John Ball
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# Ball and Moore's **Essential Physics for Radiographers**

Fourth Edition

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# Essential Physics for Radiographers

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# Ball and Moore's
# Essential Physics for Radiographers

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# Contents

# Preface

The decade leading up to the publication of the third edition of *Essential Physics for Radiographers* in 1997 saw a revolution in the education and training of radiographers in the UK. By contrast, the 10 years which have elapsed since then have been a period of consolidation. Although in most 'schools of radiography' traditional physics and equipment are no longer taught as separate subjects, we have remained faithful to our original concept of focusing on the physical principles underpinning radiography and have resisted the temptation to write an integrated physics and equipment book. Our aim remains to ensure the 'essential physics' on which the integrated approach is based is made clear and readily understandable to students. Consequently, some sections remain largely unchanged except for the updating of references to the applications of physical principles.

However, the introduction of new radiation safety legislation in the past decade demanded that we employ a more drastic approach to the revision of the chapter on radiation safety. With this in mind, and with an eye on the future of 'Ball and Moore', we took the opportunity to invite long-time friend and colleague Steve Turner onto our writing team. Steve has brought a fresh mind and valuable expertise to the project. He has contributed the whole of Chapter 21 as well as influencing the revision of other chapters.

We have retained the extremely successful and popular innovations introduced in the last edition: the *Maths Help File*, decimal numbering of paragraphs and sections, and reference citations, updated to include Internet sources. The physical principles of magnetic resonance imaging form the basis of a new chapter, Chapter 23.

We are happy to acknowledge the help we have received from many sources during the 2-year revision period. As always, we have been sustained in our efforts by the support and encouragement offered by our professional colleagues and by our friends and families. We also thank the editorial staff of Blackwell Publishing for their continuing commitment to our work.

*John Ball*
*Adrian D. Moore*
*Steve Turner*
*2007*

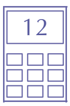
# How to use the Maths Help File

## A note to the reader

It has been our experience as teachers that students of radiological physics are frequently confused by some of its mathematical aspects. Often, the student may merely need to be reminded of the mathematical procedures involved. In other cases, the student may be totally unfamiliar with a particular procedure or concept and will benefit from a fuller explanation.

To overcome these difficulties, we have provided an appendix called the *Maths Help File*, following Chapter 23, which offers extra help on some of the mathematical methods and concepts found in the main text.

As you work through the book, you will encounter the *Maths Help File* icon in the left-hand margin, particularly alongside many of the mathematical worked examples, e.g.




The icon indicates that extra help is available, if you require it, in the *Maths Help File.* The number on the calculator (e.g. 12) tells you in which section of the *Maths Help File* you will find guidance and explanation relevant to the specific mathematical problem involved.

We hope that you will find the *Maths Help File* both easy to use and a valuable resource.

## Chapter 1

# General Physics



## 1.1 Energy and matter

Physics is concerned with the study of two concepts: energy and matter, and the relationships between them.

### 1.1.1 *Energy*

Energy is described as the ability to do work. Consider what would happen if there were no energy available. Without energy nothing would happen, nothing would ever change and nothing would ever get done. Energy is needed to make things happen. It exists in many forms and can be converted from one form to another, e.g.

- The human body converts chemical energy (obtained from the food we eat and the oxygen we breathe) into energy of movement (kinetic energy) when we walk or run.
- Light energy is converted into electrical energy in a solar-powered electronic calculator.

#### 1.1.1.1 Conservation of energy

As well as being converted from one form to another, energy can also be stored, but it is not possible to create or destroy energy. In other words, in a self-contained or closed system (i.e. one with no 'leaks') the total amount of energy does not change. This concept is embodied in the **law of conservation of energy**, which states that the total energy in the universe is constant. This concept is fundamental to our understanding of physics.

## 1.1.2 *Matter*

Matter is the name given to the material of which all things, including us, are made. It normally exists in one or more of the three main physical states of matter **solid**, **liquid** and **gas**, but it may also exist in **liquid crystal** and **plasma** states.

Matter can be converted from one form to another by physical or chemical means, e.g.

- Ice can be melted and turned from a solid into a liquid. This is a *physical* change because both the solid and the liquid are made of the same substance (water). The process is reversible: liquid water can be frozen back into ice.
- Wood can be burned and changed into ash. This is a *chemical* change because wood and ash are fundamentally different materials. Although it is not possible to reverse this process by converting ash back into wood, some chemical changes *are* reversible; e.g. the chemical combination of oxygen with the haemoglobin of red blood cells, which takes place in the lungs, is reversed when oxygen is released from haemoglobin in the tissues.

### 1.1.2.1 Is matter conserved?

In most everyday situations, when a physical or chemical change occurs matter is neither created nor destroyed: the total amount of matter involved remains constant. For example, when melted, a 1-kilogram block of ice forms 1 kilogram of liquid water: there is no net gain or loss of matter. In the case of the burning of wood, however, matter does not at first sight appear to have been conserved: 1 kilogram of wood produces less than 1 kilogram of ash. Nevertheless, if all the matter involved in the process is taken into account (i.e. the oxygen gas consumed and the smoke particles, gases and water vapours produced during combustion), a balance *can* be demonstrated and it is found that matter *has* been conserved.

