Quality Assurance
in Measurement

Module 1 - Introduction to Metrology

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Quality Assurance in Measurement

The **International Committee for Weights and Measures** (abbreviated **CIPM** from the French ***Comité international des poids et mesures***) consists of eighteen persons from Member States of the Metre Convention (*Convention du Mètre*) appointed by the General Conference on Weights and Measures (CGPM) whose principal task is to ensure world-wide uniformity in units of measurement by direct action or by submitting proposals to the CGPM. 40540090107549

1 - The Importance of Metrology

1.1 Introduction

Metrology is the field of knowledge concerned with *measurement* - how to make measurements and how to assess the *accuracy* and reliability of measurements.

The competitiveness of a company's products depends on a number of inter-related factors amongst which the standard and the reliability of the performance of a product are crucial elements.

A product's quality of performance and reliability depend crucially on it being manufactured to a good enough degree of accuracy. In turn, this has implications for the capabilities of the various processes required for the manufacture of the product. Accordingly industry devotes great attention, and very large resources, to the quality assurance of the product in which measurement has a vital role to play.

It should be clear then that reliable measurements of physical quantities (mass, length, force ...) are of fundamental importance to manufacturing industry. The reliability of measurements rests on a company holding *reference standards* and *secondary standards* which can be traced back to *(primary) national* and *international* standards. Since the provision of standards demands high quality scientific research and development many national standards laboratories have been established; in the United Kingdom the National Physical Laboratory (NPL), (www.npl.co.uk)

1.2. A short history of measurement

Metrology is the field of knowledge concerned with measurement. Evidence exists for the use of measures and standards as long as 5000 years ago, at least. Instruments were not used for purely scientific enquiry prior to 300BC, broadly speaking, but largely in the contexts of:

- work
- trade
- government
- and religion.

In this module, we are very much concerned with the impact at *today's workplace* of the *trading situation* and *government legislation:*

QUALITY ASSURANCE

In the earliest known civilizations the need for *weights,* particularly in money exchange, and for measures *(length* and *distance)* had arisen and the concept of *balance* was well established. With the inclusion of *time* measurement the Ancients realised the basic requirements for:

SYSTEMS OF UNITS
mass/weight length time
(independent, *base* quantities)

After the Dark Ages the peoples of Western Europe had to re-learn to a great extent, the experience of the Ancients. For instance the Magna Carta (1225 AD) contains clauses about the standard measures for wine, ale and corn, but the specifications would not be regarded as very tight today!

"There is to be one measure of wine throughout our kingdom, and one measure of ale, and one measure of corn, namely the quarter of London, and one breadth of dyed, russet and haberget cloths, that is, two ells within the borders; and let weights be dealt with as with measures."

1.2.1 Length

In the earliest days short distances were measured in terms of readily available objects e.g. parts of the body. Wide ranging travel was not experienced by the mass of the people and, accordingly, long distances were defined more vaguely. However, increasingly widespread trade, particularly by sea, stimulated surveying (and time-keeping).

It seems that the historic cubit (about 0.5 metre) was based on the length of the forearm from the elbow to the fingertips. Since such standards as existed were "local" it is not surprising that there is evidence of variations between different regions of the ancient world of 40% of the average cubit. But, of course, for a *standard* to be useful widely it must be *transferable* between locations.

In Western Europe science (and what we would term mechanical engineering today) developed at an increasing pace through the 16th and 17th centuries.The dramatic increase in trade and the associated stimulus to wealth creation led to mass-production which, in turn, determined a need for reliable and widely accepted standards for units of measurements (of *length, mass and time* inparticular).

To cut short a long story a *standard of length* was typically a *metal bar (or* the distance between two engraved marks on a bar). As originally conceived in revolutionary France in the 1790's (and before the requisite surveying had been carried out) the *metre* was to be one ten-millionth of the Earth's quadrant on the meridian through Paris. In other words, if we had a length of wire from the North Pole through Paris to the equator then each section of wire would be classed as one metre.

This idea reflects a trend to create *primary standards* which are as free as possible from environmental factors such as temperature, humidity, corrosion.... and, furthermore, are safe from tampering; the Earth was assumed to have an unchangeable and perfectly spherical shape.

However, the practical primary standard for the metre became:

The distance between two engraved lines on a certain platinum-iridium bar kept at the International Bureau of Weights and Measures at Sèvres, France (www.bipm.org).

The demands of science and technology for increasingly stable and increasingly precise standards led, after 1960, to the primary standard of length being related to the *wavelength* of the light waves emitted by atoms of certain elements under tightly specified physical conditions.

The first atomic length standard was the wavelength of light from Krypton atoms but today the light emitted by a highly stable helium-neon laser is used, the wavelength being reproducible to 3 : 10^{11} (three parts in one hundred thousand million).

As far as current knowledge goes, for any particular element the properties of all atoms of that element in the Universe are identical and do not change with time.

This fundamental assumption is central also to the current standard of time based on *atomic clocks* (see section 1.4 below). Again we see the drive to realise primary standards which are as independent as possible of environmental factors.

