INTRODUCTION

> "When you can measure what you are speaking about, and express it in numbers, you know something about it.; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind.; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to Science, whatever the matter may be." *Sir William Thomson, Lord Kelvin*.

When I was studying science at school, then at university, I kept coming across laws and principles that were named after the scientists who first discovered or formulated them: Boyle's Law; Charles' law; Ohm's law; Newton's laws of motion; the Avogadro number; the Bernouilli effect. In fact science is littered with the names of scientists who have been immortalised by having a scientific law or principle named after them. At the time these meant nothing to me apart from a name. But on finishing my studies and passing my exams, I began to take a wider interest in these men and women who populated the history of science, and wanted to find out about the people themselves and their lives. I discovered that, more often than not, advances in science in former centuries were made by scientists and researchers working in cloistered isolation in their laboratories, rather than by large research teams. Each scientist built on the work of his predecessors. Not for nothing did Sir Isaac Newton famously declare in 1675: "If I have seen further it is by standing on the shoulders of giants." Initially, having specialised in atomic and nuclear physics during my degree studies, I read about the men and women who had founded the age of modern physics; who had explored the structure of the atom, split the atom, and built the first atomic bomb.

In the main, the names of these scientists are only familiar to those who are specialists in a particular scientific field. Then there are some scientists that are so famous that everyone has heard of them and knows a little bit about what they are famous for. Most people would not be hard-pressed to name Einstein as formulating the principle of relativity (though most would struggle to explain what that is), or Faraday as the father of electricity, or Newton as the 'inventor' of gravity.

Yet there are some scientists whose names are used in everyday speech by almost everybody, but about whom very little is known. More remarkably, probably most people are not even aware that the words that slip off the tongue so easily are in fact named after scientists, inventors and engineers. How many people who talk about a 12-volt car battery, or a 13-amp fuse, or a 3-kilowatt electric fire are aware of the scientists who gave these units of electricity their names - Alessandro Volta, André-Marie

Ampère and James Watt? And how many people who tune their radio sets to 93.5 Megahertz (BBC Radio 4, FM) know anything about Heinrich Hertz?

This book does contain some mathematical equations. But don't worry if you cannot follow them – they can be skipped over without spoiling the thread of each chapter. Stephen Hawking, when preparing his bestselling *A Brief History of Time*, was warned that each equation would reduce sales by half. I doubt whether that is actually true, but I make no apology for including equations, for in many cases these equations represent the culmination of a life's work of a scientist described in this book. Science is all about trying to find out how things work, trying to establish the rules that govern the behaviour of things, from steam engines to electric motors, from stars to atomic particles. Once a theory, or set of rules, has been produced, it is tested for its ability to predict new phenomena. If the prediction does not agree with the practice, the theory is modified. That is how science progresses.

Since the behaviour of things is expressed in terms of measurable quantities, i.e., numbers, the rules are the relationships between those quantities. And mathematics is the language for expressing relationships between numerical quantities. So when we define velocity as distance travelled per unit time (e.g., miles or kilometres per hour), we express this mathematically as $v = \frac{d}{t}$.

More often than not, a mathematical equation expresses the sheer elegance and simplicity of a theory. It is essentially a shorthand which uses symbols rather than words. For example, Newton's Law of Universal Gravitation can be stated as: 'the force exerted on a body by another body is proportional to the mass of each body and inversely proportional to the square of the distance between their centres of mass'. How much more elegant is the simple mathematical equation:

$$F = \frac{G m_1 m_2}{R^2}$$

I have attempted to put events in the lives of the scientists, and their discoveries and writings, into chronological order, for that best demonstrates the development of some of the key concepts and discoveries covered in this book. This has not always been possible, however, since often a theme seems to reoccur at intervals during a scientist's life, or it involves a number of scientists each contributing some fresh insight, and it seemed best to deal with that theme in one go.

Chapter 1 is a brief history of measurement, leading to the development of a coherent system of units and measurement known as the *Système International d'Unités* (abbreviated to SI). Commonly called the Metric System, it is used by scientists and most ordinary people the world over.

The people who developed the system deliberately adopted the convention of naming new units after eminent scientists, thereby ensuring that their contribution to science would be honoured for posterity. This chapter, then, provides the background for what follows, but may be skipped if desired without affecting the main thrust of the book.

