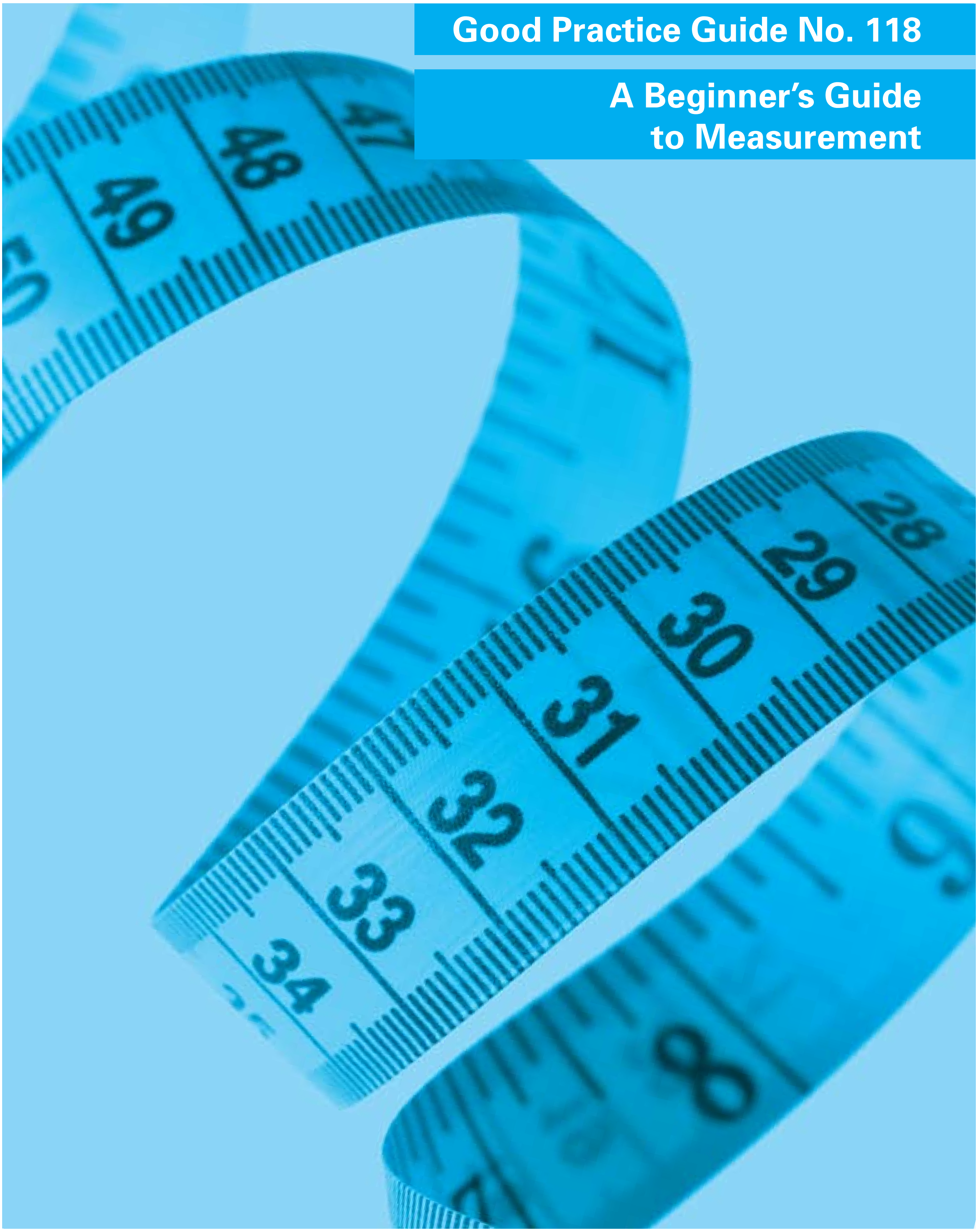
NPL National Physical Laboratory

Good Practice Guide No. 118

A Beginner's Guide to Measurement



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A Beginner's Guide to Measurement

Version 3

Mike Goldsmith

This Beginner's Guide explains the fundamental concepts and basic facts about measurement, and in particular accurate measurement. It includes brief accounts of the role of measurement in modern and historical societies and explains the SI system, its base units and their relation to other units. The various organisations involved in measurement are introduced and their roles in linking all measurements to the SI base units through traceability chains explained. It includes general guidance about practical issues that affect the making of measurements, gives the meanings of key measurement terms, and explains the significance of such fundamental concepts as measurement traceability and calibration.

Messen ist Wissen

(Measurement is knowledge)

Georg Simon Ohm (1789-1854)

Foreword

This beginner's guide is intended for people with little or no experience of making accurate measurements but who wish to find out more about them, either because they intend to make or use accurate measurements themselves or to work with those who do.

It may be of use to those starting careers in metrology or engineering, and to managers, research scientists, teachers, university students and those involved in the sale or marketing of measuring instruments.

It has been written in a form that is intended to be as painless as possible for those who are being required to read it, while being sufficiently accurate to avoid undue irritation to any actual metrologists who may happen to encounter it. For readers who wish to find out more, suggestions for further reading are listed at the end of the book.

The guide is likely to have two audiences and has been divided into two parts accordingly: the first contains background information on the concepts and history of measurement, which may be of interest to the general reader or to those involved in marketing or management within the measurement field. The second part summarises the types of practical issues that impact the actual making of accurate measurements, and may be more relevant to working metrologists.

The subject of accurate measurement is more important than ever. It is key to such disparate areas as global warming, the control of performance-enhancing drugs and observational cosmology. Consequently, and despite the vast number of science and technology books, magazines, TV programmes and websites, it is surprising that the subject has been almost entirely overlooked. Perhaps this book will go a small way towards demonstrating that, despite its low profile, measurement matters.

A world of measurements

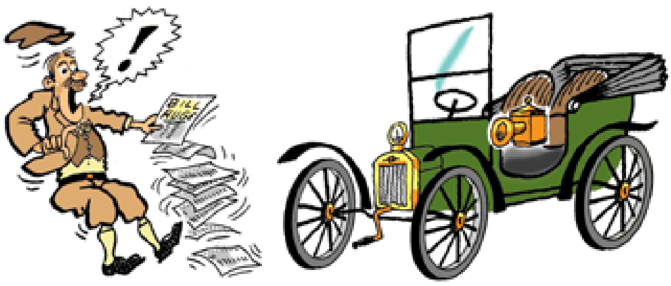
1. Why measure?

We all make measurements, every day of our lives: think how often you glance at your watch or your car's speedometer. And we are surrounded by the outputs of measurement devices too, from the wind speeds on weather forecasts to the figures on gas bills. Then there are all those behind-the-scenes measurements needed to ensure that pills contain the doses they should, to prepare and package food and to check whether our houses are full of smoke.

Some everyday measurement devices are very accurate – and some aren't. Even the cheapest digital watches are accurate to a few seconds a year, while the readings of oven thermometers are frequently wrong by several degrees. If your watch was only as accurate as your oven, it might easily lose an hour a week. That's fine for cooking, because the accuracy of the measurement you need not to miss an appointment isn't the same as is required to bake a cake*. As we'll see, making measurements that are neither more, nor less accurate than we need is important for many applications.

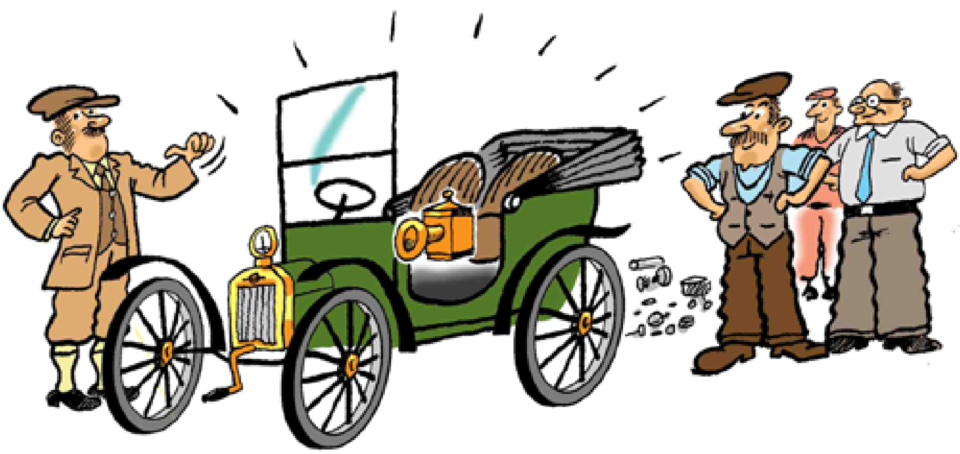
Many of the measurements on which modern life depends are hidden. For instance, though the precise dimensions and electrical properties of the many components of your car or computer are of no interest to you, they make all the difference between functioning and failure. Long ago, when cars and other machines were hand-built, exact measurements didn't matter – each part was made to fit together with the parts that were already there, thanks to a considerable amount of shaving bits off and forcing things together.

Sadly however, all that individual attention was liable to cost the customer a small fortune...



.... which led Henry Ford, and people like him, to pioneer the idea of standard-sized parts.

Today, this approach is vital: about 80% of the components used by any manufacturer are made by other companies - often overseas - so every manufacturer needs to tell its subcontractors the ranges of acceptable values of the dimensions, electrical characteristics and other parameters of all those components. Otherwise a lot of things would fall apart, or not fit together in the first place.



* Having said that, the fact that so many ready-meals bear some such discouraging words as 'all ovens vary' or 'adjust cooking times to suit your oven' may suggest a bit more work needs to be done here.

It was Ford who applied the idea of standardised parts to industrial processes. However, the idea of using standardised parts had a more violent origin: in about 1778, Honoré Blanc began producing some of the first firearms with interchangeable parts, and, twenty years later, Eli Whitney demonstrated the same idea to the US Congress by jumbling a heap of parts together and then assembling guns from parts selected at random from the pile. Congress loved the idea and it wasn't long before new pieces could simply be ordered for guns that failed, rather than being specially made to fit.