For many years, the conservation of matter was believed to be as fundamental a concept as the conservation of energy. All the experiments and observations seemed to confirm that matter was indeed conserved. Since the beginning of the twentieth century, however, it has been known that there are processes in which matter is *not* conserved; e.g. the nuclear fusion process which generates the energy output of the sun involves a net loss of matter and a net gain of energy. Consequently, although the conservation of matter remains a useful concept, it no longer warrants the status of a physical law because it is not universally true.

## 1.1.3 *The relationship between energy and matter*

Albert Einstein showed that energy and matter are not two entirely different concepts and that it is possible to convert one into the other. It seems that matter is a special form of stored energy and, in certain circumstances, its energy can be released and used.

Einstein's famous equation $E = mc^2$ (see Section 17.2.4) quantifies the relationship between matter and energy. It shows us that the conversion of only a minute amount of matter releases an enormous quantity of energy (as in a nuclear explosion). Conversely, a massive amount of energy must be converted to produce even a small quantity of matter.

In some respects, energy is rather like money:

- You can do lots of things with it, but you cannot do an awful lot without it!
- Energy can be converted from one form to another (just as currency can be converted, e.g. from US dollars to pounds sterling).
- Energy can be stored, e.g. in an electrical battery, and released on demand (rather like keeping cash in a purse or trouser pocket).
- Energy can be converted into matter (and money can be converted into assets, e.g. by buying antiques) and can be released when required. (The assets can be realised by selling the antiques!)

However, it is wise not to take this analogy too far. For example, one would hope to make a profit when selling an antique, but energy stored as matter neither appreciates nor depreciates over a period of time. Moreover, when energy is obtained from its conversion from matter, it may not necessarily appear in the most desirable form; e.g. it often appears as **internal energy** (Section 2.1) rather than as the more versatile electrical energy.

## 1.2 Measurement and units

Physics is concerned with quantities. As well as knowing what and why things happen, physicists also like to know *how much*; i.e. measurements are essential in physics.

In order for measurements to have meaning, units of measurement have to be created and be widely accepted among those who are going to make and use the measurements.

In science, there is a vast range of different quantities that may require measurement, each of these quantities requiring its own properly defined unit of measurement (Darton & Clark, 1994). Furthermore, relationships often exist between different quantities. For example, relationships exist between the quantities *speed*, *distance* and *time*:

$$\text{Speed} = \frac{\text{distance}}{\text{time}} \qquad \text{Distance} = \text{speed} \times \text{time} \qquad \text{Time} = \frac{\text{distance}}{\text{speed}}$$

The same relationships must apply between the *units* of speed, distance and time; i.e. the units must be mutually compatible.

### *1.2.1 Systems of units*

A comprehensive set of properly defined and mutually compatible units of measurement is termed a *system* of units. A number of such systems have evolved or been devised and are discussed in the following sections.

#### 1.2.1.1 British imperial system

This system evolved over hundreds of years and was in common use in the United Kingdom until recently, both in everyday life and in engineering. Imperial units include the *foot* (length), the *pound* (mass) and the *second* (time). Interestingly, in the year 1305, the yard (=3 feet) was defined as the length of the arm of King Edward I, while the inch (=one-twelfth of a foot) was the width of a thumb (Ramsey, 1970). Although more precise definitions were to follow, the imperial system has largely been abandoned in science and engineering, but it is still widely used in everyday life despite attempts to phase it out.

#### 1.2.1.2 Continental or metric system

This is a system for which Napoleon Bonaparte was partly responsible. Its units include the *centimetre* (length), the *gram* (mass) and the *second* (time). The metre (=100 centimetres) was originally defined as one ten-millionth part of a quadrant of the earth's circumference, while the gram was the mass of one cubic centimetre of water. Again, these early definitions were later refined or replaced by more constant standards. This metric *centimetre–gram–second*, or 'cgs', system has a long tradition of application in science, and examples may still be seen in many scientific texts written before the mid-1960s.

#### 1.2.1.3 International System of Units (in French, Le Système International d'Unités)

This is the name adopted by the *Eleventh General Conference on Weights and Measures*, held in Paris in 1960, for a universal, unified, self-consistent system of measurement units. The international system is commonly referred to as *SI*, after the initials of Système International. Its units include the *metre* (length), the *kilogram* (mass) and the *second* (time). This system is now used throughout the world in science and engineering and is gradually gaining more general everyday use in Europe and, to a lesser extent, in the USA. However, it is not uncommon for UK radiographers to quote X-ray film and cassette sizes in inches (e.g. $17'' \times 14''$, $12'' \times 10''$, etc.), even though for over 30 years manufacturers' catalogues have specified these dimensions in centimetres (e.g. $35 \times 43$ cm, $24 \times 30$ cm, etc.).