Each subsequent chapter focuses on one particular scientist (or in some cases, more than one scientist), but is not intended to be a detailed account of that scientist's life – full biographies have been written for most, and are far more comprehensive than space in this book would ever allow. Rather, I have tried to draw out the main events in the subject's life and their major discoveries and contributions to scientific progress.

Each chapter is more or less self-contained, not relying substantially upon knowledge of the previous chapters. However, while the chapters can be read in any order, it will be best to read them through from first to last, as they follow a rough chronology of ideas.

It has proved a fascinating journey. What emerges is the story of the development of some of the key concepts in physical science – astronomy, electricity, magnetism, heat and temperature. It is the story of the quest for understanding the forces that bind the universe together and how that understanding has changed all our lives.

The main scientists and the units named after them

	Dates	*Unit*	*Quantity*	*Symbol*
Pascal	1623 – 1662	pascal	Pressure	Pa
Newton	1642 – 1727	newton	Force	N
Fahrenheit	1686 – 1736	degree Fahrenheit	Temperature	°F
Celsius	1701 – 1745	degree Celsius	Temperature	°C
Watt	1736 – 1819	watt	Power	W
Coulomb	1736 – 1806	coulomb	Electric charge	C
Volta	1745 – 1827	volt	Electromotive force	V
Ampère	1775 – 1836	ampere	Electric current	A
Ohm	1789 – 1854	ohm	Electrical resistance	Ω
Faraday	1791 – 1867	farad	Capacitance	F
Joule	1818 – 1889	joule	Energy	J
Kelvin	1824 – 1907	kelvin	Thermodynamic temperature	K
Maxwell	1831 – 1879	maxwell	Magnetic flux	Mx
Hertz	1857 – 1894	hertz	Frequency	Hz
Tesla	1856 – 1943	tesla	Magnetic flux density	T

1 – MEASURE FOR MEASURE

The History of Measurement

"Man is the measure of all things"- Protagoras, the great Sophist philosopher of the fifth century B.C. quoted by Plato in Theaetetus.

The basis of measurement

Measurement is fundamental even in the most rudimentary science. Indeed, measurement is fundamental to society and the economy. For to buy and sell with the assurance that one is not being cheated, a standard way is needed of measuring the quantity of goods being sold - whether by length, area, volume or weight. Indeed, in early Old Testament times, we read the exhortation to the people of Israel: "You shall do no wrong in judgement, in measures of length or weight or quantity. You shall have just balances, just weights…"[1] Today we take for granted the need for standard measurements, but it was certainly not the case in medieval times. There was such a confusion of units that, in 1215 AD, the Magna Carta declared "there shall be but one weight and one measure" for the realm.

But to go back to basics, what is measurement? We can define it as the means by which numbers can be assigned to different things so as to be able to compare them on the basis of some property common to all of them. This process implies some unit which, by being counted, defines the measure. Up to the early eighteenth century, only three fundamental properties were recognised: length, weight and time. These three had been the basis of measurement for thousands of years, and by combining them in different ways they could be extended to measure other quantities such as speed (length combined with time), area (length × length) and volume (length × length × length) as well as density (volume combined with weight).

The familiar imperial units of length – inches, feet, yards and miles – go back to ancient Roman times or earlier. They were based on anatomical measurements – parts of the human body. The foot is obvious. (But how many people have feet of exactly the same length?) The inch was the width of the thumb; its name derives from the Latin *uncia*, one twelfth, since it was one twelfth of a foot. (The English 'ounce' is also derived from the same Latin word.) The mile derives from *mille passuum*, or 'thousand paces', where a pace was two marching steps of 2.5 feet. Thus the Roman mile was equal to 5000 feet. There was also the fathom – the distance between the furthest fingertips of a man's outstretched arms, and the cubit

– the distance between the fingertip and the elbow. These measurements were depicted in Leonardo da Vinci's famous drawing of the Vitruvian man, based on the descriptions by the Roman architect Vitruvius.

However, we find that units of measure in antiquity developed to meet special cases rather than to provide a universal standard. Thus metrical systems were only valid in particular contexts, often defined by professions, such as that of the apothecary, farmer or architect. Also, the variation between different people's builds meant that units of length based on the human body varied from person to person. With the arrival of the Normans in Britain in 1066, and their new centralised regime, England needed standard definitions of weights and measures.