Then there's science. A brave new theory might start with an apple falling on your head, but it won't get much further without accurate measurements to confirm – or reject – it.

Isaac Newton, for example, delayed publishing his Law of Universal Gravitation for years because the brilliantly simple equation he came up with could not quite predict the right value for the speed of the Moon. Finally, when Jean Picard came up with an improved value of the radius of the Earth, it turned out that the equation worked just fine, and went on to explain the motions of the rest of the Solar System very nicely too. Except, that is, for the planet Mercury – accurate measurements of its orbit revealed regular changes that could not be accounted for by Newton's equations. Many years later, Einstein's theory of gravity explained those changes, and scientists had to accept that Einstein's theory was superior to Newton's.

As Lord Kelvin (after whom a unit of temperature is named) said: "When you measure what you are speaking about and express it in numbers, you know something about it, but when you cannot express it in numbers your knowledge is of a meagre and unsatisfactory kind... "

As a result of its importance, measurement has a science of its own, called metrology, from the Greek words metron ('measure') and logos ('study').

Metrological definitions

Scientific metrology

the science of measurement, including the development and provision of measurement standards

Industrial metrology

the application of measurement science to manufacturing and other processes

Legal metrology

measurement activity underpinning fair trade and consumer protection

What do we really mean by a measurement?

The fundamental idea is that of a quantitative comparison, made using one of more instruments. So, to measure the length of a piece of wood, one might compare it with a tape-measure on which units of length, such as centimetres, are marked – the result of the measurement being expressed as a number of centimetres.

2. Measurement through history

People have been measuring since they began to buy, own and sell things, which means that the history of measurement is as long as that of civilisation. In fact, many aspects of civilisation would be impossible without measurement: science, for instance. Throughout history, science and measurement have worked in a virtuous circle, in which the technological developments that science produced permitted accurate measurements to be made, which then fed back into the testing and refinement of new scientific theories. Meanwhile, the growing internationalism of trade led to clarification and harmonisation of measurement systems. It's too long a story for a short space, but some of its highlights are:

About 3000 BCE, Egypt

The cubit is defined as the length of the Pharaoh's forearm plus the width of his hand. Once this measurement has been made and carved into a granite block, wooden and stone copies are given to builders. Architects have the responsibility to check them each full Moon – with execution the penalty if they don't.

1196 ADE, England

The first documented call is made for standardisation of units in England, in the Assize of Measures. The primary concern is that beer and wine are properly measured.

1215, England

Magna Carta requires uniform measures throughout England, stating that 'There shall be standard measures of wine, ale, and corn ... throughout the kingdom. There shall also be a standard width of dyed cloth, russett, and haberject, namely two ells within the selvedges. Weights are to be standardised similarly.'

About 1612, Italy

Thermometer invented, perhaps by Giovanni Francesco Sagredo (1571–1620).

About 1643, Italy

Barometer invented by Evangelista Torricelli (1608-1647).

1657, Netherlands

The pendulum clock is patented, by Christiaan Huygens (1629-1695) and the first one is built soon after. It is accurate to around 10 seconds per day, an amazing improvement on the six minutes a day or so 'accuracies' of previous mechanical clocks.

19 January 1762, Jamaica

William Harrison disembarks from his ship, carrying a very special watch: a chronometer called H4. His father, John Harrison, had designed it to keep time at sea with sufficient accuracy for sailors to work out their longitudes*. Despite being on board the ship since 18th November the previous year, H4 is only 5.1 seconds slow, a significant achievement for a mechanical device.

* i.e., how far East or West they were from some convenient reference-point.

1791, Paris

The French National Assembly agrees to standardise the metre as one ten-millionth part of a quarter of the Earth's circumference. As no-one knows exactly how long this is, various people set off to find out. Unfortunately, France fixes its official standard of length before all the results are in, and as a result the standard metre bar is a fifth of a millimetre too short. This also means the circumference of the Earth (through the poles) is a bit more than the forty million metres everyone was expecting it to be.

1799, Paris

The metric system is set up, through the adoption of two platinum/iridium alloy standards: a metre length and a kilogram mass.

1824, London

An act of Parliament introduces an improved and more widespread system of measurements, and an imperial standard yard is constructed. The yard is placed in the Houses of Parliament for safe keeping – which doesn't turn out to be all that safe after all when they burn down in 1834. After this, a new standard yard bar is made and kept in a fireproof box, which is then bricked up in a wall in the new House of Commons and only taken out every 20 years to check the lengths of standard copies.

1842, London

The Excise Laboratory is founded in London to carry out chemical analysis to detect the adulteration of tobacco. This laboratory later becomes the Laboratory of the Government Chemist (now LGC) and is the oldest official chemical laboratory in Britain.

1875, Paris

Seventeen nations sign the Convention of the Metre, and the International Bureau of Weights and Measures is set up.

1955, Teddington, England

The first accurate atomic clock is built by Louis Essen (1908-1997) at the National Physical Laboratory (NPL). It keeps time to better than one millionth of a second per day.

1960, USA

The first working laser is constructed by Theodore Maiman (1927–2007) in California. Initially a discovery in search of an application, it rapidly becomes essential to the accurate measurement of time, length and luminous intensity.

1960

The International System of Units (SI System) is established, including units of mass, length, time, temperature, current and luminous intensity.

1971

A seventh unit, of amount of substance, is added to the set of SI base units.

1994

The National Measurement Office (NMO) starts testing the accuracy of the UK's national lottery balls.

3. What do we measure?

For a very long time, Britain used units which were based on familiar things - like feet.

If everyone's feet were the same size, this would be an extremely simple and convenient system (and not just for shoemakers). As they aren't, a foot of a particular length had to be defined as a standard. Other units were treated in the same way until there were accepted values, used throughout the country, of all common units (though no-one ever seems to have got round to defining leagues properly, beyond deciding it took an hour to walk one).

A problem with this approach was that other countries naturally wanted similarly handy units, so they came up with similar-but-not-quite-the-same definitions, which in turn led to lots of argument when people in different countries tried to sell goods to one other. As it would be very inconvenient for countries to change the values of their units, and even more difficult to decide which countries were to change and which stay the same, these differences persist. For instance, to this day the British gallon is about one fifth larger than the US version of the unit with the same name.

There were even more problems when people in different countries tried to work together to make things. Problems of this sort came to a head in the Second World War, when efforts made by the Americans and British to build things together were frequently distrupted by the American foot being 0.0004% longer than the British version. Since an engine part that is 0.0004% too large is sometimes wrong enough not to fit, it was soon clear that this problem needed urgent attention, so experts sprang into action to agree a common definition of the foot. Twenty years later, they succeeded. Sadly for them, by then the foot was being elbowed out by the metre as a standardised measure of length in the UK.

It wasn't only length units that were changing, nor were the changes confined to Britain. By many triumphs of diplomacy and horse-trading, in 1960 the world* agreed to adopt a single primary system of units, called the International System of Units, or SI for short.

Martian blunder

Although it might seem that all the international measurement differences have been nicely ironed out, they are still lurking to take their revenge on the careless. In 1999, NASA's Mars Climate Orbiter (which had cost $125M) had completed more than 99% of its journey very successfully when a steering rocket was fired to control its final approach to the Martian atmosphere. NASA had specified the thrust value in metric units. Sadly, its operator assumed that the value was in old-fashioned British units. The Orbiter was lost in space and the face of Mars wasn't the only one that was red.

* Other than Liberia, Myanmar-and the USA, where units based on the old British Imperial ones, like ounces, are still almost universally used.

Quantity	SI unit	Symbol	Example
Length	metre	m	Height of double-decker bus: about 4.5 m
Mass	kilogram	kg	Large loaf of bread: about 0.8 kg
Time	second	s	Time between heart-beats (at rest): about 0.8 s
Electric current	ampere†	A‡	Kettle: about 10 A
Temperature	kelvin	K	Human body: about 310 K
Luminous intensity	candela	cd	Candle: about 1 cd
Amount of substance	mole	mol	Water molecules in a cupful: about 14 mol

Why 'amount of substance'?

You may be wondering why it's necessary to measure atoms and molecules by 'amount of substance' rather than mass. The main reason to work in moles is because that's what nature does. Take a very simple chemical reaction like:

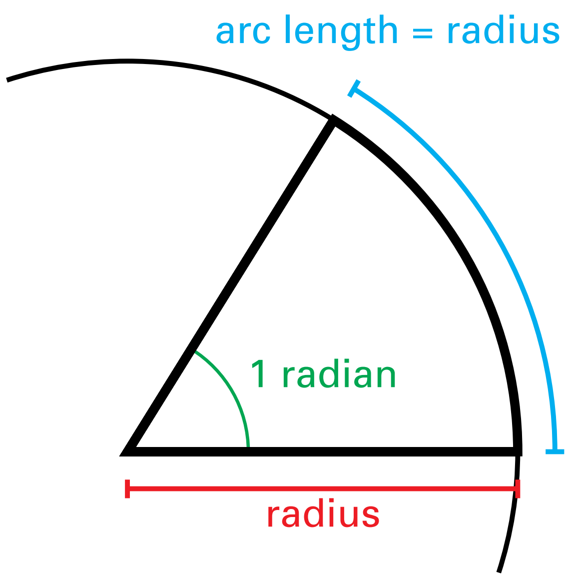
Na + Cl = NaCl

This says that sodium (Na) will combine with chlorine (Cl) to make table salt (NaCl, sodium chloride). But, how much sodium, chlorine and salt are involved here? If you wanted to make 2 kg of salt, you might be tempted simply to buy 1 kg of sodium and 1 kg of chlorine and encourage them to combine. If you tried this, you would soon use up all your chlorine and have lots of sodium left over, because you get a great many more sodium atoms to the kilogram, as they are lighter than chlorine ones. However, if you bought one mole of each element, that would make one mole of salt.

The problem with the mole is that it can't be measured directly, since atom-counting machines haven't been invented yet. So, amounts of substance are actually worked out from mass or volume measurements or electrolysis.

