interval occupied by 9 192 631 770 cycles of the radiation corresponding to the transition of the caesium-133 atom.

Time Symbol: t Unit: **second (s)**

Although the standard submultiples of the second are used, the multiple units are often replaced by minutes (min), hours (h), days (d) and years (a).

The *ampere* is defined in section 2.7.

Electric current Symbol: I Unit: **ampere (A)**

The *kelvin* is 1/273.16 of the thermodynamic temperature of the triple point of water. On the Celsius scale the temperature of the triple point of water is 0.01 °C, hence

$$0°\text{C} = 273.15\text{ K}$$

A temperature interval of 1 °C = a temperature interval of 1 K.

The *candela* is the unit of luminous intensity.

1.2 SI derived units

Although the physical quantities of area, volume, velocity, acceleration and angular velocity are generally understood, it is worth noting their symbols and units.

Area	Symbol: A	Unit: **square metre (m^2)**
Volume	Symbol: V	Unit: **cubic metre (m^3)**
Velocity	Symbol: u	Unit: **metre per second (m/s)**
Acceleration	Symbol: a	Unit: **metre per second squared (m/s^2)**
Angular velocity	Symbol: ω	Unit: **radian per second (rad/s)**

The unit of force, called the newton, is that force which, when applied to a body having a mass of one kilogram, gives it an acceleration of one metre per second squared.

Force Symbol: F Unit: **newton (N)**

$$F = ma \qquad [1.1]$$

$$F\,[\text{newtons}] = m\,[\text{kilograms}] \times a\,[\text{metres per second}^2]$$

Weight The weight of a body is the gravitational force exerted by the Earth on that body. Owing to the variation in the radius of the Earth, the gravitational force on a given mass, at sea-level, is different at different latitudes, as shown in Fig. 1.1. It will be seen that the weight of a 1 kg mass at sea-level in the London area is practically 9.81 N. For most purposes we can assume

$$\text{The weight of a body} \simeq 9.81m\text{ newtons} \qquad [1.2]$$

where m is the mass of the body in kilograms.

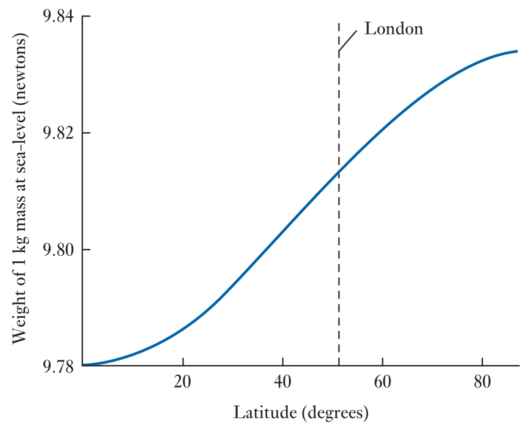

Fig. 1.1 Variation of weight with latitude

Example 1.1

A force of 50 N is applied to a mass of 200 kg. Calculate the acceleration.

Substituting in expression [1.1], we have

$$50\,[\text{N}] = 200\,[\text{kg}] \times a$$

$$\therefore \quad a = \mathbf{0.25\ m/s^2}$$

Example 1.2

A steel block has a mass of 80 kg. Calculate the weight of the block at sea-level in the vicinity of London.

Since the weight of a 1 kg mass is approximately 9.81 N,

$$\text{Weight of the steel block} = 80\,[\text{kg}] \times 9.81\,[\text{N/kg}] = \mathbf{785\ N}$$

In the above example, it is tempting to give the answer as 784.8 N, but this would be a case of false accuracy. The input information was only given to three figures and therefore the answer should only have three significant numbers, hence 784.8 ought to be shown as 785. Even here, it could be argued that the 80 kg mass was only given as two figures and the answer might therefore have been shown as 780 N. Be careful to show the answer as a reasonable compromise. In the following examples, such adjustments will be brought to your attention.

1.3 Unit of turning moment or torque

If a force F, in newtons, is acting at right angles to a radius r, in metres, from a point, the turning moment or torque about that point is

Fr newton metres

Torque Symbol: T (or M) Unit: **newton metre (N m)**

If the perpendicular distance from the line of action to the axis of rotation is r, then

$$T = Fr \qquad [1.3]$$

The symbol M is reserved for the torque of a rotating electrical machine.