Over the centuries that followed, successive English kings attempted to standardise. According to legend, Henry I (who reigned from 1100 to 1135) decreed that the yard should be defined as the distance from the nose to the farthest fingertip of an arm extended to the side horizontally. King John in the Magna Carta called for standard measurements throughout the kingdom. At the end of thirteenth century King Edward I (who reigned from 1272 to1307) had a master yardstick made; it was known as the 'Iron Ulna' – *ulna* (meaning arm-bone) was the old name for yard. It was to be used as the standard throughout the land, and it defined a range of units of length. One ulna was defined as three feet, one foot as twelve inches, and one inch as three grains of barley laid end to end: "It is ordained that three grains of barley, dry and round, make an inch, twelve inches make a foot; three feet make an ulna…"[2] Over the years, the unit of three feet came to be known as the yard, from the Saxon word *gyard*, meaning straight stick or rod. Incidentally, the barleycorn was also used as the smallest unit of weight, so presumably any variation between different crops was slight.

Fig. 1.1 British Imperial standards mounted outside the main gates to the Greenwich Observatory, London, sometime before 1866

Standardisation was enforced by dispatching sets of standard weights and measures throughout the country to all major towns and cities, and by the eighteenth century, Britain was leading the way in standardisation when compared to other European nations. This was, of course, the height of the British Empire, when Britain dominated international trade, and standard weights and measures were essential.

When it came to measuring longer distances, it was more difficult; you cannot lay people (or even barleycorns) end to end to measure distances on a geographical scale! Rather, such distances tended to be measured in terms of travelling time. Thus we get expressions such as ‘a day’s journey’, or ‘an hour’s walk’ or ‘a ten-minute journey’. The preference for referring to long distances in terms of the time taken still forms part of our everyday language. It holds true even in scientific domains – witness the measure of cosmological distances in terms of the time taken for light to travel: the light-year (equal to 9,460,800,000,000 km) is the distance light travels in one year.

Which brings us to time. Until the seventeenth century, time was measured predominantly by observing the motion of the Earth, Sun and Moon. Describing theories developed 600 years earlier, Ptolemy (c150 AD), in his astronomical treatise known as the *Almagest*, explains:

> “They [the ancients] saw that the Sun, Moon and other stars were carried from the east to the west along circles which were always parallel to each other, that they began to rise up from below the Earth itself, as it were, gradually got up high, then kept on going round in a similar fashion and getting lower, until falling to the earth, so to speak, they vanished completely, then, after remaining invisible for some time, again rose afresh and set; and [they] saw that the periods of these [motions], and also the places of rising and setting, were on the whole fixed and the same.”[3]

The cosmic order thus defines three fundamental units: the day, the month and the year, which are the periods, respectively, of the Earth’s rotation about its own axis, the moon’s orbit around the Earth, and the Earth’s orbit around the sun. These periods so dominate human existence that they have been used for measuring time since prehistoric days. The year is, of course, based on the cycle of the seasons: spring, summer, autumn, winter, and the changing lengths of day and night, and is measured as the time from one winter solstice to the next. The basis of seasonal change is the fact that the Earth’s axis of rotation is inclined (at about 23º) to the axis of the Earth’s orbit around the sun. In the northern hemisphere, for example, summer occurs when the North Pole is tilted towards the sun during the months of June to August, and winter is when it is tilted away from the sun during the months of December, January and February. In the southern hemisphere, the opposite holds true.

When it comes to units of time such as hours and seconds, the story becomes more complex. The reason we divide a day into 24 hours is not at all obvious – it could just as easily have been divided into 10 or 20, for instance. It is thought that the division into 24 is based on the rising of significant stars or constellations during the night, which divided the period of the night into more or less twelve equal parts; daylight was also divided in the same way into twelve equal parts. Thus we get 24 hours in each day. This system is the ancestor of our current system of AM and PM, although in many parts of the world this has been superseded by the 24-hour clock. Actually the story is even more complicated, due to the fact that the length of daylight and night-time vary with the time of year. Well into the modern era, people used to divide daylight into twelve equal parts and night was likewise divided into twelve parts, resulting in hours that varied in length depending on the season. The resulting hours were known as ‘unequal’ or ‘seasonal’ hours!