The actual number of atoms or molecules in one mole is about 602,214,150,000,000,000,0 00,000, or around 6.02×10^{23} for short*. This number is called The Avogadro Constant.

In addition to the seven base units, there are also a number of supplementary and derived units. For example the SI also defines the unit of angular measure to be the radian, which is the angle subtended at the centre of a circle by an arc the same length as the circle's radius:



One radian is about 57.2968°.

† The names of the units aren't capitalised, even when they're named after someone (like André-Marie Ampère) ...

‡ ... but the same isn't always true of their abbreviations

* 10^{23} means '10 multiplied by itself 23 times', which is 1 followed by 23 zeroes. This way of writing numbers is called scientific notation.

From these few units, all the other units that people need to measure anything can be derived, such as:

Quantity	Unit	1 such unit equals:
Area	square metre	1 metre x 1 metre
Volume	cubic metre	1 metre x 1 metre x 1 metre
Speed	metre per second	1 metre ÷ 1 second
Acceleration	metre per second per second	1 metre ÷ 1 second ÷ 1 second
Force	newton	1 kilogram x 1 metre ÷ 1 second ÷ 1 second
Energy	joule	1 kilogram x 1 metre x 1 metre ÷ 1 second ÷ 1 second
Power	watt	1 kilogram x 1 metre x 1 metre ÷ 1 second ÷ 1 second ÷ 1 second

One of the strengths of the SI is that absolutely any measurement can be expressed in terms of the seven base units (and angle if needed).

Thanks to the SI and a well-organised set of agreements and procedures to make it work, everyone all over the world can not only agree just how fast their cars are, they can make sure their components fit together properly too.

Since it would be inconvenient to measure everything using only the pure base or derived units - motorists don't want road distance in metres, for instance - a shorthand system of prefixes was agreed as part of the SI system. So, for example:

10 metres =1 decametre

10 decametres = 1 hectometre

10 hectometres = 1 kilometre.

All the prefixes are related to each other by numbers like 10, 100 or 1,000; which are called powers of 10. For instance, '10 to the 3rd power' means 10 multiplied by itself 3 times, or 10x10x10 or 1,000. In general there are named prefixes for factors or multiples of 1000.

Throughout the SI system, the same prefixes are used for the same multiples, no matter what the unit - except for the kilogram. Because the kilogram already includes a prefix in its name we don't refer to a thousandth of a kilogram as a millikilogram.

Some of these units aren't used much – decimetres, for example, are uncommon, and megametres are practically unheard of. And the prefixes aren't used for time, where there was already an internationally agreed system in place long before the SI came along. So no-one is likely to ask you whether you are 1300 megaseconds old (~41.3 years), even if you really do look it.

Metrology is a pragmatic science, and its practitioners appreciate that many people are so used to certain traditional units that it would be unreasonable to expect them to change. So, the following units are accepted for use with the SI. The first three are alternative measures of angle, and are based on π, the number of times the radius of a circle fits into its diameter (about 3.1459).

The fact that the SI system uses powers of 10 – which is to say it's a decimal system – makes it very easy to use. For instance, given that there are 1000 metres in a kilometre, how many metres are there in 7 kilometres? Working out that the answer is 7,000 is so easy that 'working out' hardly seems the right way to describe it. But how many feet are there in 7 miles? As there are 5,280 feet in one mile, the answer is 36,960 – which does take some actual work to discover. It's also not that easy to remember that there are 5,280 feet in a mile.

Prefix	Symbol	Decimal	Power of 10
yotta	Y	1000000000000000000000000	10^{24}
zetta	Z	1000000000000000000000	10^{21}
exa	E	1000000000000000000	10^{18}
peta	P	1000000000000000	10^{15}
tera	T	1000000000000	10^{12}
giga	G	1000000000	10^{9}
mega	M	1000000	10^{6}
kilo	k	1000	10^{3}
hecto	h	100	10^{2}
deca	da	10	10^{1}
deci	d	0.1	10^{-1}
centi	c	0.01	10^{-2}
milli	m	0.001	10^{-3}
micro	μ	0.000001	10^{-6}
nano	n	0.000000001	10^{-9}
pico	p	0.000000000001	10^{-12}
femto	f	0.000000000000001	10^{-15}
atto	a	0.000000000000000001	10^{-18}
zepto	z	0.000000000000000000001	10^{-21}
yocto	y	0.000000000000000000000001	10^{-24}

Name	Symbol	Quantity	Equivalent SI unit
minute	min	time	1 min = 60 s
hour	h	time	1 h = 3600 s
day	d	time	1 d = 86400 s

Name	Symbol	Quantity	Equivalent SI unit
degree of arc	°	angle	1° = (π/180) rad
minute of arc	′	angle	1π = (π/10800) rad
second of arc	″	angle	1π = (π/648000) rad
hectare	ha	area	1 ha = 10000 m^2
litre	l or L	volume	1 l = 0.001 m^3
tonne	t	mass	1 t = 1000 kg

Not everything can be measured (though NPL will always have a go if at all possible): measurements require artificial devices, so that rules out things to which no device can respond, like emotional states, although things that are related to emotional states, like heart-beats, can be measured.

Similarly, subjective reactions to things, like the impression we call the loudness of a sound, can't truly be measured, though we can sometimes find objective things which correlate to them. Loudness is related to the energy of sound waves, for example. But even here, the relation is quite complicated: the frequency of a sound needs to be taken into account, and so does the length of time it lasts for: generally, very short sounds are louder than longer ones of the same total energy. When people – noise control engineers for instance - wish to go further and determine the relationship between the loudness of a sound and the annoyance it causes, things get even more complicated.

The subject of 'soft metrology' aims to find ways to measure things which lie outside the traditional areas of metrology, including some things that we otherwise can only judge qualitatively. This covers such topics as visual appearance, taste, odour, product usability, customer satisfaction and intelligence.

Not just any comparison counts as a measurement. If you discover that one of your shoelaces is longer than the other by comparing them side by side, that's not a measurement. But if you use a ruler to give the difference in length a value, this is a measurement, because now you are making a quantitative comparison.

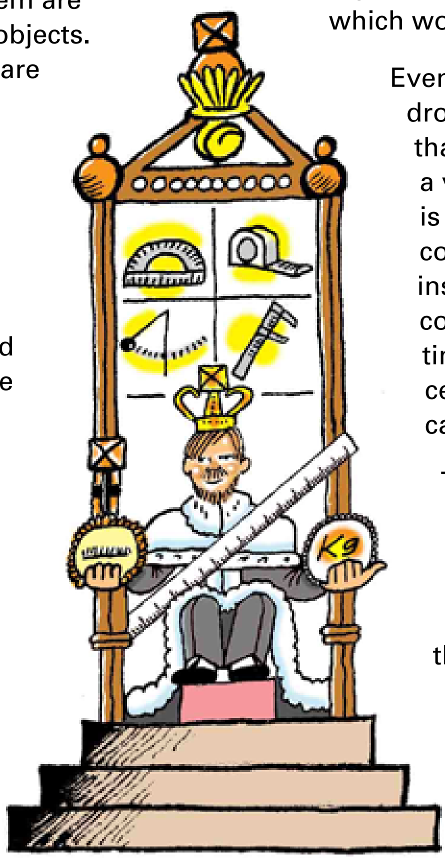
4. Weights and measures

How many clocks do you have? Taking into account the ones in your computers, car, microwave, central heating controller, iPod and phones it would be surprising if there are fewer than a dozen, and even more surprising if they all told the same time. Even if you were keen or bored enough to synchronise them all one day, it's not very likely that they would all be telling the same time a year later. The fact that they get out of step shows that the units they are counting with are not exactly one second long. And the same applies to other measuring instruments too, such as kitchen scales.

Sometimes, not being able to quite trust the result of a measurement is no more than a minor irritation. At other times – if you're an athlete trying to beat the world record or waiting for the results of a drugs test – you really do want to know you can trust the measuring instruments involved.

The most obvious way to check that measuring instruments are working correctly is for there to be things which are definitely exactly, precisely, unarguably one metre long, last one second, have a mass of one kilogram and so on, so that the measuring instruments can be checked against them. And, in a way, there are such things – though, as we'll see, most of them are precise descriptions, rather than objects. And how do we know they really are what they seem? Perhaps rather disappointingly, the answer is 'by definition.' In the past, the person ultimately responsible for the definition was often a country's ruler. Nowadays, since countries need to talk the same measurement language, kings and queens – in certain respects - have been replaced with a committee: the International Committee for Weights and Measures (or CIPM, short for Comité International des Poids et Mesures) in Paris. The organisation for which the committee is responsible is the Bureau International des Poids et Mesures (BIPM).

It may not seem very scientific that the values of units are set by a human authority, even an international one, rather than something more, well, scientific, but it's an inevitable consequence of the fact that the units we use are actually arbitrary. The world would get along just fine if all the seconds were a bit longer, or all the metres were a little longer.



So, somewhere in Paris, are there really ultimate versions of the kilogram, metre, ampere, kelvin, mole, and second?

Yes and no. There is indeed a lump of metal (platinum-iridium alloy, since you ask) called the international prototype kilogram, to which all the kilograms in the world defer. A number of copies, as close in mass as possible to the international prototype, have been made and are kept in various laboratories around the world. The UK's copy is number 18, and it is kept at NPL.

The importance of the international prototype is immense, because it is unique – it is the only thing there is in the Universe which we know to have a mass of exactly one kilogram – by definition. Because this object is defined as one kilogram then, even if it should change its mass one day (by being dropped, for instance, so that a bit snapped off it), it would still, by definition, be one kilogram, despite being suddenly a little lighter. The rest of the world's 'kilograms' would of course then weigh more than the international prototype, which would cause all sorts of problems.

Even though no-one ever does actually drop the kilogram, and despite the fact that it is very carefully maintained, in a vacuum, at a fixed temperature, it is nevertheless changing. Atoms are constantly falling off it, disintegrating inside it or getting stuck to it. The corresponding changes in mass are tiny (a few tens of micrograms per century), but they mean the kilogram can't possibly do its job indefinitely.