Today there is widespread and increasing interest in industry in the manufacture and use of components and devices of extremely small size and/ or of a very high accuracy of finish. The name *Nanotechnology* has been coined for the field where dimensions and/or tolerances are in the range 10^{10} metres to 10^{7} metres, i.e. from atomic dimensions up to one ten-millionth of a metre.

1.2.2 Mass

Although this sub-section is entitled "Mass" it is "Weight" that we will be concerned with initially. The distinction between these two concepts is often a cause of confusion.

Mass is the *Quantity of Matter* in a physical object.
Weight is the *Gravitational Pull* (Force) on the object.
The mass of an object is constant whereas its weight is not.

For instance the weight of an object varies slightly with position on the earth. More spectacularly, if translated to the Moon, the objects weight would be only about 1/6 th of its weight on Earth, hence the giant leaps of the astronauts!

Historically it is probably fair to say that there has been most controversy over units and standards of weight because of their vital importance to trade. Traders were suspected of having separate sets of weights for buying and for selling! Many rulers fell foul of their subjects because of cheating over coinage and standards of weight, particularly as they related to taxation.

The distinction between mass and weight emerged in the 17th century with Sir Isaac Newton's laws of motion, of mechanics, and of gravitation.

Many standards and systems of weight evolved around the world (e.g.the Imperiaf system in Great Britain:- pounds, tons, inches, feet....) but, bearing in mind the worldwide adoption of the International System (SI), we will focus on the definition of the *kilogram.*

The primary standard for the kilogram was originally related to the mass of an accurately defined volume of water under specified physical conditions (the standard of volume being derived from the standard metre). Today, however,

The kilogram is the mass of a particular cylinder, made of platinum-iridium alloy, which is considered to be the internationa prototype of the kilogram, and is preserved in the care of the International Bureau of Weights and Measures in a vault at Sèvres, France.

Unlike the metre and the second, the kilogram is an arbitrary amount; it is not related to any specific natural feature or phenomenon in the Universe. Remember the distinction between mass and weight?

The weight of a one kilogram mass situated on the Earth's surface is 1 x 9.81 = 9.81 N

Here the factor 9.81 is the intensity of the Earth's gravitational pull and varies slightly, but significantly, over the surface of the Earth. The symbol N stands for *Newton* the name given to the SI unit of force. The newton is a *derived quantity* in SI.

1.2.3 Time

The concept of time has intrigued man since the earliest civilizations; it is the fourth dimension of the Universeadditional to the three space dimensions. There are two aspects to time, namely ongoing time (the "Arrow of time") and duration. The first aspect is a fascinating field of speculation in fundamental physics and philosophy but it is with the second aspect that we are interested primarily.

Durations of time: e.g. year, day, hour, second, millisecond

Throughout the Ages it has always been possible to measure time more precisely than length and mass. Further, and very importantly, the standards of time duration have always been very more uniform and reproducible throughout the world than those of length and mass. The reason is, of course, that standards. of time everywhere were based on the extremely regular motion of the Earth around the Sun and the rotation of the Earth about its own axis which gave the Year /Seasons and the Day respectively. The (apparent) motion of the pattern of stars in the heavens was also of great interest to the Ancients.

You may have wondered why it is that in the metric and decimal world the ratios between the day/ hour/ minute/ second are 24:1 and 60:1 !

It seems that the early Middle Eastern civilizations were influenced by the "360" days in the yearly cycle and "30" days in the lunar monthly cycle. Whether it was cause or effect is not obvious but these civilizations also used a number system having the base 60 (in contrast to the decimal system which is to the base 10): 60 is divisible exactly by ten numbers whereas 10 is divisible evenly by 5 and 2 only.

The circle. like the year, corresponds to a complete rotation and so was divided into 360 parts or angles *(degrees).* There have been serious attempts to have a decimal angular measure adopted but they have not prevailed. The sub-divisions of the degree are the minute (of arc) and the second (of arc).

The relationship between angular measure and clocks extends beyond the fact that both use minutes and seconds. In non-digital clocks, at least, the rotation of the hands indicates ongoing time on a circular scale divided into minutes and seconds. Today with the profusion of digital timepieces the link between time and angle measurement may not be so widely appreciated. The hour was the smallest unit of duration in widespread use for thousands of years with, eventually, fractions such as the half- and quarter-hour coming into use.

The earliest clocks were probably of the "sun-dial" variety followed by "egg-timers", water clocks, burning candles, etc.. Eventually clocks controlled by regularly swinging pendulums and then clocks using springs and escapements were invented and refined. The *regular, cyclical, processes* which are at the heart of the latter two types of clock epitomise the basic feature of modern clocks.

The precise and reproducible repetitive period of duration of a

fundamental physical process serves to define a (repeated) time duration. The most precise and stable time standard which is available currently is based on the properties of caesium atoms - the "atomic clock".

The primary standard adopted internationally in 1967 is precise to about $1:10^{13}$. A global time scale is available which is synchronised to one ten-millionth of a second.

1.2.4 Electromagnetism

It is now accepted that electric charge is a *fundamental feature* of the universe;it cannot be explained in terms of other (more) fundamental entities such as mass, length, and time so far as we know. Nor can electric charge or electric current be expressed in a convenient and practical way in terms of mass, length, and time.