We shall use SI as our basic measuring system throughout this book, although other units will be included where appropriate.

### 1.2.2 *Base units and derived units*

When devising a coherent system of units it is not necessary to create completely new units for each different physical quantity to be measured. Instead, it may be possible to express one quantity by combining previously established units; e.g. the quantity speed may be expressed by combining a unit of length (the metre) and a unit of time (the second) (i.e. speed may be quoted in metres per second). However, a minimum number of **base units** must be established, from which the combination or **derived units** can be constructed. In our example, the *metre* and the *second* are base units, while the *metre per second* is a derived unit.

**Table 1.1** SI base units

| Quantity | Unit | Symbol |
|---|---|---|
| Length | metre | m |
| Mass | kilogram | kg |
| Time | second | s |
| Electric current | ampere | A |
| Thermodynamic temperature | kelvin | K |
| Amount of substance | mole | mol |
| Luminous intensity | candela | cd |

### *1.2.3 SI units*

Standards have been defined for the seven base units listed in Table 1.1. The aim is to define each of the base units in terms of a laboratory procedure which can be reproduced under identical conditions throughout the world. Only the definition of the kilogram (see Section 1.3.1) fails in this respect but a new approach to defining and realising the kilogram is being explored by the **Avogadro Project** (NPL, 2007). The definitions themselves are revised periodically as the technology of measurement improves; e.g. the metre was redefined in 1983 as the length of the path travelled by light in a vacuum during a time interval of 1/299 792 458 of a second. The symbols (m, kg, s, etc.) given in the right-hand column of Table 1.1 are the authorised abbreviations and are the same in all languages.

The SI units for all other quantities are derived from the seven base units. Examples of some SI-derived units, expressed in terms of base units, are shown in Table 1.2. Some derived units are used so often that they have been assigned special names, usually those of scientists or engineers, as shown in Table 1.3. In addition to the seven base units described above, there are two **supplementary units** used to express angular measurements. The **radian** (rad) is the unit for two-dimensional or *plane* angles, while the **steradian** (sr) is the unit for three-dimensional or *solid* angles. Some derived units may incorporate supplementary as well as base units; e.g. angular velocity is expressed in radians per second (rad $s^{-1}$).

**Table 1.2** Some examples of SI-derived units, expressed in terms of base units

| Quantity | Derived SI unit | Symbol |
|---|---|---|
| Acceleration | Metres per second squared | m $s^{-2}$ |
| Area | Square metres | $m^2$ |
| Density | Kilogram per cubic metre | kg $m^{-3}$ |
| Luminance | Candela per square metre | cd $m^{-2}$ |
| Magnetic field strength | Ampere per metre | A $m^{-1}$ |
| Velocity | Metres per second | m $s^{-1}$ |
| Volume | Cubic metres | $m^3$ |

**Table 1.3** Some examples of SI-derived units named after scientists and engineers

| Quantity | Name of unit | Symbol | Equivalent in other SI units |
|---|---|---|---|
| Absorbed dose (radiation) | gray | Gy | $J\ kg^{-1}$ |
| Energy, work | joule | J | N m |
| Electrical capacitance | farad | F | $C\ V^{-1}$ |
| Electric charge | coulomb | C | A s |
| Electrical potential | volt | V | $J\ C^{-1}$ |
| Electrical resistance | ohm | Ω | $V\ A^{-1}$ |
| Force | newton | N | $kg\ m\ s^{-2}$ |
| Frequency | hertz | Hz | $s^{-1}$ |
| Magnetic flux | weber | Wb | V s |
| Magnetic flux density | tesla | T | $Wb\ m^{-2}$ |
| Power | watt | W | $J\ s^{-1}$ |
| Pressure | pascal | Pa | $N\ m^{-2}$ |
| Radioactivity | becquerel | Bq | $s^{-1}$ |

#### 1.2.3.1 Conventions for writing SI units

To avoid ambiguity, there are strict conventions for the way SI units are written down:

- When abbreviated, no punctuation marks are used; e.g. 1 kilogram is written as ‘1 kg’, *not* ‘1 Kg.’.
- The abbreviations have no plural form; e.g. 500 metres is written as 500 m, *not* 500 ms.
- When written in full, the names of units never commence with a capital (uppercase) letter, e.g. 310 kelvin, *not* 310 Kelvin. (Note also that no ‘degree’ symbol (°) is used when expressing temperature in kelvin units; write 310 K, *not* 310° K.)

1.5

- Mathematical indices notation should be used rather than the slash sign (/) when dividing units; e.g. metres per second should be abbreviated to m $s^{-1}$, *not* m/s.
- Abbreviation symbols employ an uppercase letter only if the unit is named after a person; e.g. 1.5 ampere is written as 1.5 A. (The ampere is named after André Marie Ampère, a nineteenth-century French scientist.) Note, however, that some prefixes employ uppercase letters in their abbreviated form (see Table 1.4).