The kilogram would be more stable if it were locked away permanently and never moved or touched, but of course it's no use at all unless it is compared occasionally with the masses of its official copies, to make sure nothing untoward has happened to them.

In consequence of such problems, there are two international research projects currently attempting to base the definition of the kilogram on a definition instead of an object (see box).

Given the problems of using a unique artefact such as the international prototype kilogram, metrologists prefer not to use artefacts to define the other base units. Indeed, it's hard to imagine what sort of object some of them – the kelvin, for example – could possibly be. Instead of objects, there are definitions which, when turned into reality, can make something which is exactly one metre long, something else which has one candela of luminous intensity and so on. This means that, even if every measuring instrument were destroyed tomorrow, realisations of six of the base units could be reconstructed from their definitions. This also means that these base units are truly international – any country which wishes to invest in the necessary scientists and technology can realise copies of the units for itself.

The actual definitions of the units are hard to understand without knowing some physics, (some salient bits of which are explained in the Appendix). This is no coincidence. To achieve the greatest possible exactness in defining what the units are, it's necessary to tap into some of the most fundamental properties of the physical world. For instance, something as simple and familiar as a second is really a slippery and hard-to-pin down thing, as Einstein showed: two identical clocks cease to tell the same time when subjected to different gravitational pulls. Since the Earth's gravity varies slightly with altitude, latitude and longitude, that means that no two clocks of Earth can keep exact time with each other, not because of any imperfections in the clocks, but because the times they measure are passing at different rates. On the plus side though, if you want to lose a bit* of weight, you could always go to a mountain-top. You'll live a bit* longer there, compared to people at sea-level, too.

New kilograms?

Because the masses of atoms of the same type are identical and unchanging, the kilogram could be defined as the mass of a particular number of a particular type of atom. So, one project is attempting to 'count' the number of atoms in a pure crystal of silicon of known mass, working from a knowledge of the spacing of the atoms and a measurement of the volume of the whole crystal.

In a second project, an electromagnet is used to apply an upward force to an object so that the downward pull of gravity on it is exactly balanced. The mass of the object can then be related to the electrical current flowing through the electromagnet.

The challenge faced by both approaches is the need to provide mass values which are as well-determined as that of the international prototype kilogram, which translates to about one part in a hundred million - a millionth of a percent. At the moment, neither have achieved this objective. So, the international prototype can't be thrown away just yet.

* 'bit' here should be understood in the special technical sense of 'mind-bogglingly tiny amount'.

Defining six of the seven base units in such a way that most of the world agreed with them, and that didn't depend on an arbitrary object like the length of someone's foot, was essential, but, by themselves, the definitions are of no use whatsoever in actually measuring anything. The next step was to build equipment that used those definitions to produce – or 'realise' – close approximations to the second, metre, kelvin, ampere, candela and mole. Real objects or phenomena could then be compared with them.

For some of the base units, this equipment works as the definition would suggest: the second is indeed realised through a clock that measures the transition frequency of caesium 133. But a glance at the definition of the ampere isn't very encouraging to anyone who doesn't happen to have two infinitely long pieces of wire at their disposal, to say nothing of a slightly larger vacuum to put them in. And the definition of the mole really gives no clue at all as to how an actual version might be brought into being.

In practice, there are several ways to realise most of the base units, and only brief details are given here.

SI Base Unit definitions

Metre

The length of the path travelled by light in vacuum during a time interval of 1/299792458 of a second.

Kilogram

The mass of the international prototype of the kilogram.

Second

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

Ampere

The constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per metre of length.

Kelvin

1/273.16 of the thermodynamic temperature of the triple point of water.

Mole

The amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon 12. The elementary entities may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.

Candela

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

Measurements in chemistry and biology

Compared to biologists and chemists, physicists have easy lives, at least when it comes to measuring things. Of course, many SI units, such as the kilogram and the metre, are as useful to chemists and biologists as they are to physicists. But making measurements to answer apparently simple questions such as ‘How many bacteria are there in a litre of milk?’ or ‘How much lead is there in a sample of paint?’ can present significant challenges. Such questions open the door to several potentially tricky issues: How is the quantity of interest (number of bacteria, amount of lead….) to be measured? If the composition of the sample is changing over time (as in the case of bacterial growth) at what point should the measurement be made? Is the sample tested in the laboratory representative of the bulk material from which it was obtained? And so on.

One of the key challenges in chemical and biological measurement is finding suitable standards to calibrate measuring instruments. Many measurements are multi-stage processes which use different items of measuring equipment, each requiring calibration with suitable standards. For example, a chemist presented with the task of measuring the amount of lead in a paint sample will need to weigh out a suitable portion of the sample, find a way of separating the lead from other components of the paint and finally measure the amount of lead present. While it is relatively straightforward to envisage how the balance used to weigh out the sample can be calibrated using suitable reference weights, calibrating instruments to measure the amounts of elements or chemical compounds present is more complex. A suitable reference standard is required for each element or compound and this relies on having reference materials with accurately known purities or concentrations. An added complication is the need for extraction and clean-up steps to separate the compounds of interest from the rest of the sample matrix and get them in a form suitable for analysis. The presence of these steps potentially breaks the ‘chain of traceability’ – see page 15) that should link all measurements to suitable references such as the SI. This issue is addressed by using ‘matrix reference materials’, similar in composition to real test samples, in which the amounts of the chemicals of interest have been accurately determined. Matrix reference materials are available for a wide range of measurements – it is possible to buy reference foodstuffs certified for components such as fats, sugars and vitamins, and standard waters and soils certified for concentrations of toxic metals. However, if one takes a moment to consider the huge number of chemical elements and compounds which might need to be measured, and the vast range of materials in which they might occur, the scale of the challenge becomes apparent.

In biology, things are even more challenging. Something like the mass of a protein molecule is a highly difficult thing to measure – it can be very tricky to establish its structure in the first place, let alone isolate, extract, and measure the amount present. An even more challenging issue is that often the things that biologists would like to measure are reactions of a living organism so change over time (often very rapidly) and in relation to the organism’s response to its environment and its growth stage, – like the reactivity of a muscle cell to a drug.

Often in biology, the approach is to develop an ‘assay’: for instance, in testing whether an athlete has used performance enhancing drugs, immuno-assays are carried out in which antibodies are introduced to a urine or blood sample, and then react to the presence of the drug. The strength of the response is a measure of the amount of drug present. However, such immuno-assays are rather inaccurate and can’t be relied on unless they are checked against other measurements of related quantities, and their relation is the SI has not been firmly established.

Many challenges remain in chemical and bio-metrology but laboratories are working at the international level to address these issues, through the production of suitable reference standards, the development of reference measurement procedures and the designation of standard measurement units.

Realising the base units

Length is established in two ways: long distances are determined by measuring the time that light takes to travel over them in a vacuum, and multiplying that time by the speed of light (299,792,458 metres per second). Shorter distances are compared directly with the lengths of light waves, using a technique called interferometry.

Time is measured using an atomic clock in which the ‘ticking’ of the clock is the vibration of an individual atom. In one such type of clock, a group of caesium atoms is first cooled and then exposed to microwaves. The microwaves are then tuned to the value at which the electrons in the atoms vibrate most strongly. This is a frequency of 9,192,631,770 vibrations per second (hertz) – and this is used to define the second.

Despite the fact that the definition of the kelvin is based on the properties of water, the unit of temperature is actually realised by using the freezing points of metals and the triple points of gases to define a temperature scale, often on an instrument called a platinum resistance thermometer.

The candela, which refers to the intensity of a light source as observed by the human eye, is realised by first determining the power of a laser beam using a cryogenic radiometer. This measures the power by detecting the temperature rise of a cold object caused by the light. Once the beam power is known it can be used to adjust a photometer, an instrument which mimics the response of the human eye to luminous intensity. Finally, this photometer is used to measure the luminous intensity of a tungsten lamp in candelas.

The mole, the unit of amount of substance, is the number of atoms in a particular mass, so it can be realised by dividing the mass of a sample of a substance by the mass of one of its atoms. Atomic masses can be measured by a mass spectrometer, and accurate weighing gives the mass of the substance sample. Sounds simple? Well... it might be if it weren’t so tricky to get a sufficiently pure sample, and if the atoms of a pure substance were all the same mass (they’re not, because of the presence of isotopes (page 34)).

Rather than realising the ampere, the unit of electric current, its value is determined from the watt, the SI unit of power. Power is related to current through the equation

$\text{Power} = \text{Current}^2 \times \text{Resistance}$

To realise the watt, electrical power is generated and its level determined by comparison with mechanical power. An accurate measurement of resistance is then made and the value of the ampere is calculated.

The kilogram, the unit of mass, is simply the mass of the international prototype.

5. Who's who in measurement?

In a small number of laboratories around the world, the base units are realised as accurately as is technically possible, which involves a great deal of expensive, complex, and delicate equipment, not to mention a number of highly trained metrologists. Which is not very convenient when it comes to actually measuring things.

So, a route is needed from the realised base units (known as primary standards) to the watch on your wrist or the thermometer in your ear. This route must ensure that your watch and thermometer make their measurements with the accuracies you expect, and it must be a route that people have confidence in.

The route that bridges the gap, and gives both the confidence and convenience that people need, is called measurement traceability, and it works like this.

1. The primary standards are held at a national level, by National Measurement Institutes (NMIs).

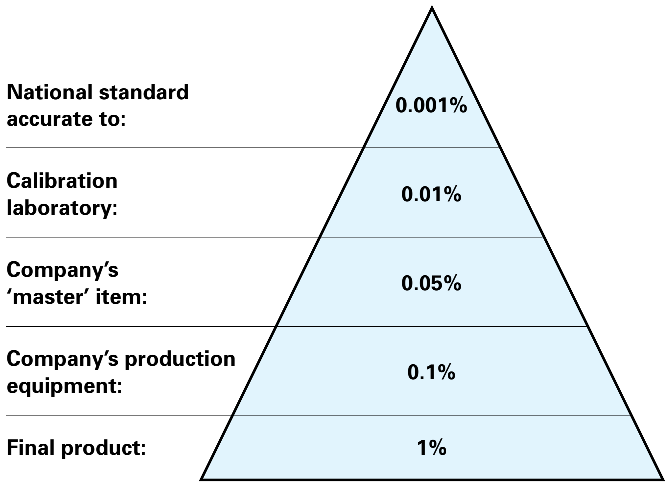
2. The primary standards are used to check the values of reference standards held by calibration laboratories around the country.