Electrical phenomena belonging to what, today, we would call *static electricity* were recognised in the early civilizations. Knowledge did not advance much further until the end of the 18th century when sources of *continuous electric current* were developed (the voltaic cell) and subsequently the *magnetic effects* of electric currents were recognised by Oersted.

Magnetism had been known for hundreds of years before this and had been exploited, notably in ship's compasses, but Oersted's discovery demonstrated the fundamental link between electricity and magnetism.

The basic quantity of electricity is the amount of electric charge carried by the sub-atomic particle called the *electron.* However, this a tiny quantity and the practical called standard (independent *base quantity)* which has been adopted is the unit of electric *current* called the *ampere* (note: charge in motion constitutes an electric current).

The ampere is defined in terms of the magnitude of the force of interaction, measured in newtons, between two straight wires carrying electric currents of identical values.

1.2.5 Temperature

The notion of the temperature of a human body measured in degrees harks back to medical treatments in ancient Greece. There were four "degrees" of heat of the body, the highest one being mortal and a medicine was meant to "temper" its opposite. A "cooling" medicine, for example, would be administered to counteract a high temperature. So these early ideas, based on subjective sensations of hot and cold, were the origins of our use of temperature sea/es marked in degrees.

However, it was not until the early 18th Century that quantifiable temperature scales began to emerge, but even so the nature of temperature itself remained elusive. The development of heat engines, in particular, stimulated an interest in investigations into the nature of heat, energy and temperature.

The term *heat* came to be reserved for the transfer of energy that occurs between two physical systems ("energy-in-motion") as a result of a *temperature difference* that exists between them.

Thermodynamics is the study of energy-in-motion.

Practical thermometers utilise temperature-dependent properties of physical systems. For example, in a mercury-in-glass thermometer the *change in length* with changing temperature of a "thread" of liquid mercury is exploited.

Note that temperature is not measured directly but through the variation of a temperature-dependent property. This is true for all practical thermometers.

A temperature scale can be established by measuring the values of the physical variable in question (e.g. the length of a thread of mercury) when the thermometer is immersed successively in two systems each of which is known to be at a well-defined temperature. Well known examples are the melting point of ice and the boiling point of water. In the Celsius and the Kelvin scales of temperature this temperature interval is divided into 100 degrees.

Actually there are some very subtle, but important, differences between scales of Temperature based on the properties of different materials such as mercury-in-glass, platinum resistance thermometer, gas thermometer.... but these will not be elaborated here.

1.2.6 Provision and dissemination of standards

It is very important to note that the word "standard" is used in two senses in English. In one sense it means the specification (French "norme") such as a document issued by the British Standards institution (BSI). On the other hand it means the physical embodiment (French "etalon") of a measure (e.g. the kilogram, a standard resistor .....) or the measuring system intended to define, realise, conserve or reproduce a unit.
The National Physical Laboratory (NPL) is the national standards laboratory for the United Kingdom and holds the primary standards. The secondary standards held by other organisations are derived from these primary standards.

Remember that a standard of measurement is not an unchanging quantity at the highest level of accuracy.

An *international* standard is a value which has been adopted internationally *for the time being,* but can be changed by international agreement. The evolution of standards of time duration is probably the clearest example, where the rapid expansion and increasing sophistication of navigation and telecommunications systems, especially using artificial satelites, has required increasingly precise standards of time and of clock synchronisation.

The NPL, and the National Metrology Institutes (NMI) of other countries, are required to improve existing standards and to develop new standards in response to the needs of both established and emerging technologies.

A standard is the current best estimate (made by statistical inference) of the resuts of many experiments.

1.3 International metrology organisations

The vitally important international harmonisation of standards is the concern of the organs of the International Weights and Measures Organisation which was established under the treaty known as the "Convention of the Metre" (1875).

General Conference on Weights and Measures (GCPM)

(Overall control at the political level)

International Committee for Weights and Measures (CIPM)

(Committee of scientists responsible for preparing recommendations to and executing decisions of CGPM for the supervision of BIPM)

Consultative Committees for:	International Bureau of Weights and Measures:
Definition of the metre (CCDM) Definition of the second (CCDS) Electricity (CCE) Standards of Measurement of Ionising Radiations (CCEMRI) Photometry and Radiometry (CCPR) Thermometry (CCT) Units (CCU)	Laboratory at Sèvres responsible for BIPM standards and their dissemination.

The international organisation for standards in support of trade (the National Measurement and Regulation Office in the United Kingdom) Is the International Organisation for the Legal Metrology (OIML – www.oiml.org). Other important international organisations are the International Electrotechnical Commission (IEC - www.iecl.ch) and the International Organisation for Standardisation (ISO - www.iso.org).

On the first of January 1988 EUROMET (www.euromet.og) became operative with the general aim of developing a collaborative approach to the maintenance, and improvement, of standards in Western Europe through the National Metrology Institutes of the various member states.

1.4 Framework for measurement

The U.K. *primary standards* of measurement are maintained at the NPL. Secondary standards, which are held by industrial and government organisations are derived from these primary standards. In turn the measuring instruments used at the work place are calibrated and re-calibrated by reference to such secondary standards.