Where, then, did the division of the hour into sixty minutes, and the subdivision of the minute into sixty seconds, arise? To answer this question, we have to go back to the ancient Babylonians, who are known for having given us the so-called ‘place-value notation’ of numbers. (This was far superior to the Roman number system, where a complex feat of arithmetic has to be performed to interpret the meaning of, say, MCMXVIII as 1000+900+10+5+3 = 1918!) When we write the decimal number 2359, the position of each numeral in the sequence tells us by how many powers of ten it should be raised. In this case, the number means 2×10^3 (i.e., 2 × 1000) plus 3×10^2 (i.e., 3 × 100) plus 5 × 10 plus 9 units. The Babylonians devised an earlier form of this number system using a base 60 rather than base 10, as in the decimal system. Thus 3469 in this system would mean 3×60^3 plus 4×60^2 plus 6 × 60 plus 9 units. Their choice of sixty as a base was most likely influenced by the observation that there were ‘360’ days in a year, and ‘30’ days in a month.

In case the reader should dismiss this base 60 system as arcane, we should note that base 60 number systems are in everyday use for minutes and seconds, not only for time but also for angular measure. In the latter, a circle is divided into 360 equal parts – degrees – which are in turn divided into 60 minutes, each having 60 seconds. For example, the map co-ordinate of 51º 28´ 38˝ (the latitude of Greenwich) means 38 seconds of arc, plus 28 × 60 of the same unit, plus 51×60^2. When our clock reads 8:15:55, this is telling us that the time is 55 seconds, plus 15 × 60 seconds, plus 8×60^2 seconds past midnight.

The measurement of time of day or night was, from the earliest days, by means of observing the altitude of the Sun or a star above the horizon. One of the most ingenious devices for telling the time was the astrolabe, which can be dated back to 150 BC. It consisted of a disc, often made of brass, with various pointers and dials representing the passage of the Sun, Moon and stars through the sky. By lining it up correctly, it was possible to determine the time of day or night, calculate the times of sunrise and sunset, and solve a whole host of other astronomical problems.

The most common way, however, of finding the time during the day has, for centuries, been to use a shadow-casting device, the sundial, consisting of a style (or gnomon) which casts a shadow on to a plane or curved surface. Lines marked out on the surface indicate the hours. According to Diogenes Laertius, in his *Lives of Eminent Philosophers*, the sundial was invented by Anaximander (611-546 BC). However, shadow-clocks appeared in ancient Egyptian astronomy in the 15th century BC, one thousand years earlier.

The measurement of the passage of time was not so obvious. From ancient times well into the seventeenth century, the water-clock or *klepshydra* (from the Greek, 'water thief') was the most common method of measuring time intervals. The change in water level inside the vessel is measured either as it rises, being filled by a steady flow from an outside source, or as it falls, due to water escaping steadily through a hole. The best-known interval-measuring device from the Middle Ages is the hour-glass or sand-glass. Both names are slight misnomers as, most often, these instruments neither measured hours, nor did they use sand! Usually it was powdered rock or, sometimes, crushed eggshells. Water-driven clocks had developed during the centuries by the addition of a mechanism to ring out the hour, and by the fourteenth century, weight-driven clocks appeared, where a set of falling weights was connected via gears to the dial. In the main, the mechanics of the large-scale tower clock remained unchanged for the next few centuries, the main improvements being more compact clockwork for domestic use, and the introduction of a coiled spring for the driving force.

Arguably the single most important advance in clock-making technology occurred in the mid seventeenth century with the invention of the pendulum as the time-keeping element by the Dutchman, Christiaan Huygens (1629-1695). Although Galileo had conceived the idea for a pendulum clock in 1641, and even drawn up a design for it, there is no evidence that he ever made it a practical reality. Huygens showed that the period of the pendulum that swings through a circular arc depends only on its length.*

But he realised that this only holds true for small angles of swing and where the pendulum consists of a mass suspended at the end of a (practically) weightless string. To make a perfectly equal swing, the pendulum actually needed to follow a 'cycloid' – the curve traced out by a point on the edge of a wheel as it rolls along the ground. He devised attachments to the pendulum's pivot that forced it to follow the correct

* Period $T = 2\pi\sqrt{(l/g)}$ where l is the length of the pendulum, g is gravitational acceleration (9.8 m/sec^2).

path, and attached a falling weight to keep the pendulum from coming to a halt through friction and air resistance. His design for the clock was completed in 1656, and clocks were first manufactured to this design in The Hague in 1657 by the clockmaker Solomon Coster. The mathematical basis for Huygens' pendulum clock was described in his book *Horologium Oscillatorium*, published in 1673. It was with Huygens' pendulum clock that the era of accurate time-keeping may be said to have begun.