3. These calibration laboratories then check the values of working standards which they receive from the organisations who make or use measuring instruments. These organisations might be the people who make your watch or thermometer, or they might be – for example - factories, hospitals or research laboratories.

This series of steps is sometimes known as a 'chain of traceability' for a measurement.

The reference standards and working standards may be measuring instruments – thermometers for example – or they may be physical objects, like gauge blocks (standardised metal shapes used for judging distances). In some areas, standard samples are used, such as a sample of a radioisotope with a particular activity, or a chemical solution with a specified concentration.

There is a price to be paid for the convenience that this system provides: at each stage of the chain of traceability that runs from the lasers at your NMI to the watch on your wrist, the uncertainty of measurement increases. NMIs and calibration laboratories try to minimise this increase, for example by radio-linking clocks directly to national time standards. But this cannot be done for all units and at each stage of the calibration process, a little extra uncertainty is introduced:



In some cases the pyramid is shorter than this. For example, hospitals may send their instruments directly to an NMI to be checked. This usually happens either because only the NMI can provide the accuracy that is needed, or because such a small number of instruments are used that it's not economic for anyone else to get involved.

Measurement Accreditation

Calibration laboratories have a key function in the calibration pyramid, and they not only have to carry out their work correctly, but their clients need to be confident that they do so. In order to assure this, the laboratories have to go through a process called accreditation, which means that they are assessed against internationally recognised standards to demonstrate their competence, impartiality and capability. In the UK, the organisation responsible for carrying out accreditation is the United Kingdom Accreditation Service (UKAS).

The calibration system is – and must be - a global one, partly since it is essential to international activities like trade, manufacturing and research, and partly because not every country has its own NMI and not every NMI holds primary standards of all the base units. Also, an important aspect of checking that national standards really have the values they are supposed to is the concept of international comparison. In such a comparison, a standard artefact is sent round to the NMIs of several countries, all of whom measure it and report their results to each other. Anyone whose system isn't working properly is likely to get a result noticeably* different from the rest.

So, the system requires a great deal of ongoing co-operation between countries. The authority which oversees all this international activity is the Bureau International des Poids et Mesures (BIPM), which keeps close contact with the world's NMIs.

In some countries, just one organisation acts as the NMI (such as NIST** in the USA), but in others, including the UK, the role is split between different laboratories (see box).

The UK's NMIs

The National Physical Laboratory (NPL) maintains the majority of the UK's measurement standards.

LGC maintains chemical and biochemical standards.

TUV NEL maintains standards of flow.

The National Measurement Office (NMO, formerly the National Weights and Measures Laboratory) maintains standards for mass, length and volume and is also responsible for legal metrology.

NMIs also work with each other through groupings focused on particular regions or issues. For instance, legal metrology is harmonised at an international level through The International Organisation of Legal Metrology (OIML), while European NMIs work together through the European Association of National Metrology Institutes (EURAMET).

The internationally agreed recipes that describe how a laboratory should carry out accurate measurements are called International Standards, and The International Organization for Standardization (ISO) is responsible for defining and revising them. It is based in Geneva, Switzerland. Among many others, ISO is responsible for ISO 17025, 'General requirements for the competence of testing and calibration laboratories' which is the Standard that specifies how UKAS (and its overseas equivalents) accredits calibration laboratories National bodies such as BSI (British Standards Institution).

Despite this international system, there are still areas where stated values are not really fit for purpose: would you be confident that a pair of shoes in your size would actually fit? And as for clothes:

So far, this guide has concentrated on the concepts that underlie measurement. If you want to learn about practical measurements issues, read on ...

* more technically, dodgy systems are likely to give results which are outside the expected range of uncertainties – see page 21.

** National Institute of Standards and Technology.

PART TWO

MEASUREMENTS IN PRACTICE

This part of the guide introduces the practicalities that affect many or all areas of measurement. Its purpose is to explain why, rather than exactly how, these issues should be addressed: in many cases, more details will be found in 'A Beginner's Guide to Uncertainty of Measurement' (Stephanie Bell, NPL, 2001). Each section concludes with a partial checklist summarising the topics covered. These checklists are collated together on page 41 and it may be useful to run through this checklist prior to undertaking a series of measurements. Please bear in mind though that for most actual measurements, addressing the issues in the checklists fully will require more specific information than this guide can provide.

6. How accurate can a measurement be – and what does 'accurate' mean?

This section explains:

Why no measurement is perfect;

Why this doesn't matter;

The meanings of key measurement terms.

It's not possible to talk for long about measurement without mentioning the concepts of accuracy or of uncertainty of measurement, in consequence of a possibly-alarming fact:

No measurement is, or ever can be, exactly right

But this is really no cause for alarm. In fact, it doesn't matter at all – because none of us ever needs measurements to be exactly right; it is enough that they have whatever accuracy we need, or uncertainty we can tolerate. Asking for more than that is liable to cause problems: imagine measuring the height of one of your relatives and marking it on the wall, as some people do. It's not something where a great deal of accuracy is required – the nearest centimetre will suffice (which is to say that the uncertainty of measurement is about a centimetre). At this level we can happily and easily conclude that Jeff's height is 182 cm, armed with no more than a ruler or two and a marker pen.

However, if we were to ask for the uncertainty to be reduced to a millimetre, the answer would be a lot trickier to supply. A number of questions now need to be dealt with: should Jeff take his socks off too? Does he need to hold his breath? If so, should he breathe in or out first? What about his hair – do we measure to the top of it, flatten it down, or cut it off? What about the thickness of the line the pen makes on the wall? Is the horizontal ruler really horizontal?

Issues like these typically arise when the requested measurement accuracy increases, and should always be prefaced by: 'Do we really need to know the answer this accurately' or, more formally, 'What level of uncertainty is sufficiently small for our purpose?'

Answering these questions makes things a whole lot easier, through saving us from worrying about factors which actually don't matter. In fact, limitations on accuracies of measurements aren't just conveniences – if one tried to measure with limitless accuracy, just for fun, a fundamental problem would arise (see box).

So the key challenge for metrologists here is not to get the right answer, but to decide on the uncertainty they can tolerate. This in turn leads to the need to express the degree of uncertainty of a measurement in a clear and unambiguous way. And of course, before this can be done, clear definitions of such concepts as 'uncertainty' and 'accuracy' are needed.

The limit of knowledge

If you wanted to track an atom by measuring its exact velocity and position over time, how might you go about it? You could try looking at it under a powerful microscope, but unfortunately, because the waves of light are larger than atoms, nothing useful could be seen (trying to see something smaller than the light waves you are using is like trying to feel inside something which is smaller than your fingers). Instead, you might try something with a much smaller wavelength, like a high-frequency X-ray. This is indeed small enough to 'see' an atom, but a new problem emerges – X-rays carry a lot of energy, enough to give any atom a sizeable nudge, thus changing both its position and velocity. It turns out in fact that there is a well-defined limit to the accuracy of uncertainty with which you can measure the atom's velocity (or strictly its momentum) and its position. And, because you would need to know both to track its path exactly, exact tracking is impossible.

This phenomenon was summarised by Werner Heisenberg in his Indeterminacy (or Uncertainty) Principle, which states that the product of the uncertainties of the position and momentum of any object can never fall below a certain fixed value.

One of the problems that arises from the fact that measurement is so much a part of daily life is that measurement words which are used in an exact and rigorous way by scientists are also used every day by everyone else, with no rigour at all, much to the irritation of the scientists. (Though it's only fair to say the words did start off vague in the first place and were only acquired, tidied up and locked down by scientists later on).

Another slight complication to defining the various terms related to measurement is that some of them only make sense when several measurements of the same thing are being considered. That's because making a good measurement is much like trying to hit a target, and your chances of ending up with a satisfactory result are greatly increased if you make several attempts. After all, would you want to rely on a single measurement of, say, the girth of a snake?

An apparent problem with defining measurement terms is that many of them refer to 'true' values, and this may seem inconsistent with the fact that these true values cannot ever be known. This problem is similar to one affecting absolute zero (of temperature) – a very useful concept in physics, but something which can never be realised in a laboratory (or anywhere else for that matter). The solution in both cases is the same – by making enough effort, we can approach the true value of a quantity, or absolute zero, as closely as we wish for the job in hand.

The following few pages explain what some key measurement terms mean - when metrologists use them, anyway.

Error and uncertainty

Error refers to the difference between the measured value and the true one, while uncertainty is the doubt that exists about the result of any measurement. (Though this definition sounds rather doubtful itself, uncertainty is actually a very well-defined concept, as we'll soon see).

Accuracy and precision

If you make several measurements and find that they also agree closely with each other, then they are precise. If they agree closely with the actual value, then they are accurate.

Trueness

Trueness is a similar concept to accuracy, but while accuracy refers to the closeness between an individual measurement and the true value, trueness refers to the closeness of agreement between the average value obtained from a set of test results and the true value.

Bias

Bias is the opposite of trueness – the greater the bias the lower the trueness. So, when a measuring instrument consistently gives readings which are too high or too low, it is said to be biased.

Repeatability and reproducibility

If you measured the weight of an apple three times a minute using the same kitchen scales, you would be surprised to get a different answer each time. But, if your Aunt Ethel weighed the same apple next Tuesday on her scales, and then her cousin Arthur weighed it on Thursday at NPL, different answers would become much less surprising. Repeatability describes the agreement within sets of measurements like the first one, where the same person uses the same equipment in the same way under the same conditions (including place and, as far as possible, time). Reproducibility, on the other hand, describes the agreement within a set of measurements like those in the second example, where different people, equipment, methods or conditions are involved.