The British Calibration Service (BCS) and the National Testing Laboratory Accreditation Scheme (NATLAS) merged in 1985 to form the National Measurement Accreditation Service – NAMAS

The United Kingdom Accreditation Service (UKAS) – www.UKAS.com - resulted from the merger in 1995 of NAMAS (National Measurement Accreditation Service) and NACCB (National Accreditation Council for Certification Bodies.

- UKAS assesses conformity assessment bodies for competence against internationally recognised standards
- UKAS accredits (recognising competence of organisations to provide conformity assessment tasks)

UKAS issues accreditation certificates and schedules showing the limits of the accreditation for a particular conformity assessment body and permits the use of the UKAS mark on accredited certification provided that it is accompanied by the UKAS Accreditation Number of the accredited body. The validity of an accreditation should be checked on the UKAS website. UKAS Certificates do not bear an expiry date

2.0 Physical quantities and units of measurement

2.1 System International (SI) units

This is the *coherent system of units* adopted and recommended by the General Conference on Weights and Measures (CGPM).

2.1.1 Units

Système international d'unités, **SI,** is the modern version of the *metric* system based on *practical* units. To measure a physical quantity it is first necessary to choose a *unit* for the concerned quantity. The measure of the quantity will then be the number of units it contains. For example,

$$\text{length of object in metres} = \frac{\text{length of object}}{\text{length of the (standard) metre}} \qquad (2.1)$$

Now, the size of a physical quantity, such as the length of an object, is *independent of the system of units* chosen and so

$$\frac{\text{measure in System A}}{\text{measure in System B}} = \frac{\text{size of unit in System B}}{\text{size of unit in System A}}$$

Table 1.1 of the Seven SI BASE units	
Quantity	**Unit (Symbol)**
Time	second (s)
Length	metre (m)
Mass	kilogram (kg)
Electric current	ampere (A)
Thermodynamic temperature	kelvin (K)
Amount of substance	mole (mol)
Luminous intensity	candela (cd)

Supplementary units	
Plane angle	radian (rad)
Solid angle	steradian (sr)

2.1.2 Dimensions

Dimension can refer to physical length, width, thickness, and also to angle. However there is a wider meaning to the word dimension that we use here.

Consider, for example, the physical quantity speed,

$$\text{speed} = \frac{\text{distance travelled}}{\text{time taken}}$$

Remember that length and time are base quantities (the other base quantities being mass, electric current, temperature, "amount of substance", and "luminous intensity").

We say that the physical "dimensions" of speed are: "length divided by time".

Square brakets [..] are traditionally used to denote the dimensions of a pysical quantity. So,for speed,

$$[\text{speed}] = \frac{[\text{length}]}{[\text{time}]}$$

$$\text{i.e. } [\text{speed}] = \frac{[L]}{[T\}}$$

All physical quantities have dimensions that can be expressed in terms of the base quantities. [1]

For example:-

$$\text{acceleration} = \frac{\text{change in speed}}{\text{time over which the change occurred}}$$

or

$$[\text{acceleration}] = \frac{[\text{speed}]}{[\text{time}]}$$

which means that

$$[\text{acceleration}] = \frac{[L]/[T]}{[T]}$$

This is written as,

$$[\text{acceleration}] = \frac{[L]}{[T]^2}$$

or

$$[\text{acceleration}] = [L]\,[T]^{-2} \qquad (2.5)$$

In SI, “metres per second per second” or “metres per second squared”.

Using the symbols m and s for metres and seconds respectively this is written as:

m/s^2 or $m\ s^{-2}$

Note, however, that some *pure numbers* are commonly encountered. They are usually *ratios* such as π, which is the ratio of the circumference of a circle to its diameter. Numbers are dimensionless.

An important advantage of SI is that not only are the base units practical units but so also are the derived units.

This is what is meant by a *coherent* system of units. Two further examples may be used to illustrate the principle of dimensions.

Example 1 The concept of force is often introduced in a quantitative way as *inertial* force, i.e. to impart an *acceleration* to a body a force must be applied to overcome the *inertia* of the mass of the body:

force = mass x acceleration

so

[force] = [mass] x [acceleration] (2.6)

Therefore, using equation (2.5):

$[\text{force}] = [M]\,[L]\,[T]^{-2}$ generally

and in SI we have the expression for force in terms of base units: $m\ kg\ s^{-2}$ (2.7) where "kg" is the symbol for kilogram.

The force required to impart an acceleration of *one* ms^{-2} to a mass of *one* kg has *unit* magnitude in SI; this unit is called *one newton.* The SI symbol for the newton is "N".

***Example* 2**

$$\text{pressure} = \frac{\text{force}}{\text{area}} \tag{2.8}$$

$$[\text{pressure}] = [\text{force}] / [\text{area}] = \frac{[M]\,[L]\,[T]}{[L]^2}$$

and in SI the expression for pressure in terms of base units is m $^{-1}$ kg s^{-2} (2.9)

A force of *unit* magnitude (1 N) applied to an area of *unit* magnitude (1 square metre or 1 m^2) produces a pressure of *unit* magnitude. In SI the unit is called the *pascal* and the SI symbol is "Pa".