1.4 Unit of work or energy

The SI unit of energy is the *joule* (after the English physicist, James P. Joule, 1818–1889). *The joule is the work done when a force of 1 N acts through a distance of 1 m in the direction of the force.* Hence, if a force F acts through distance l in its own direction

$$\text{Work done} = F\,[\text{newtons}] \times l\,[\text{metres}]$$
$$= Fl \text{ joules}$$

Work or energy Symbol: W Unit: **joule (J)**

$$W = Fl \tag{1.4}$$

Note that energy is the capacity for doing work. Both energy and work are therefore measured in similar terms.

If a body having mass m, in kilograms, is moving with velocity u, in metres per second

$$\text{Kinetic energy} = \tfrac{1}{2}mu^2 \text{ joules}$$

$$\therefore \qquad W = \tfrac{1}{2}mu^2 \qquad [1.5]$$

If a body having mass m, in kilograms, is lifted vertically through height h, in metres, and if g is the gravitational acceleration, in metres per second squared, in that region, the potential energy acquired by the body is

$$\text{Work done in lifting the body} = mgh \text{ joules}$$

$$W \simeq 9.81mh \qquad [1.6]$$

Example 1.3

A body having a mass of 30 kg is supported 50 m above the Earth's surface. What is its potential energy relative to the ground?

If the body is allowed to fall freely, calculate its kinetic energy just before it touches the ground. Assume gravitational acceleration to be 9.81 m/s².

$$\text{Weight of body} = 30\,[\text{kg}] \times 9.81\,[\text{N/kg}] = 294.3\text{ N}$$

$$\therefore \qquad \text{Potential energy} = 294.3\,[\text{N}] \times 50\,[\text{m}] = \mathbf{14\,700\ J}$$

Note: here we carried a false accuracy in the figure for the weight and rounded the final answer to three figures.

If u is the velocity of the body after it has fallen a distance l with an acceleration g

$$u = \sqrt{(2gl)} = \sqrt{(2 \times 9.81 \times 50)} = 31.32\text{ m/s}$$

and

$$\text{Kinetic energy} = \tfrac{1}{2} \times 30\,[\text{kg}] \times (31.32)^2\,[\text{m/s}]^2 = \mathbf{14\,700\ J}$$

Hence the whole of the initial potential energy has been converted into kinetic energy. When the body is finally brought to rest by impact with the ground, practically the whole of this kinetic energy is converted into heat.

1.5 Unit of power

Since power is the rate of doing work, it follows that the SI unit of power is the *joule per second*, or *watt* (after the Scottish engineer James Watt, 1736–1819). In practice, the watt is often found to be inconveniently small and so the *kilowatt* is frequently used.

Power Symbol: ***P*** Unit: **watt (W)**

$$P = \frac{W}{t} = \frac{F \cdot l}{t} = F \cdot \frac{l}{t}$$

$$P = Fu \qquad [1.7]$$

In the case of a rotating electrical machine

$$P = M\omega = \frac{2\pi N_r M}{60} \qquad [1.8]$$

where N_r is measured in revolutions per minute.

Rotational speed Symbol: N_r Unit: **revolution per minute (r/min)**

In the SI, the rotational speed ought to be given in revolutions per second but this often leads to rather small numbers, hence it is convenient to give rotational speed in revolutions per minute. The old abbreviation was rev/min and this is still found to be widely in use.

Rotational speed Symbol: n_r Unit: **revolution per second (r/s)**

There is another unit of energy which is used commercially: the kilowatt hour (kW h). It represents the work done by working at the rate of one kilowatt for a period of one hour. Once known as the Board of Trade Unit, it is still widely referred to, especially by electricity suppliers, as the unit.

$$\begin{aligned} 1\text{ kW h} &= 1000 \text{ watt hours} \\ &= 1000 \times 3600 \text{ watt seconds or joules} \\ &= 3\,600\,000\text{ J} = 3.6\text{ MJ} \end{aligned}$$

Example 1.4

A stone block, having a mass of 120 kg, is hauled 100 m in 2 min along a horizontal floor. The coefficient of friction is 0.3. Calculate:

(a) the horizontal force required;
(b) the work done;
(c) the power.