It may sound like repeatability is preferable to reproducibility, but in fact each has a key role in science. If you want to be as sure as you can of the weight of an artefact, then you need to repeat your measurements many times, and a high repeatability suggests you have got a good result. But, if your equipment – your home-made radio telescope, for instance - tells you that you have discovered an amazing new phenomenon – like a message from Pluto – it really would be a good idea to make sure plenty of other scientists make the same observations and find the same thing (i.e. that your results are reproducible) before phoning the newspapers.

Confidence level

If you make a number of measurements of something – like the concentration of carbon monoxide gas in your vicinity - you are very likely to get a range of answers. From those answers, you might conclude that the true value lies between, say, 9 parts per million (ppm) and 11 ppm – probably (or, you might say, that it is 10±1 ppm). You could not be sure that this was the case, but you could express your confidence that it is. So you might decide that you are 90% confident that the answer lies between those values.

Tolerance

A tolerance is the maximum acceptable difference between the actual value of some quantity, and the value specified for it. For example, if an electrical resistor has a specification of 10 ohms and there is a tolerance of ±10% on that specification, the minimum acceptable resistance would by 9 ohms and the maximum would be 11 ohms.

As usual in science, clear definitions of words are just the start; for those words to be useful, numbers need to be attached to them. It is one of the triumphs of metrology that initially vague concepts like uncertainty can be pinned down in such a way that they can be expressed in numbers.

☑ Section 6 Checklist

Before making a set of measurements, do you know:

- ☐ What the measurements are for, and hence the uncertainty of measurement you are seeking?
- ☐ How many times you should repeat the measurement?
- ☐ The acceptance criteria (the tolerance, for example) for the result?

7. Six guiding principles

This section explains:

The six guiding principles, developed by NPL, that should be followed to achieve a good measurement result.

The number of quantities that can be measured is vast, and the number of measuring instruments is far larger. Length (or distance), for example, might be measured by a tape-measure, a sonar system, or a laser range finder, depending on whether you're a tailor, a submariner or a builder. The number of ways to misuse these devices is also rather large, and this section is an attempt to reduce that number a little.

If you wanted to make your own door, you would want to know the size of the doorway to an uncertainty of about a millimetre or two. A not-too-cheap tape measure could be fine for the task, but, as this is an important measurement and could waste a lot of time and money if you get it wrong, you might want to check it is sufficiently accurate. You could do that by laying it beside a different tape measure, or you might possibly measure something of known length with it. Then, you would need to use it correctly, ensuring that the end is just touching the threshold, that the tape lies straight down the jamb, and that you can clearly see the point where it reaches the top of the door. Finally, you would definitely want to measure the other side of the door frame too, to make sure the doorway is a true rectangle. If you get an answer which is different by more than a couple of millimetres, then you would repeat your measurements to find out whether the sides of the door really are different or your measurement is wrong for some reason.

All measurements are based on the same approach used to measure doorways, and have been helpfully boiled down (by NPL) to six guiding principles.

1. The right measurements

A measurement is made for a reason, and that reason needs to be clearly defined and understood if the measurement is to be a good one. This is of course especially important when the measurement is being carried out for someone else. When a system which involves routinely repeated measurements is being devised (such as a system to measure the sizes of vegetables), a pilot study is a useful first approach, to discover where any problems lie and where improvements can be made to the procedure.

2. The right tools

The measuring instruments used need to be appropriate for the task, in a good state of repair, and calibrated (see Section 8) – and they need to be used according to the instructions of their owner or manufacturer.

3. The right people

Whoever makes the measurement (sometimes referred to as the 'operator') needs to have received the right instructions and training. For complex measurements, this training will often include formal qualifications. Where a group of operators is involved, their individual roles and responsibilities need to be formally agreed and clearly understood.

4. Regular review

Measuring instruments are often easily damaged and their performance frequently changes as time passes, so they need to be checked. These checks should be carried out at regular intervals rather than just before they are needed, to avoid delays. Since many individual instruments may be involved in making a measurement (to check environmental conditions, for instance), a written schedule is usually essential. In many cases this schedule will include both internal checks and less frequent external assessments. Measurement procedures (see below) also need to be reviewed regularly.

5. Demonstrable consistency

A measurement result isn't much use if it's only valid at the place where the measurement is made. For highly accurate measurements, there are often all sorts of local factors that need to be taken into account if this is to be avoided. The force of gravity, for example, varies by up to 1% from place to place on the Earth's surface (and changes with time too, as a result of the shifting gravitational influences of the Sun and Moon, among other things). In turn, this affects the weights of objects (as measured, for example, by spring balances). So, an assessment of such factors should be made in planning an important measurement. What happens next depends on the outcome of the assessment – it may be that the factors are too small to significantly affect the uncertainty of the results, or that they can be corrected for by the user, given appropriate data and instructions, or that it may be that the result should be quoted with higher uncertainty. In addition to this approach, for important or difficult measurements, other operators in other laboratories should carry out the same measurements and their results compared. Depending how different those results prove to be, it might again be necessary to make corrections, increase quoted uncertainties, or carry out further investigations.

6. The right procedures

As there are so many factors which need to be addressed to ensure that the result of a measurement is a good one, it's important that important or complex measurements are carried out in accordance with written procedures. Though these might simply be the documents supplied by the manufacturer, these may not be sufficient, especially where a number of different pieces of equipment are involved. An important function of a written procedure is to safeguard health and safety, so it will often be backed up by a risk assessment for this purpose.

☑ Section 7 Checklist

Are you confident you are:

- ☐ Making the right measurements?
- ☐ Using the right tools?
- ☐ Involving the right people?
- ☐ Carrying out regular reviews?
- ☐ Able to demonstrate consistency?
- ☐ Following the right procedures?

8. Validation and calibration

This section explains:

What validation, calibration and certification are and why they matter;

When instruments should be calibrated.

How is it determined whether the people, procedures, equipment and other factors actually are the right ones? The process of checking this is called validation and it takes many forms, but the fundamental approach is to rely on the judgment of experts that all these factors are fit for purpose. These experts usually include people who will be using the measurement results, others with thorough knowledge of the items being measured, and experienced metrologists.

Another key measurement concept is calibration, which is the comparison of an instrument or artefact against a more accurate instrument (or sometimes a well-controlled reference signal or other reference condition), to discover whether it meets the manufacturer's specification. As a result of this comparison, a certificate is produced, which reports the instrument's readings and compares them to a reference value or values.

If the results are consistent with the reference values (i.e., any differences between them are within acceptable limits), then no further action is needed. If the results are significantly different, the measuring instrument under test can, in some cases, be adjusted until the results agree, and these adjustments are then recorded on the certificate. (In general, NPL does not make such adjustments, though they are routine in some organisations). Sometimes, calibration corrections are applied to the results, rather than to the instrument.

Depending on the type of weight being calibrated and class of accuracy, NMO may be able to adjust the weight for a customer if its calibration reading is outside the tolerances of legal metrology. However, the customer will then have to pay to have the weight re-calibrated.

In general, measuring instruments are first calibrated by their manufacturer. Sometimes, they are returned periodically to that manufacturer for re-calibration, or they may be calibrated either in-house by the owner, or by a calibration laboratory.

Any calibration certificate can only report the behaviour of the measuring device at the time the calibration was carried out, but it is usually assumed that the device will remain 'in calibration' – i.e. performing according to its specification – for some specified time-period, such as a year. (Though in some cases the time-period is much less than this – in particular, measuring instruments based on electronic sensors can drift quite rapidly.) When used for legal purposes, it is essential that that the calibration certificate is still valid in this sense. It's important to bear in mind that this time-period does assume that the measuring device has been kept in conditions appropriate to it and not mishandled, just as a sell-by date on a sandwich assumes it's been kept in a fridge and generally well-treated. And, though preliminary checks on the instrument should be carried out just before you use it, these are much like sniffing the sandwich just before you eat it – worth doing, and useful for spotting major problems, but not enough to rely on in themselves.

Of course, when a device has been dropped, miss-used or otherwise badly treated, it will often need to be re-calibrated straight away, and the same applies if it begins behaving oddly.

Some instruments also need to be calibrated more often depending on how they are used – flow meters, for example, will need more frequent attention when the fluids they measure are corrosive or erosive.

Breathalysers?

Most breathalysers work by triggering a visual display once a certain level of alcohol vapour in the breath sample is reached (the level being set according to the legal limit of blood/alcohol concentration). But the alcohol sensor built in to a breathalyser gradually becomes saturated, which makes it less sensitive. So, the breathalyser is sent regularly to a laboratory where it is placed in a controlled environment containing alcohol solutions and simulators which reproduce the alcohol fumes in breath. The solutions themselves are checked using gas chromatography. The simulators allow the amount of alcohol in the air to be controlled, and this amount is set to the appropriate trigger level. If the detector does not trigger at the correct point, its sensitivity is reset or, if the difference is too large, its sensor is replaced.

☑ Section 8 Checklist

Has every measuring instrument you intend to use:

- ☐ Been calibrated as and when its manufacturer specifies?
- ☐ Been kept in inappropriate conditions, not misused, or damaged (in which case it should be checked and if necessary calibrated)?

Will the instrument:

- ☐ Be checked before the measurements begin?

9. Factors affecting the measurement results

This section explains:

The factors which affect the results of a measurement;

Some ways in which those factors can be controlled.

Unless the six guiding principles (section 7) are followed, there's not much hope of making a good measurement – but even if they are, there are still a number of factors that either can't be controlled at all, or can only be controlled to a limited extent, and which will influence the result.

Instruments

While calibrations and preliminary checks can confirm that measuring instruments are behaving as they should before a measurement begins, a number of factors can impair their performance during the measurement itself. Electrical measuring instruments can be affected by electrical noise, either in the form of electromagnetic radiation or disturbances to voltage supplies. Proper earthing of equipment is also important, which can be tricky when several electrical instruments are involved in the same measurement, in which case common earths may need to be set up and checked, to avoid earth loops.