This invention was the spring-board for a tremendous interest and rapid evolution in movement design, and swiftly led to the development of what proved to be the basis for modern mechanical clock design. In 1675, Huygens proposed adding a balance spring to the watch mechanism; this paved the way for a timekeeping device which was not only accurate but also portable. The significant increase in accuracy of these clocks meant that scientists could now make precision measurements of time, which proved a tremendous asset to all scientists, particularly astronomers.

This century has seen improvements in accuracy, by a factor of millions, in the measurement of time intervals. As early as 1928, two American scientists had created a clock driven by a quartz oscillator, but these only became a reality for the domestic user in the 1970s. Currently the most accurate device is the atomic clock (see later in this chapter). Scientists at the National Physical Laboratory in London and the Paris Observatory are working on ever more accurate devices, which it is hoped will measure time to an accuracy of 'one part in ten to the power of eighteen'. This equates to one second in 10 billion years, or approximately one second in the lifetime of the universe itself!

When it came to weight, there was no obvious natural standard. Earliest weights were based a grain of wheat or barley. For instance, the British pound was originally defined as the weight of 7000 grains. With 16 ounces to a pound each ounce was then equivalent to 437.5 grains.

The Origins of the Metric System

As civilisation progressed, technological and commercial requirements led to increased standardisation. Units were usually fixed by edict of local or national rulers and were subdivided and multiplied or otherwise arranged into systems of measurement. Despite local standardisation, there were considerable variations in units of weight between professions and between different countries. Until well into the nineteenth century the pound (or Pfund) in Germany had 12 ounces, whereas in Britain it had 16. Within the English units of measurement, there were three different systems of weights (avoirdupois, troy, and apothecaries'), of which the most widely used was (and still is, by many people in Britain and America for everyday use) the avoirdupois. The troy system (named after Troyes, in north-east France, a prosperous commercial town in the Middle Ages, noted for its annual fairs which used to set standards of weights and measures for all of Europe) was used only for precious metals. Apothecaries' weights were used in pharmacy and based on troy weights. In the troy and apothecaries’ systems there were 12 ounces in a pound, whereas the more familiar avoirdupois system has 16 ounces in a pound, 112 pounds in a hundredweight and 20 hundredweight in a ton.

Interestingly, the pre-decimal monetary system in Britain was based on troy weights, and the names of monetary units derived accordingly. The penny coin was one ‘pennyweight’ of silver. There were 240 pennyweights in one pound troy, so one pound of sterling silver gave rise to the unit of currency, one pound sterling.

Whereas by the eighteenth century Britain had standardised weights and measures using the imperial system, in France things were in chaos. One Englishman travelling through France just before the Revolution found that “the infinite perplexity of the measures exceeds all comprehension. They differ not only in every province, but in every district and almost every town.”[4] It was estimated that under the guise of 800 names, the *ancien regime* in France had a staggering total of around 250,000 different units of weights and measures. The whole system was absurdly complicated and confusing. For example, a given unit of length recognised in Paris was about 4% longer than that used in Bordeaux, 2% longer than that in Marseilles, and 2% shorter than the same unit of length in Lille!

It was this appalling state of affairs that had led to royal commissions being set up in the years preceding the French Revolution to consider how to establish a uniform system. The most frequent, and most obvious, suggestion was that the Paris standard of length (an iron bar mounted in the wall of Le Châtelet defined as one *toise* and divided into six *pieds*) be adopted as a standard throughout France.

However, in the previous century there had been several advocates of a universal unit of length. Inspired by the advances in science made during the seventeenth century, scientists pushed for ways of basing units of length on natural phenomena. After all, the measurement of time was based on the Earth’s rotation about its axis, so could length be based somehow on a fundamental property in nature? Two possibilities were proposed.

The first was based on the fact that the period of a simple pendulum’s swing depends only on its length, a fact utilised by Christiaan Huygens in 1657, as we have seen, for the first accurate pendulum clock. A pendulum 0.993 metres long takes just two seconds to complete one cycle of swinging, one second for the swing one way, and one second for the return swing. Such a pendulum is known as a ‘seconds pendulum’. Thus the unit of length could be the length of a seconds pendulum.