2.1.3 Multiples/sub-multiples of units

In SI the standard prefixes to indicate multiples and sub-multiples of units are:-

Table 1.2

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10^{16}	exa	E	10^{-1}	deci	d
10^{15}	peta	p	10^{-2}	centi	c
10^{12}	tera	T	10^{-3}	milli	m
10^{9}	giga	G	10^{-6}	micro	µ *
10^{6}	mega	M	10^{-9}	nano	n
10^{3}	kilo	k	10^{-12}	pico	p
10^{2}	hecto	h	10^{-15}	femto	f
10^{1}	deca	da	10^{-18}	atto	a

* pronounced "mew"

2.2 Base units

2.2.1 Length

"The metre is the length of the path travelled by light in vacuum during a time interval of 1/299 792 458 of a second."

This definition, which is possibly surprising, requires some explanation. As first mentioned in section 1.2.2 there is a drive to produce standards that are as independent as possible of environmental factors. We now believe that the speed of light waves in vacuum is a universal constant with the value 2.99792458×10^{8} m/s.

Since, distance travelled = speed X time taken, the above definition of the metre follows.

If our basic unit of length was 30 kilometre and our basic unit of time was 1/10,000 second then the speed of light would be ONE length unit per time unit!

This might appear to be a simpler situation but it is too late to change now and, in any case, it would not be a very practical system!

The wave length of the visible radiation from an ultra-stable helium-neon laser is used to realise the metre; the wavelength measurements are reproducible to about 3 parts in 10^{11}.

Lengths of interest to physicists range from the "diameter" of the observable universe (10^{26}m?) down to roughly 10^{-15} m (the diameter of an atomic nucleus). In engineering the range of lengths of interest is more restricted and the lower limit is of the order of atomic dimensions (10^{-10} m).

End standards of length are calibrated at the National Physical Laboratory (NPL) using an optical interferometer. Gauge blocks, length bars, diameter standards, linear scales as well as surveying tapes can be *calibrated* through the services offered by NPL. The uncertainty of measurement of gauge blocks is typically of the order of a few tens of micrometres ("microns").

2.2.2 Angle (degree)

Historically angles were first measured in "degrees", a full circle being divided into 360° (see section 1.2.3). The radii of a circle that define four equal quadrants are at right angles (90°) to each other.

A degree is divided into 60 *minutes* of arc and a minute is divided into 60 *seconds* of arc. An angle is denoted in degrees, minutes and seconds as:-

23^0	15'	31"
degrees	minutes	seconds

Sometimes, a part of a degree is expressed as a decimal fraction, e.g. 37.25° = 37° 15'.

2.2.3 Angle ("Circular measure" - radian)

Plane angle: the *radian* is the plane angle between two radii of a circle which subtend an arc of length equal to the radius of the circle.
Since the circumference of a circle = $2\pi r$, it follows that 360° = 2π radians (SI symbol "rad"). 1 rad = 360/2π degrees = 57.30°

The radian is a *supplementary* unit in SI.

A *primary standard* in the form of an artefact having a defined angle is not required, strictly speaking, since known angles can be realised by accurate sub-division of a circle. In practice, however, traceable industrial reference standards are required. Measurement uncertainties of less than 0.5 seconds of arc can be achieved on precision polygons, for instance.

2.2.4 Solid angle

The *steradian* is that solid angle which, having its vertex at the centre of a sphere, subtends an area of the surface of the sphere equal to that of a square with sides of length equal to the radius of the sphere .

Since the surface area of a sphere = $4\pi r^2$ it follows that the whole surface area of a sphere subtends a solid angle of 4π steradian at the centre of the sphere. The SI symbol for the steradian is "sr". The steradian is a *supplementary* unit in SI.

2.2.5 Mass

The unit of mass is the kilogram (kg) - it is equal to the mass of the international prototype of the kilogram.

The British copy (No.18) is kept at the NPL (see Section 1.2.2 for an introduction to the significance of mass and weight). Kilogram masses and sub-multiples of 1 kg can be compared at the NPL to about a microgram by using a precision balance.

2.2.6 Time

The second is defined in terms of the cyclical period of a certain characteristic electromagnetic radiation which is emitted by caesium atoms under carefully controlled conditions. The approved definition is:

The second is the duration of 9,192,631,770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the caesium-133 atom.

This standard can be realised in caesium atomic clocks with an uncertainty of about 1 ps (pico-second). The frequency of the 9,192,631,770Hz signal from the standard atomic clock can be subdivided to provide standard frequencies of lower value on world-wide scale. For example the BBC 200 kHz "long wave" transmission, which can be detected by a simple radio receiver, is stable to about $1:10^{10}$ over the duration of a day.

2.2.7 Electric current

The unit of electric current is the *ampere* which is defined today as:

That constant current which if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed one metre apart in vacuum would produce between these conductors a force equal to 2×10^{-7} newton per metre of length.