In some cases the instrument itself can have a significant effect on the thing to be measured – this is always an issue with measurements of tiny quantities (see The limit of knowledge on page 20) but can affect larger-scale measurements too. For instance, acoustic measurements are frequently required to be made in anechoic conditions - that is, environments in which there are no reflections of sound from objects. While chambers can be provided with special wall coverings to scatter and absorb sound waves, the detector itself can be a source of troublesome acoustic reflections.

The object to be measured

Hardly anything that is measured is truly stable: many people shrink by over a centimetre over the course of a day, fruit and vegetables slowly dry out and their chemical compositions change as they ripen and rot, colours fade and shift, electrical resistance alters with temperature and so on. Therefore, a consideration of the significance of such changes is important in planning measurements. In some cases, they may be small enough to be disregarded ('negligible'). In others, they can be corrected for or averaged out. In yet others they can be reduced or halted by controlling the environmental conditions. Sometimes the variation itself is of direct interest, for example in measuring the stability of blood-chemistry, the constancy of flow in pipelines or the flicker of light-sources. Measurements which track such changes (rather than simply averaging them out) are referred to as 'dynamic.'

Sampling, and other aspects of the measurement process

The measurement technique needs to be well-designed and the people who use it well-trained to get the most out of a measurement. This is especially important in those cases where the thing to be measured varies across space and time – the noise inside a car, the speed of the wind or the temperature of seawater can all be measured very accurately, but the answer will be of no value unless measurements are made in sufficient numbers, and at appropriate positions and times – that is to say, that they are representative.

Another issue is that some samples can alter after they are taken but before they are measured. Blood, for example, undergoes many changes once it is removed from the body. So, characteristics of blood samples are not necessarily the same as those of in the bloodstream. In cases like this, a combination of appropriate storage, prompt measurement, and knowledge of expected changes is required.

Sometimes there are aspects of the measurement process which cannot be completely controlled or planned, however excellent the people, equipment and procedures may be. In those cases it is essential to make clear what the limitations on the measurement results are.

Operator skill

Measurements involve human skills, and there are limits to these, no matter how well trained, diligent or highly-motivated the operator is. Often, setting up the measuring equipment and preparing the thing to be measured is even more challenging than carrying out the measurement itself.

An important consideration here too is that those limits vary widely between individuals, so a measurement which can be carried out to a certain level of uncertainty by one person may be unachievable by another (see box).

Environmental factors

The environment – especially its temperature, air-pressure and humidity – can affect the results of measurements of many kinds, by altering the characteristics of the measuring instrument, the thing to be measured, or both. In some cases, for example where mass has to be very accurately determined, the measurement is carried out in chambers under which all these factors are controlled, at a precise temperature and sometimes in a vacuum (and hence zero air pressure and humidity). However, measurements like this are expensive to make, in terms both of the facilities involved and the time required, Furthermore, many items to be measured, including liquids and living things, don't take kindly to being measured in a vacuum.

Air pressure is especially difficult to control, but can make a significant difference to a wide range of things, including the weights of objects* and the speeds of light and sound. Consequently, corrections are often applied to the measurement results, based on the air pressure recorded when the measurement is made. These corrections can be determined by calculations based on a knowledge of the physics involved, or by experiments.

A personal issue

In 1796, Nevil Maskelyne (the Astronomer Royal), and his assistant, David Kinnebrook, were measuring the times at which stars crossed a line in the field of a telescope. Maskelyne noticed that Kinnebrook's timings were always about 0.8 seconds later than his own – and sacked him for his slow reaction times. Many years later, Friedrich Bessel used the data from the two astronomers to develop the idea of the 'personal equation,' which describes the unavoidable bias associated with a particular person's measurements.

✓ Section 9 Checklist

In planning your measurements, have you assessed and minimised the effects of:

- ☐ Instrument performance limitations?
- ☐ The object to be measured?
- ☐ Sampling?
- ☐ Operator skill level?
- ☐ The environment?

* This is because any objects in the air are buoyed up by it, just as water buoys up things that are in (or on) it. The effect depends on the density of the air, and therefore on its pressure.

10. Expressing measurement results

Measurement results need to be written down clearly, and the SI system includes a set of rules to help.

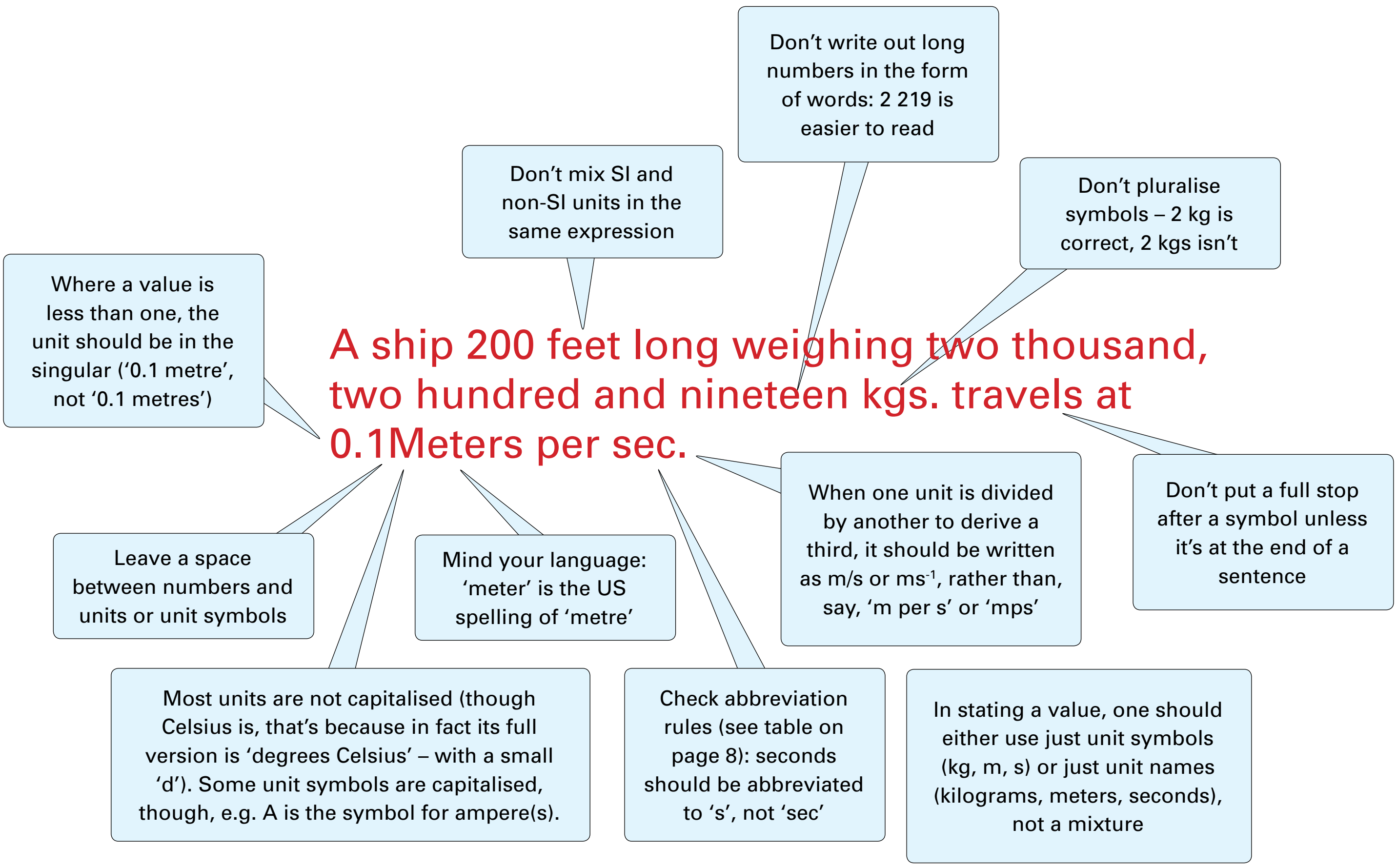
This section explains:

Some common errors in writing down the results of a measurement.

Full details are given in Section 5 of the BIPM publication 'The International System of Units (SI)', which is freely accessible at:

www.bipm.org/utils/common/pdf/si_brochure_8_en.pdf

Most of the rules are broken here:



☑ Section 10 Checklist

In expressing the results of your measurements, do you

- ☐ know the SI rules?

☑ Checklist: how to make good measurements

Before making a set of measurements, do you know:

- ☐ what the measurements are for, and hence the uncertainty of measurement you are seeking?
- ☐ how many times you should repeat the measurement?
- ☐ the acceptance criteria (the tolerance, for example) for the result?

Are you confident you will be:

- ☐ making the right measurements?
- ☐ using the right tools?
- ☐ involving the right people?
- ☐ carrying out regular reviews?
- ☐ able to demonstrate consistency?
- ☐ following the right procedures?

Has every measuring instrument you intend to use:

- ☐ been calibrated as and when needed?
- ☐ been kept in appropriate conditions, not missused, or damaged (in which case it should be checked and if necessary calibrated)?

Will the instrument:

- ☐ be checked before the measurements begin?

In planning your measurements, have you assessed and minimised the effects of:

- ☐ instrument performance limitations?
- ☐ the object to be measured?
- ☐ sampling?
- ☐ operator skill level?
- ☐ the environment?

To express the results of your measurements, do you:

- ☐ know the SI rules?

Glossary

The following brief explanations of some key measurement concepts are not formal definitions – if required, those can be found in many of the references in the previous section.

Accreditation: formal process that assures the quality of organisations and the work they carry out.

Accuracy: closeness of the agreement between measurement result and true value.

Base unit: fundamental unit of measurement on which other units are based.

Bias: the opposite of trueness, as occurs when the indication of a measuring instrument is consistently too high or low.

Calibration: comparison of an instrument against a more accurate one (or against a reference signal or condition), to find and correct any errors in its measurement results.

Confidence (level): number (e.g. 95%) expressing the degree of confidence in a result.

Correction: number added to an instrument reading to correct for a bias.

Decimal system: a system based on the number 10.

Error: deviation from the correct value.

Measurand: quantity being measured, such as time or flow-rate.

Metrology: the science of measurement.