#### 1.2.3.2 The use of prefixes

One advantage of SI over other systems of measurement is that it is a *coherent* system; i.e. its derived units are expressed as products and ratios of the base and derived units, *without the need for numerical conversion factors*. Unfortunately, this results in some units being far too large for practical purposes and others far too small. For example, the SI unit of radioactivity (the becquerel) is so miniscule that even the very low activities of the radiopharmaceuticals used for radionuclide

**Table 1.4** Some of the prefixes used with SI base and derived units[a]

| Multiplication factor | Prefix | Symbol |
|---|---|---|
| $10^{9}$ | Giga | G |
| $10^{6}$ | Mega | M |
| $10^{3}$ | Kilo | k |
| $10^{-1}$ | Deci | d |
| $10^{-2}$ | Centi | c |
| $10^{-3}$ | Milli | m |
| $10^{-6}$ | Micro | µ |
| $10^{-9}$ | Nano | n |
| $10^{-12}$ | Pico | p |

[a] Only those most commonly encountered in radiographic science are included.

imaging have to be measured in millions or even billions of becquerels (see Chapter 20). To overcome this difficulty, prefixes such as those given in Table 1.4 are used with base and derived units. Examples relevant to radiography include the *gigabecquerel* (GBq), *megajoule* (MJ), *kilovolt* (kV), *centigray* (cGy), *milliampere* (mA), *microfarad* (µF) and *nanometre* (nm). Because double prefixes are not used, and because the base unit name *kilogram* already contains a prefix, prefixes are used with the gram rather than the kilogram, so a gram (equal to one-thousandth of a kilogram) is never called a millikilogram!

## 1.3 Physical quantities

In physics many commonplace terms have very specialised meanings. We shall consider five of the most important quantities: mass, force, work, energy and power.

### *1.3.1 Mass*

Matter, the material of which everything is made, can be quantified in a number of ways. For example, we could express the amount of matter in a body by:

- Stating the number of *elementary particles* (e.g. atoms or molecules) it contains. The SI unit known as the **mole** is based on this approach. One mole of matter contains $6 \times 10^{23}$ elementary particles. ($6 \times 10^{23}$ is a fundamental physical constant known as **Avogadro's number**.)
- Judging how successfully the body resists an attempt to change its state of rest or its state of movement. In other words, we can measure a quantity of matter by reference to its *inertia* (if it is at rest) or its *momentum* (if it is in motion).

Mass is a method of quantifying matter based on the latter approach. The kilogram is the SI unit of mass.

*Definition*. The kilogram is the mass of the *International Prototype Kilogram*, a platinum–iridium cylinder kept at Sèvres near Paris in France.

## 1.3.2 Force

Physical sciences are concerned with understanding why things happen. Every effect must have a cause. Consider two simple observations:

- If we release a pencil we are holding, it falls.
- If we are cycling along a level track and stop pedalling, we slow down and eventually come to a halt.

Why is this so? Although the two events described above at first seem quite different, there are similarities between them, which suggest a common cause. In both cases, a *change* in the motion has occurred. In general, a change in the motion of an object is said to be due to the presence of a force. In the case of the falling pencil, the force causing it to fall is called the force of gravity; in the case of the cycle, it is the forces of air resistance and friction which cause it to slow down and stop.

Force is thus a generalised concept, which encompasses all the various reasons why objects speed up, slow down or change their direction of travel. In 1687, Sir Isaac Newton encapsulated this idea in his first law of motion: *a body will continue in its state of rest or uniform motion in a straight line, unless it is acted upon by an external force.* In other words, force is the *agency* by which a body's state of motion is changed.

In physics, any change in the motion of a body is described as acceleration, so we can deduce that acceleration is *always* caused by the action of one or more forces. There are many different kinds of forces: electric forces, magnetic forces, mechanical forces, as well as the gravitational and resistance forces mentioned above, but each of these forces satisfies the general description set out in the definition of a force.

*Definition*. Force is that which disturbs the state of rest or uniform motion of a body.

The unit of force is obtained by specifying the amount of acceleration achieved when a force is applied to a body of known mass. A simple relationship exists between a force ($F$), the mass ($m$) and the acceleration ($a$), which results:

$$F = ma$$

In SI units, mass is expressed in kilograms and acceleration in metres per second squared (m s$^{-2}$) (Table 1.2), so force is expressed in kilogram metres per second squared (kg m s$^{-2}$). This derived unit is called the **newton** (N).

*Definition*. A force of 1 N will produce an acceleration of 1 m s$^{-2}$ in a body whose mass is 1 kg, if it is free to move and not acted upon by any other forces.

#### 1.3.2.1 Scalar and vector quantities

When describing a force it is not enough to quote the magnitude (i.e. strength) of the force, e.g. 6 N. It is also necessary to specify its direction, e.g. vertically downwards. Quantities such as this, having direction as well as magnitude, are known as *vector* quantities, or *vectors*. Quantities having only magnitude (e.g. mass) are known as *scalar* quantities.