There are obvious practical difficulties in realising the experimental conditions implicit in this definition (infinite length, negligible cross-section, perfect vacuum) but neverthless considerable ingenuity has been deployed in the construction of "current balances" which allow the ampere to be determined to 3 parts in ten million. The SI symbol for the ampere is "A". In quite commonly encountered practical situations currents may be as small as 1 nA or as large as 1000 A, and much greater in transient discharges.

2.2.8 Temperature

At a fundamental level the temperature of a sample of material is proportional to the average energy of motion of the consituent atoms: a *statistical* average taken over the myriad (billions at least) of vibrating/ moving/ colliding atoms in a sample of "laboratory" size. The higher the temperature the higher the average energy.

The average energy of the atoms cannot be measured directly and so in thermometers a temperature-dependent property of a substance is exploited such as the expansion of liquid in a mecury-in-glass thermometer, or electrical resistance in a resistance thermometer.

Note that on the thermodymanic temperature scale the Absloute Zero of temperature is 0 K which is equal to -273.15°C.

The unit of thermodynamic temperature, the Kelvin (K), is the fraction 1/ 273.16 of the thermodynamic temperature of the triple point of water.

(Note: The triple point of water is that temperature 0.01°C at which water, ice, and water vapour coexist in thermal equilibrium).

The triple point cells used at NPL reproduce the water triple point temperature to 0.1mK

In the realm of engineering temperatures range from a few K (cryogenic engineering) to a few thousand K (in furnaces).

2.2.9 Amount of substance

Substances are composed of basic units which may be single atoms or may be molecules (groups of atoms which are bonded together chemically). In the following term "molecule" is used to denote the basic unit of a substance whether that basic unit is an atom or a chemical molecule.

A mole of a substance is the amount of that substance that contains as many molecules as there are molecules in 0.012 kilogram of carbon-12, ^{12}C.

The isotope of carbon, carbon-12 (^{12}C), is taken as the reference standard and the number of molecules in a mole is 6.0225×10^{23}

This number is called Avogadro's number and is usually denoted by the symbol "N_o". N_o is known to about 6 parts in 10^7. The abbreviation for mole is "mol".

2.2.10 Luminous intensity

The unit of luminous intensity of sources of light, namely the candela (cd), is defined as:

The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} Hz and has a radiant intensity in that direction of 1/683 watt per steradian.

"Monochromatic" source means, literally, single colour. This is in contrast to a source of light such as tungsten filament bulb which emits a mixture of colours of light extending from red through yellow and green to blue. As a matter of interest, light of the frequency quoted in the definition is green in colour.

The watt is the unit of power (energy per second).

2.3 SI Derived units

2.3.1 Examples of SI derived units expressed in terms of base units

Table 1.3

Quantity	**Name**	**Symbol**
area	square metre	m^2
volume	cubic metre	m^3
mass density	kilogram per cubic metre	kg/m^3
specific volume	cubic metre per kilogram	m^3/kg
speed	metre per second	rn/s
acceleration	metre per second squared	m/s^2
moment of inertia	kilogram metre squared	$kg\ m^2$
concentration (of amount of substance)	mole per cubic metre	mol/m^3
current density	ampere per square metre	A/m^2
magnetic field strength	ampere per metre	A/m
luminance	candela per square metre	cd/m^2

2.3.2 SI derived units with special names

Table 1.4

Quantity	Name	Symbol	Expression in terms of other units
frequency	hertz	Hz	
force	newton	N	
pressure, stress	pascal	Pa	N/m^2
energy, work, quantity of heat	joule	J	N m
power, radiant flux	watt	W	J/s
quantity of electric charge	coulomb	C	sA
electrical potential difference	volt	V	W/A
capacitance	farad	F	C/V
electric resistance	ohm	Ω	V/A
electric conductance	siemen	s	A/V
magnetic flux	weber	Wb	Vs
magnetic flux density	tesla	T	Wb/m^2
inductance	henry	H	Wb/A
Celsius temperature	degree Celsius	$^{\circ}C$	
luminous flux	lumen	Im	
illuminance	lux	Ix	Im/m^2
activity (of a radionunclide)	becquerel	Bq	
absorbed dose, specific gray energy imparted, kerma, absorbed dose index	Gy	J/kg	
dose equivalent dose equivalent index	sievert	Sv	J/kg

Table 1.5 Examples of SI derived units expressed by means of special names.

Quantity	Name	Symbol
moment of force (torque)	newton metre	N m
surface tension	newton per metre	N/m
dynamic viscosity	pascal second	Pas
heat flux density, irradiance	watt per square metre	W/m^2
heat capacity, entropy	joule per Kelvin	J/K
specific heat capacity, specific entropy	joule per kilogram Kelvin	J/(kg K)
specific energy	joule per kilogram	J/kg
thermal conductivity	watt per metre kelvin	W/(mK)
energy density	joule per cubic metre	J/m^3
electric field strength	volt per metre	V/m
electric charge density	coulomb per cubic metre	C/m^3
permittivity	farad per metre	F/m
permeability	henry per metre	H/m
molar energy	joule per mole	J/mol
molar heat capacity, molar entropy	joule per mole Kelvin	J/ (mol K)
exposure (X-and gamma-rays)	coulomb per kilogram	C/kg
absorbed dose rate	gray per second	Gy/s