Metric System: a decimal system of units based on, among other units, the metre.

Precision: a measure of the scatter of a number of measured values.

Repeatability: closeness of the agreement between repeated measurements of the same thing carried out in the same place, by the same person, on the same equipment, in the same way, at similar times.

Reproducibility: closeness of the agreement between measurements of the same thing carried out in different circumstances (e.g. by a different person or a different method, or at a different time).

Tolerance: the maximum permissible difference between an actual value and its specification.

Traceability: a measurement is traceable if it can be connected to national or international standards through an unbroken chain of comparisons.

Trueness: closeness of a measurement to the average of a large set of measurements.

Uncertainty (of measurement): quantified doubt about the result of a measurement.

Validation: confirmation that some aspect of a measurement process is fit for purpose.

Further reading

Bell, S. (2001), Measurement Good Practice Guide No. 11 (Issue 2): A Beginner's Guide to Uncertainty of Measurement

BIPM (2006), The International System of Units (SI), Eighth Edition, (Paris: Organisation Intergouvernementale de la Convention du Mètre)

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Jerrard, H. G. & McNeill, D. B. (1992), A Dictionary of Scientific Units: including dimensionless numbers and scales (New York: Chapman and Hall.)

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Stout, K. J. (1998) From Cubit to Nanometre, a History of Precision Measurement (London: Penton Press)

Appendix: the science behind the units

Length, measured in metres

One way to establish a distance is to measure the time it takes for something to move, and divide that time into the speed* of the moving thing. It is simplest to use something which always travels at exactly the same speed under any conditions, because then no conditions have to be specified in the definition. Fortunately, there are things which have this property, including light (though only when it travels through a vacuum – it slows down a bit when it travels through matter). So, we can establish a distance by timing light's journey over that distance. Because light travels so fast (it could go round the Earth seven times a second) this is only useful for quite large distances.

To establish short distances, like the lengths of objects, an alternative approach is to compare the objects with the length of something else, providing that something else has an absolutely fixed length. Again, light is what is chosen here, since it travels in waves of particular lengths.

But, while light always travels (in a vacuum) at a single speed, it doesn't have a single wavelength – lights of different colours have waves of different lengths. However, light of precise and unchanging wavelength can be produced by atoms. Atoms each contain one or more electrons, and these electrons can only exist at one of a limited number of energy levels. If an electron receives energy from outside the atom – perhaps by absorbing some light – it jumps to a higher energy level. Later, it will fall back to its previous level again, releasing the energy as a tiny flash of light. Since the electrons only have certain fixed energy levels at which they can exist, that means that the amounts of energy they receive or release when they move between those levels are fixed too. For atoms, energy is like loose change is for humans – we can only get it or spend it in particular amounts, which must be multiples of one penny.

So, atoms can radiate light with a precise frequency and, since the frequency of light is what fixes its wavelength, this means these atoms can be used as sources of light with a known, reproducible wavelength. The wavelength of visible light is less than a thousandth of a millimetre and so by measuring how many wavelengths of light there are in a particular distance we can relate the distance to a multiple of the base SI unit.

Time, measured in seconds

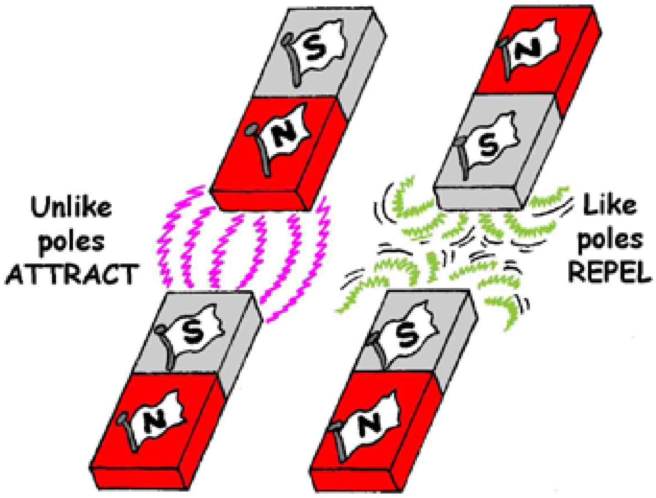
Time can be defined in terms of atoms too. Light waves are, in some ways, similar to water waves. If you float in the sea with waves going past you, you can see the shapes of those waves and, if you were a metrologist, you might very well try to measure their lengths (by measuring the distance between adjacent crests). You could also time how frequently you bob up and down as the waves pass you. You would find that the shorter the waves, the more frequently you bob – showing that shorter waves have higher frequencies. But what if you had no watch? If you knew the speed of the waves, you could, rather than measuring their frequency, calculate it: if the waves are one metre long and they are moving at one metre per second, their frequency must be one per second (i.e., one hertz).

Since the speed of light (in a vacuum) is constant, that means light of a particular wavelength always has a particular frequency, so metrologists can use the light from certain atoms to provide precise and unchanging frequency values. And frequencies can be used very simply to establish time units – in the water-wave example above, knowing that you bob up and down with a frequency of one bob per second means that one second is the duration of a single up-and-down bob (or 'period').

* Or, to be exact, the velocity, which is speed in a particular direction.

Current, measured in amperes

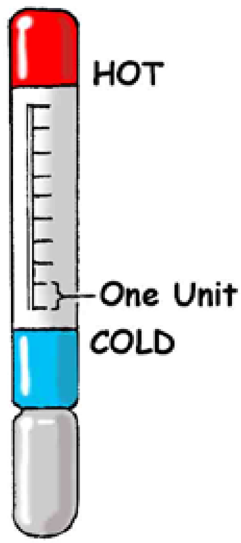
Two magnets will either pull or push on each other depending which way round they are:



Magnetic forces like this also appear whenever there is a flow (current) of electricity, an effect which is used to make the electromagnets that pick up old cars in scrap yards. The stronger the current, the stronger the force – so, by measuring the force it is possible to determine what the current must be. This is the basis of the definition of the ampere, the unit of current.

Temperature*, measured in kelvins

What we call temperature is usually actually the speed of molecules. The molecules of hot water move faster than those of cold water, and, if you put your hand in, some of the motion of the molecules will be transferred to the molecules of your skin, causing the sensation of warmth. Molecules never quite stop moving, but if they did, the temperature would be zero – at least, it would if it were measured on the kelvin scale (in the Celsius scale, it would be –273.15 °C). This not-quite-attainable temperature is known as absolute zero.



One might try to define the unit of temperature in terms of the motion of molecules directly but, as there are so many types of motion to consider, and they are so hard to measure, and the relationship between them and temperature is so complex, this would be a very difficult undertaking. A much simpler approach is to select two temperatures and divide the difference between them up into units.

Absolute zero is an obvious choice for the lower of these two temperatures, but choosing the other was more challenging. In the end, it was decided to use the properties of water.

Water, like many substances with which we are familiar, exists in three phases, or states: solid (ice), liquid (water), and gas (water vapour)**.

To change from one phase to another only needs a change of temperature, pressure or both. For instance, heating water to around 100 °C will make it boil, turning the liquid rapidly to water vapour, but if you reduce the air pressure, this process will happen at a lower temperature. (Which makes it hard to brew a really good pot of tea on a high mountain). So, there isn't

* Strictly, the quantity that the SI system refers to is called the thermodynamic temperature; this is the type of temperature that is associated with the large-scale objects, like cups of tea or air masses, that we are used to.

** Actually, there are more than three states of matter, another called plasma is when atoms are disintegrated into their component electrons and nuclei – this state is found in a fluorescent tubes and plasma TVs.

just one temperature at which water boils, but a whole range, which depend on the air pressure. At any of these temperature/pressure combinations, the liquid and gas phases of water will happily co-exist.

But, it is much less easy for all three forms of water to co-exist indefinitely – in fact, there is only one combination of temperature and pressure at which this occurs. This is called the triple point and, as it is unique, it provides a suitable upper temperature point for the temperature scale.

The only remaining issue is, how to divide the difference between those two points – absolute zero and the triple point of water – to define the temperature unit. Given that the SI system is so enthusiastic about the number 10, one might expect to divide the difference into 10^{ths} or perhaps 100^{ths}. In fact, it is divided by 273.16^{ths}, which makes the size of the resulting unit similar to the widely-used degree Celsius. This in turn means that it is easy to convert from one scale to the other: one simply has to subtract 273.16 from a temperature in kelvin to convert to the Celsius value.

Amount of substance, measured in moles

Atoms are composed of a tiny core containing protons and neutrons, surrounded by a (relatively) large volume occupied by one or more electrons. In a particular element, all the atoms have the same number of protons – the element carbon, for example, has 6 protons in every atom. Carbon comes in different types, called isotopes, each with a different number of neutrons. The carbon 12 isotope contains 6 neutrons.

All the atoms of carbon 12 in the Universe have exactly the same mass – so, if we have a particular mass of carbon 12 that means it must contain a particular number of atoms. The mass of carbon 12 that contains one mole of atoms is 12 grammes.

Luminous intensity, measured in candelas

Light can be thought of as a shower of particles called photons*, and bright lights are dazzling because of the energy these photon-showers supply to your retinas. By using a lens to increase the number of photons arriving each second, the light becomes even more dazzling. Technically, what is increasing here is the intensity of the light, which is the amount of energy that falls on a particular area of your retina per second.

Actually, it turns out that a more useful way to define intensity is in terms of ‘solid angle’ rather than square centimetres (think of a cone of light that starts at the light-bulb and ends at your eye: if the cone is stubby it has a large solid angle, if it is more pointed it has a small one).

The candela is unusual in that it refers not simply to a physical phenomenon, but to a human reaction to that phenomenon: it takes into account how the human eye perceives light. It does this by using what is known as a luminosity function, a standardised model of the sensitivity of the human eye. Involving human reactions in this way makes the value of the candela the least accurately known of all the base units.

* I know it says on page 32 that light travels in waves. 17th , 18th and 19th century physicists spent a lot of time trying to work out whether light is made of waves or particles, but 20th century ones decided it is really neither, but can behave like either, depending on how it is measured.