#### 1.3.2.2 Gravitational force

On the earth's surface, when a body is released it falls downwards, accelerating at a rate of 9.81 m $s^{-2}$ (i.e. every second its downward speed increases by 9.81 m $s^{-1}$). This value of acceleration is often called $g$, the acceleration due to gravity. In 1589, Galileo is reported to have performed a famous experiment in which he dropped two cannonballs of different masses from the top of the Leaning Tower of Pisa in Italy. Because the two objects hit the ground at the same time, Galileo had confirmed that the value of $g$ was the same for both masses. Further investigation led Galileo to conclude that the value of $g$ was the same for *all* values of mass. In 1971, the astronaut Alan Shepard repeated Galileo's experiment on the surface of the Moon, using a feather and a hammer instead of cannonballs. It was an effective, if crude, confirmation of Galileo's findings.

The gravitational force acting on a body (commonly known as its weight) is the agency which causes it to accelerate downwards, so the relationship $F = ma$ applies. In this case the force is the weight of the body ($W$), the mass is $m$ and the acceleration is $g$. Thus, $F = ma$ becomes

$$W = mg$$

This tells us, for example, that the weight of a 1-kg mass is 9.81 N. When we support a 1-kg bag of sugar on our hand, we are experiencing a force slightly less than 10 N. This gives us an idea of the size, in everyday terms, of the SI unit of force.

*Force fields and field strength*

It may be timely here to introduce the general concept of a **force field**, which is simply the name given to a region in which forces are acting. We can specify the magnitude of such a force field by quoting its **field strength**.

*Gravitational field strength*

The **gravitational field strength** at a particular location is the strength of gravitational force (i.e. weight) experienced by one unit of mass placed at that location. In SI units, gravitational field strength is expressed in newtons (of force) per kilogram (of mass), or N $kg^{-1}$. At the earth's surface, the gravitational field strength is therefore 9.81 N $kg^{-1}$. A similar concept can be applied to other types of force fields, e.g. an electric field (see Section 3.4.2).

*The difference between mass and weight*

No matter where we are on the earth's surface, the value of $g$ is practically the same. In these circumstances, weight is *directly proportional* to mass and we are accustomed to using our weight (e.g. as measured on bathroom scales) to indicate how 'massive' we are.

For astronauts, the situation is more complex because they may experience gravitational forces very different from our own. On the moon's surface, the acceleration due to gravity is only 1.62 m $s^{-2}$, about one-sixth of that on the earth's surface (Moore & Hunt, 1997). An astronaut's weight measured on *lunar* bathroom scales would be only one-sixth of its terrestrial value. However, the astronaut's mass would *not* have changed because the mass of a body is independent of the value of gravitational field strength. A stretcher trolley bearing an obese patient would be just as difficult to manoeuvre around the tortuous corridors of a lunar hospital as it would here on earth because it is the *inertia* of the patient and trolley (which depends only on mass) rather than their weight (which depends on gravity and mass) that creates most of the problems. However, a moon-based radiographer would find it a lot easier to *lift* the obese patient if that proved necessary!

### 1.3.3 Work

If a force succeeds in changing the motion of a body we say that *work* has been done and we define the work done as the product of the magnitude of the force and the distance moved; i.e.

$$\text{Work done} = \text{force} \times \text{distance moved}$$
$$\text{(in the direction of the force)}$$

The SI units in which work is measured are newton metres (i.e. newtons $\times$ metres) and are called *joules* (J) (1 joule = 1 newton metre).

The scientific meaning of the term 'work' can produce consequences which seem at odds with our everyday experiences. Suppose a patient has collapsed on the floor and we try to lift him onto a stretcher trolley. If we succeed in lifting him up we have done work (we have applied a force, the lift, and moved the patient through a certain distance upwards in the direction of the force).

So far, so good. But what if, despite our exertions, we were unable to lift the unfortunate patient because of his weight? The physicist would say we had done *no* work on the patient because we had not moved him. However, we may well feel that we tried very hard to achieve the lift and even though our efforts were in vain we had definitely been working!

Work can be thought of as being energy *usefully* expended, and since, in our example, we did not move the patient in the direction of our applied force, any energy we used was 'wasted'.

### 1.3.4 Energy

As we saw in Section 1.1.1, energy is defined as the ability to do work.

Its SI unit of measurement is the same as the unit of work, i.e. the joule. In fact, the joule is a rather small unit and we shall meet larger units of energy later.

Energy can appear in many forms, e.g. potential energy and kinetic energy.

#### 1.3.4.1 Potential energy

This is the energy stored in a body due to its position or state; e.g. a compressed spring and a book on a shelf have potential energy (often abbreviated to PE).

The potential energy possessed by a body is equal to the amount of work required to 'raise' the body to its particular position or state.

Potential energy is a *relative* quantity; it has no absolute value. It is always quoted in relation to some chosen reference level or baseline, which may be stated explicitly, but is often merely implied. For a compressed spring, the baseline might be the relaxed state of the spring; for the book on the shelf, a sensible choice of baseline would be floor level. At floor level, the book would be said to have zero potential energy. Raising the book above floor level would increase its potential energy *above* zero (i.e. its potential energy would have a *positive* value). Taking the book downstairs to the floor below would reduce its potential energy *below* zero (i.e. its potential energy would take on a *negative* value).