Table 1.6 Examples of SI derived units formed by using supplementary units

Quantity	Name	Symbol
angular velocity (speed)	radian per second	rad/s
angular acceleration	radian per second squared	rad/s^2
radiant intensity	watt per steradian	W/sr
radiance	watt per square metre steradian	W/m^2sr

2.3.3 Examples of non-unit-SI units

Quantity	Name	SI.equivalent
length	Inch angstrom	25.4 mm 0.1 mm
area	Hectare square inch	1 hm^2 6.4516×10^{-4} m^2
volume	cubic inch litre	1.63871×10^{-5} m^3 0.001 m^3
angle	degree	0.01745 rad
mass	pound ton tonne	0.4536 kg 1.0161×10^3 kg 10^3 kg
angular frequency (2π x frequency)	Revolution per minute (rpm)	0.1047 rad/s
force	Kilogram-force (kgf)	9.8067 N
pressure, stress	bar pound per square inch (psi) standard atmosphere inch of mercury torr (mm of mecury)	0.1 MPa 6.895 kPa 1.0133 kPa 3.3863 kPa 0.13332 kPa
Work, enerrgy, heat	calorie British thermal unit (Btu) therm (= 10^5 Btu) electronvolt (eV)	4.1868 J 1.0551 kJ 0.10551 GJ 1.6022×10^{-19} J
viscosity (dynamic)	proise	0.1 Pa s
viscosity (kinematic)	Stokes	10-^{4} $m^2 s^{-1}$
viscosity (plasticity) of un-vulcanized elastomers	mooney	8.30×10^{-2} Nm
magnetism	Gauss maxwell	10^{-4} T 10^{-8}Wb
light	Stilb Phot	10 kcd m^{-2} 10 klx
radioactivity	Curie Rontgen rad	3.7×10^8 s^{-1} 0.258 mC kg^{-1} 10 mJ kg^{-1}

2.4 Certified reference materials and transfer standards

Reference materials serve to achieve compatibility of the *scales of measurement,* as used in the many organisations, which are required to determine physical, chemical, technical and engineering properties of materials.

Certified reference materials (CRMs) enable *traceability* to national standards of measurement.

In the United Kingdom the NPL is the ultimate authority on units of measurement in the physical sciences and is also responsible for providing a wide range of CRMs and *transfer standards.*

A CRM is a representive sample from a specially prepared stock of samples whose properties have been established for the calibibration of apparatus, vertification of measurement methods and the assigning of values to materials. A transfer standard is an artefact intended to transfer to a user's location one or more certified physical property values.

The NPL holds stocks of some reference materials issued by the US National Bureau of Standards, the French Service des Materiaux de Reference and the (European) Community Bureau of Reference (BCR).

3.0 Dimensions and Dimensional Analysis.

3.1 The dimensions of physical quantities.

All physical quantities have "dimensions" which can be expressed in terms of the base quantities mass, length, time etc.

For example,

$$[\text{speed}] = \frac{[\text{length}]}{[\text{time}]}$$

(**Note**: square brackets [....] are used to denote the dimensions of a physical quantity.}

[acceleration] = [speed] /[time]

[force] = [mass] x [acceleratlon]

[electric charge] = [current] x [time]

The base quantities cannot be expressed in terms of each other.

The dimensions of a physical quantity are Independent of the units in which it happens to be measured in a particular situation e.g. a distance has [length] whether it Is measured In cm, rn, yards, miles, light years .....

For convenience symbols such as M, L, T, I... (see below) are used to note physical dimensions;

Physical quantity	**Dimension**	**SI unit**
Mass	[M]	kilogram (kg)
Length	[L]	metre (m)
Time	[T]	second (s)
Current	[I]	ampere (A)

Also,

	force	=	mass x acceleration
or	[force]	=	$[M][L][T]^{-2}$

and

	pressure	=	force/area
or	[pressure]	=	$[M]\,[L]^{-1}\,[T]^{-2}$

Force and pressure are derived quantities. Note that the dimensions of base quantities may be raised to powers; the exponents are negative in these two examples but in general they may be positive also. A table of the dimensions of "mechanical" quantities can be constructed:

Table 1.

	Exponent of the dimension.		
Mechanical quantity.	**M**	**L**	**T**
area	0	2	0
volume	0	3	0
density	1	-3	0
speed	0	1	-1
acceleration	0	1	-2
force	1	1	-2
pressure	1	-1	-2
momentum	1	1	-1
power	1	2	-3
elastic modulus	1	-1	-2
frequency	0	0	-1
torque	1	2	-2
moment of inertia	1	2	0
viscosity (kinematic)	0	2	-1

2.2 Dimensional analysis

A general knowledge of dimensions and dimensional analysis can be useful in many ways, for example,

(a) The dimensional form of a quantity can be used to provide a conversion factor from one system of units to another.
(b) Equations in a mathematical analysis can be checked for validity.