(a) Weight of stone $\simeq 120\,[\text{kg}] \times 9.81\,[\text{N/kg}] = 1177.2\text{ N}$

$\therefore$ Force required $= 0.3 \times 1177.2\,[\text{N}] = 353.16\text{ N} = \mathbf{353\text{ N}}$

(b) Work done $= 353.16\,[\text{N}] \times 100\,[\text{m}] = 35\,316\text{ J}$

$= \mathbf{35.3\text{ kJ}}$

(c) $$\text{Power} = \frac{35\,316\,[\text{J}]}{(2 \times 60)[\text{s}]} = \mathbf{294\text{ W}}$$

Example 1.5

An electric motor is developing 10 kW at a speed of 900 r/min. Calculate the torque available at the shaft.

$$\text{Speed} = \frac{900\,[\text{r/min}]}{60\,[\text{s/min}]} = 15\,\text{r/s}$$

Substituting in expression [1.8], we have

$$10\,000\,[\text{W}] = T \times 2\pi \times 15\,[\text{r/s}]$$

$$\therefore \quad T = \mathbf{106\,N\,m}$$

1.6 Efficiency

It should be noted that when a device converts or transforms energy, some of the input energy is consumed to make the device operate. The efficiency of this operation is defined as

$$\text{Efficiency} = \frac{\text{energy output in a given time}}{\text{energy input in the same time}} = \frac{W_o}{W_{in}}$$

$$= \frac{\text{power output}}{\text{power input}} = \frac{P_o}{P_{in}}$$

Efficiency Symbol: η Unit: **none**

$$\therefore \quad \eta = \frac{P_o}{P_{in}} \tag{1.9}$$

Example 1.6

A generating station has a daily output of 280 MW h and uses 500 t (tonnes) of coal in the process. The coal releases 7 MJ/kg when burnt. Calculate the overall efficiency of the station.

Input energy per day is

$$W_{in} = 7 \times 10^6 \times 500 \times 1000$$
$$= 35.0 \times 10^{11}\,\text{J}$$

Output energy per day is

$$W_o = 280\,\text{MW h}$$
$$= 280 \times 10^6 \times 3.6 \times 10^3 = 10.1 \times 10^{11}\,\text{J}$$

$$\eta = \frac{W_o}{W_{in}} = \frac{10.1 \times 10^{11}}{35.0 \times 10^{11}} = \mathbf{0.288}$$

Example 1.7

A lift of 250 kg mass is raised with a velocity of 5 m/s. If the driving motor has an efficiency of 85 per cent, calculate the input power to the motor.

Weight of lift is

$$F = mg = 250 \times 9.81 = 2452\,\text{N}$$

Output power of motor is

$$P_o = Fu = 2452 \times 5 = 12\,260 \text{ W}$$

Input power to motor is

$$P_{in} = \frac{P_o}{\eta} = \frac{12\,260}{0.85} = 14\,450 \text{ W} = \mathbf{14.5\ kW}$$

1.7 Temperature

Some mention is required of temperature measurement, which is in the Celsius scale. Absolute temperature is measured in kelvin, but for most electrical purposes at an introductory stage it is sufficient to measure temperature in degrees Celsius.

It should be remembered that both degrees of temperature represent the same change in temperature – the difference lies in the reference zero.

Temperature Symbol: θ Unit: **degree Celsius (°C)**

A useful constant to note is that it takes 4185 J to raise the temperature of 1 litre of water through 1 °C.

Example 1.8

An electric heater contains 40 litres of water initially at a mean temperature of 15 °C; 2.5 kW h is supplied to the water by the heater. Assuming no heat losses, what is the final mean temperature of the water?

$$W_{in} = 2.5 \times 3.6 \times 10^6 = 9 \times 10^6 \text{ J}$$

Energy to raise temperature of 40 litres of water through 1 °C is

$$40 \times 4185 \text{ J}$$

Therefore change in temperature is

$$\Delta\theta = \frac{9 \times 10^6}{40 \times 4185} = 53.8\text{°C}$$

$$\theta_2 = \theta_1 + \Delta\theta = 15 + 53.8 = \mathbf{68.8\ °C}$$

Summary of important formulae

F [newtons] = m [kilograms] × a [metres per second squared]	[1.1]
i.e. $F = ma$	
Torque $T = Fr$ (newton metres)	[1.3]
Work $W = Fl$ (joules)	[1.4]
Work = Energy	
Kinetic energy $W = \frac{1}{2} mu^2$	[1.5]
Power $P = Fu$ (watts)	[1.7]
$= T\omega = M\omega = 2\pi nT$	[1.8]
Efficiency $\eta = P_o/P_{in}$	[1.9]