Although bodies have a natural tendency to move from a high (positive) potential-energy state, or position, to one which is lower (i.e. less positive, or more negative), whether they actually achieve this reduction in potential energy depends on the presence or absence of factors preventing change. For example, a ball has a natural tendency to roll down a slope, but it cannot do so if we put an obstacle in its path.

*Worked example*

Let us consider a case involving gravitational potential energy. Suppose a 50-kg patient seated in a wheelchair has to be lifted onto an examination couch which is 25 cm higher than the wheelchair. How much work must be done to achieve such a task and how much potential energy will the patient acquire as a result?

From our discussion of work in Section 1.3.3, we know that:

$$\text{Work done} = \text{force} \times \text{distance}$$

In our present example, the minimum force required is equal to the weight ($W$) of the patient since we need to apply an upward force of at least this magnitude in order to raise the patient. From Section 1.3.2.1:

$$W = mg$$

and because $m = 50$ kg, and $g = 9.81$ m s$^{-2}$, the weight of the patient must be:

$$W = 50 \times 9.81 \text{ N}$$

The patient is raised through a distance of 25 cm, but we must convert this into metres in order to be consistent with the other units we are using (25 cm = 0.25 m).

We can now calculate the work done in raising the patient:

$$\begin{aligned}\text{Work done} &= \text{force} \times \text{distance (which, in this case, is weight} \times \text{height, or } mgh\text{)}\\ &= 50 \times 9.81 \times 0.25 \text{ N m}\\ &= 120 \text{ N m (to two significant figures)}\\ &= 120 \text{ J}\end{aligned}$$

So, 120 J of work has to be done to lift the patient.

How does this affect the potential energy possessed by the patient? Reference to the statements at the beginning of this section confirms that the patient's potential energy will have been increased by an amount equal to the work done in lifting him. In other words, his potential energy will be increased by 120 J.

### 1.3.4.2 Kinetic energy

This is the energy possessed by a body because of its movement; e.g. both a falling X-ray cassette and a moving stretcher trolley have kinetic energy (as we would no doubt appreciate if we happened to get in their way!).

The kinetic energy (KE) of a body depends on its mass ($m$) and its speed or velocity ($v$), linked by the relationship:

$$\mathrm{KE} = \frac{1}{2}mv^2$$

*Worked example*

Suppose a 35 × 43-cm X-ray cassette is accidentally knocked off a shelf onto the floor. The shelf is 1.50 m high and the cassette has a mass of 2.00 kg. How much kinetic energy will the cassette possess at the instant it hits the floor, and how fast will it then be travelling? The best way of approaching the problem is to first find the kinetic energy and then from that compute the speed.

To determine the kinetic energy we must consider the *origin* of the cassette's kinetic energy. Its kinetic energy is the result of the conversion of the potential energy possessed by the cassette when it was resting on the shelf. As we saw in our earlier worked example:

$$\mathrm{PE} = mgh (\text{i.e. weight} \times \text{height})$$

so

$$\begin{aligned}\mathrm{PE} &= 2 \times 9.81 \times 1.50\\ &= 29.4\ \mathrm{J}\end{aligned}$$

That is, when the cassette was on the shelf its potential energy was 29.4 J greater than that when it was on the floor. Remembering the principle of conservation of energy (Section 1.1.1.1), it is reasonable to assume that as the cassette fell, it converted *all* 29.4 J of its potential energy into kinetic energy. So, at the moment it struck the floor, its kinetic energy was 29.4 J. How fast was it then travelling? We know that $\mathrm{KE} = \frac{1}{2}mv^2$ and we know the values of KE and $m$, so we should now be able to find $v$.

It is helpful to rearrange the relationship into a form which puts all the known quantities on the right-hand side of the equation:

$$\begin{aligned}v^2 &= \frac{2 \times \mathrm{KE}}{m}\\ &= \frac{2 \times 29.4}{2}\\ &= 29.4\ \mathrm{m^2 s^{-2}}\end{aligned}$$

So

$$\begin{aligned}v &= \sqrt{29.4}\\ &= 5.4\ \mathrm{m\ s^{-1}}\end{aligned}$$

The cassette was therefore travelling at nearly $5\frac{1}{2}\ \mathrm{m\ s^{-1}}$ when it struck the ground (or struck our toes if we were slow in moving out of the way!).

There are many other forms of energy in addition to the two we have considered above, e.g. chemical energy, internal energy, electrical energy, nuclear energy, sound energy, X-ray energy, etc. We shall be looking at some of these in later chapters.