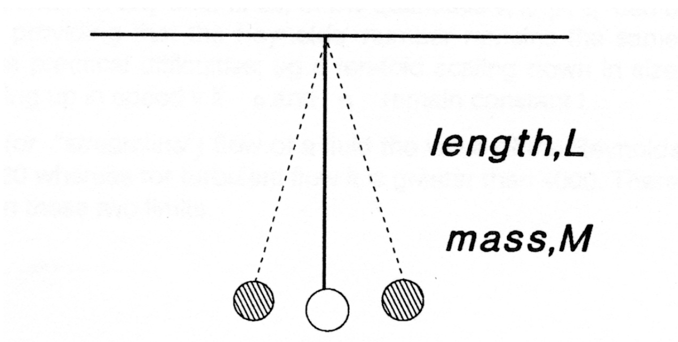
Every term in an equation describing a physical situation should have the same dimensions; this Is called ***dimensional homogeneity***.

Equations that are not dimensionally homogeneous are certainly not valid (but beware, dimensional homogeneity does not, in itself, guarantee that an equation is correct !).

(c) Dimensional analysis may provide a way of deriving a theoretical relationship between the physical variables in a particular situation (unknown constants will remain but it will often be possible to evaluate these from experimental measurements).

So (fairly) simple theory can sometimes be used to provide solutions in complex situations. (See the example of the simple pendulum below)

(d) The principle of dimensional similitude can be used to design appropriately scaled models for experimental situations.



A simple pendulum

Consider the regular swinging motion of the pendulum and denote its periodic time by T_o. Suppose we wish to find a mathematical expression for T_o in terms of the physical quantities of the system. We assume that T_o depends on the length l of the pendulum, the mass m of the bob and the local value of the intensity the gravitational field g. Further, we assume that the relationship between T_o and l, m, g can be written in the form;

$$T_o = K\, l^a m^b g^c$$

Now we apply the criterion that the equation must be dimensionally homogeneous;

$$[T_o] = [\, l^a m^b g^c] \quad \text{(K is dimensionless, remember)}$$

For [M]: $0 = b$

For [L]: $0 = (a + c)$ (since [g] = [acceleration] = $[L^{-2}]$)

For [T]: $1 = -2c$

Solving these three simultaneous equations yields;

$$a = ½ \quad b = o \quad c = -½$$

So we have deduced that the expression for T_o is of the form:

$$T_o = K\, .l^{½} g^{-½}$$

Rigorous analysis yields K = 2π and this can be confirmed by experiment.

2.3 Dimensional SimiIltude

The principle of dynamic similitude can help in the solution of many design problems, particularly where scaling of the physical size of an object can yield practical advantages. Probably the best-known applications are in the realm of fluid dynamics; the flow of fluids through pipes and the motion of objects through fluids. It transpires that a non-dimensional group of physical quantities is of paramount importance;

$$\frac{vl\rho}{\eta} \text{ (Reynolds' number)}$$

is a relevant linear dimension, v is the speed, and ρ and η are the density and viscosity of the fluid respectively.

For example, for a scaled-down model in a wind tunnel the aerodynamic drag force on the model is directly related to the drag force on the real object (e.g. an aeroplane wing) moving at its real speed provided that the Reynolds' number of the real object and the model are equal. To meet this criterion any one, or all, of the quantities v, l, ρ, and η can be adjusted, in principle, provided that the Reynolds' number remains the same. Note that there may be practical difficulties; e.g. a ten-fold scaling down in size l implies a ten-fold scaling up in speed v If ρ and η remain constant !

For laminar (or "streamline") flow of a fluid the value of the Reynolds number is less than 2000 whereas for turbulent flow it Is greater than 4000. There is a "grey" area between these two limits.

4.0 Glossary

accuracy of measurement The closeness of agreement between the result of a measurement and the (conventional) true value of the quantity subjected to measurement.

base quantity One of the quantities which, in a system of quantities, are conventionally accepted as independent of each other.

derived quantity A quantity defined, in a system of quantities, as a function of base quantities of the system.

derived unit (of measurement) A unit of measurement of a derived quantity in a given system of quantities.

dimensions of a quantity An expression which represents a quantity of a system of quantities as the product of powers of the base quantities of the system.

Etalon A material measure, measuring instrument or system intended to define, realise, conserve or reproduce a unit or more known values of a quantity in order to transmit them to other measuring instruments by comparison.

Examples
(a) 1 kg mass standard,
(b) standard gauge block,
(c) 100 Ω standard resistor,
(d) saturated Weston standard cell,
(e) standard ammeter,
(d) caesium atomic frequency standard.

primary standard (see standard)

scale An ordered set of scale marks, together with any associated numbering, forming part of an indicating device.

standard (primary) A standard which has the highest metrological qualities in a specified field.

standard (secondary) A standard whose value is fixed by comparision with a primary standard.

standard (transfer) A standard quantity used as an intermediary to compare standards, material measures or measuring instruments.
Note:- When the comparison device is not strictly a standard, the term transfer device should used.

system of units (of measurement) A set of units established for a given system of quantities comprised of a set of chosen base units together with derived units determined by their defining equation and proportionality factors.

traceability The property of the result of a measurement whereby it can be related to appropiate standards, through an unbroken chain of comparisons.

unit of measurement A specific quantity, adopted by convention, used to express quantitatively quantities which have the same dimension (see "dimension")