### *1.3.5 Power*

It may be important, on many occasions, to know the *rate* at which we are expending energy in a particular process or action. We call the rate of using energy **power**. It can also be defined as the rate of doing work; i.e.

$$\text{Power} = \frac{\text{work done}}{\text{time taken}}$$

The unit of power is therefore the joule per second (J $s^{-1}$). This derived unit is also known as the watt (W); i.e. 1 watt = 1 joule per second. The watt is a relatively small unit, being hundreds of times smaller than the older, more well known unit, the horse power (1 horse power = 746 watts).

The ideas introduced in this chapter will be referred to many times in later chapters. If possible, talk over the work with your tutors and with your fellow students until you are confident that you understand it. Some simple problems follow which should help you achieve a proper understanding. The answers are given in brackets after each question.

## 1.4 Problems

(1) An 18-month-old baby has a mass of 10 kg (22 lb). What is its weight in newtons? (Assume '$g$' is 9.81 m $s^{-1}$.) (98.1 *N*)

(2) A volume of 1 mL of water has a mass of 1 g. What is the weight of 1 L of water? (9.81 *N*)

(3) How fast will a body be travelling after it has fallen under gravity for 10 s? (Neglect air resistance.) (98.1 $ms^{-1}$)

(4) How much work is done in lifting a 100-kg patient from the floor onto a stretcher trolley 1 m high? (981 *J*)

(5) How much power would be required to achieve this lift in 1 s? (981 *W*)

(6) How much energy would be released if the same patient fell off the stretcher trolley onto the floor? (981 *J*)

(7) At what speed would he hit the floor? (*Hint*: Think about kinetic and potential energy.) (4.3 $m\,s^{-1}$*approx.*)

(8) What force would be required to accelerate a stretcher trolley at 1 m $s^{-2}$ if its mass is 20 kg and it carries a patient of 80 kg? (100 *N*)

(9) How fast will it be travelling if this force is maintained for 5 s? (5 $m\,s^{-l}$)

(10) How much energy would be needed to bring the trolley to rest? (1250 *J*)

Chapter 2

# Internal Energy, Temperature and Heat



## 2.1 Internal energy

All matter is made up of minute particles, too small to be seen even with a good microscope. The particles are called **atoms** and **molecules**, and we shall consider them in detail in Chapter 4. The important property of these particles that we are concerned with in this chapter is the fact that they are always in motion. The type of motion depends on whether the material is a solid, liquid or gas (see Fig. 2.1).

In solids, the molecules vibrate about fairly fixed positions. This is the reason why solids do not alter their shape easily. In liquids and gases, the molecules move randomly. Liquids and gases do not have fixed shapes for this reason.

Because these particles are in constant motion, they possess **kinetic energy**. The molecules, particularly in solids and liquids, also possess **potential energy** because of the forces of attraction between them. (These **intermolecular** forces are strongest in solids and weakest, or absent altogether, in gases.) We call the total kinetic and potential energy of the molecules in a system its **internal energy**.

## 2.2 Temperature

The concept of temperature arises from the idea of measuring the relative hotness and coldness of a body and from the observation that increasing the internal energy of a body leads to an increase in its temperature as long as no melting or boiling occurs.

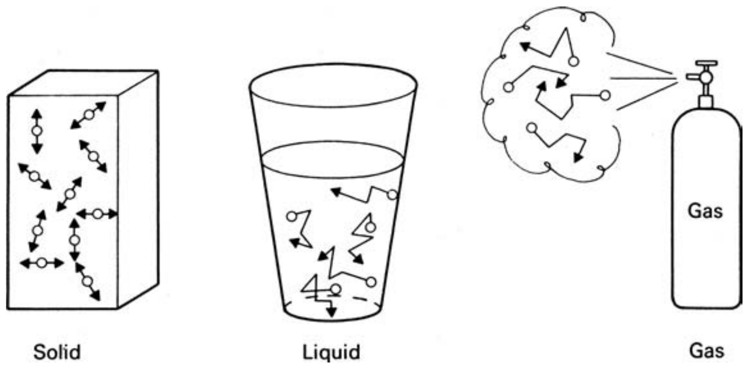



**Fig. 2.1** Motion of particles in solids, liquids and gases.

The temperature of a body depends on the average kinetic energy of its particles (and hence their speed of movement). A high temperature means that the particles are in vigorous motion, while a low temperature indicates that they are moving more slowly.

Temperature is a property of a body, a material or a substance. Thus, a vacuum (or 'space') cannot have a temperature. Temperature changes in a substance are measured by observing changes taking place in its *other* properties, as discussed below.

### 2.2.1 *Expansion and contraction*

If the temperature of a substance is increased, it expands if free to do so; if its temperature falls, it contracts. This is because as the motion of its molecules becomes more violent they occupy more space. If the specimen is *prevented* from expanding or contracting, e.g. because it is sealed in a strong containing vessel, the changes in temperature will be associated with changes in the **pressure** the substance exerts on the walls of the vessel.

**Mercury thermometers** allow us to measure temperature by observing the expansion of a mercury column in a glass capillary. The change in length of the mercury column is related to the temperature change.

### 2.2.2 *Melting and boiling*

If the temperature of a solid is increased, it eventually melts, changing from the solid into the liquid state. If the temperature of a liquid is increased, it eventually boils and changes from a liquid into a gas.

### 2.2.3 *Other effects of temperature*

Changes of temperature may also be associated with numerous other effects on the property of materials; e.g. electrical resistance and conductivity may change (Section 7.4.4.3); fluids may become more or less viscous; the rate of chemical

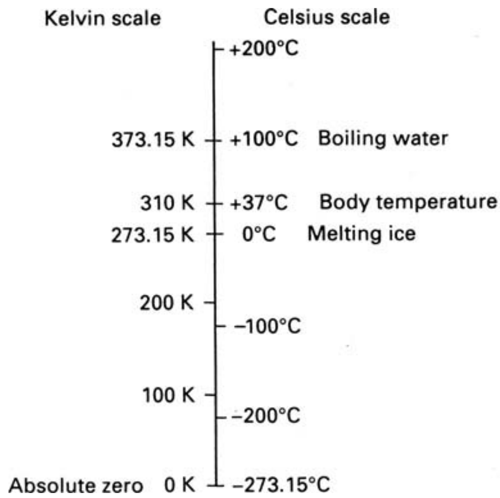



**Fig. 2.2** The kelvin and Celsius scales compared.

reactions may alter (e.g. body metabolism is markedly affected by temperature, hence the need to maintain a constant body temperature).

### 2.2.4 *Scales of temperature*

The changes in the physical state of a substance from solid to liquid and from liquid to gas are easy to recognise. Furthermore, for water, these effects occur at temperature levels which are well within our everyday experience. For this reason, the melting point of ice and the boiling point of water have been used to define scales of measurement.

The **Celsius scale** divides the range between melting point and boiling point into 100 intervals called degrees (100°C). The temperature of melting ice is zero (0°C), while the temperature of boiling water is 100°C.

The **kelvin scale**, which provides the SI unit of temperature, employs intervals of the same size as Celsius degrees, but places melting ice at 273.15 K and boiling water at 373.15 K. The significance of this scale is that at zero (0 K) the atomic particles which are normally in motion are at rest. In other words, at 0 K, a body has no internal energy at all. This temperature, which has never been achieved except in the imagination, is known as **absolute zero**. Scientists have approached this temperature very closely but have not been able to bring those last few particles to rest.

The **Fahrenheit scale** divides the range between melting ice and boiling water into 180 degrees, melting ice being at 32°F and boiling water at 212°F. Body temperature is about 98.4°F, 37°C or 310 K (see Fig. 2.2).

## 2.3 Heat and temperature gradients

Heat is the *transfer* of internal energy from one part of a body of matter to another, or from one body to another, as a result of a difference in temperature known as a **temperature gradient**. Heat is energy in transit; its tendency is always to flow *down* a temperature gradient, i.e. from a substance at a higher temperature to a substance at a lower temperature, raising the temperature of the latter and lowering that of the former.

Consider two examples:

- A hot drink placed on a table gradually cools down because it is hotter than its surroundings. Energy is transferred down the temperature gradient from the drink to the surroundings. The surroundings get slightly warmer as a result of the energy they have gained.
- A cold drink placed on the same table gets warmer because it is colder than its surroundings. Energy is transferred down the temperature gradient from the surroundings to the drink. The surroundings get slightly cooler as a result of the energy they have lost.

In both these examples, energy is being transferred *down* a temperature gradient. If we want energy to flow *up* a temperature gradient, we have to force it to do so by doing work using a system known as a **heat pump**. For example, the environment inside a refrigerator is cooled below the temperature of its surroundings by extracting energy from inside the fridge and releasing it to its external surroundings, which become warmer as a result. An energy supply (usually electricity) is necessary to do this work.

*A note about terminology*. It is quite common for the terms *heat* and *heat energy* to be used when what is really meant is *internal energy*. This confusion is perhaps understandable: after all, all three are measured in the same units (joules) and many sources (including the early editions of this book!) have perpetuated the error. However, the three terms are *not* synonymous:

- *Heat* is energy transferred as a result of a temperature gradient.
- *Internal energy* is the sum of all the molecular kinetic and potential energies in an object.
- *Heat energy* is an in-between term and we should replace it either by the term *heat* or by the term *internal energy*, according to the exact meaning we wish to convey.

### 2.3.1 *Latent heat*

A solid at melting point or a liquid at boiling point can absorb energy without experiencing a rise of temperature. Similarly, a gas which condenses into a liquid, or a liquid which freezes into a solid, can release energy without suffering a fall in temperature. This is because rather than being used to change the kinetic energy of the particles (seen as a temperature change), the energy is used to achieve the rearrangement of particles, which characterises a change of physical state (from solid to liquid, or liquid to gas). This energy change, which is not accompanied by a change of temperature, is known as **latent heat** (i.e. 'hidden' heat). For example:

- To melt 1 kg of ice (at 0°C) into water (also at 0°C) requires about 330 kJ of energy.