

Defining and Measuring Nature. The Make Of All Things. Second edition. By Jeffrey H. Williams. Institute of Physics Publishing, 2020. Price (hardcover) USD 50.00. ISBN 9780750331418. (Also available as ebook, 313 pp., price USD 40.00, ISBN 9780750331432.)

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This book is about units of measurement, which may seem like a dry and erudite topic. But not using commonly agreed units can cause catastrophic failure: in the Mars Climate Orbiter project, NASA used SI metric impulse units of newton seconds, while their contractor Lockheed Martin used pound-force seconds (see pages 125–127; page numbers refer to my Kindle for iPad copy). Units, then, are important. Let us also recall that the measurement of the fundamental constants of nature at ever better precision is important because we wish to know if the laws of physics are changing with time or not. The author is very well qualified to write on this whole topic. He was a professional experimental physicist who became Head of Publications and Communications at the Bureau International des Poids et Mesures, an organization whose mission is ensuring worldwide uniformity of measurements.

In the *Preface* we learn that the metric system was a proposal made in 1790 by Charles Maurice de Talleyrand Perigord in France. As the author delves into the history we learn that this ‘metric system’ was also proposed even earlier, by John Wilkins, and published by The Royal Society in 1668 (see page 51). Today this is known as the SI system of units, the *Système International (d’Unités)*.

The first chapter (zero) is entitled *Introduction: the origin of observation and measurement* and commences with the history from pre-BC China: the role of the heartbeat of about every one second being introduced in China (detailed in chapter 12). Chapter 1 is entitled *Measurement in antiquity*. It is a delightful description of the ancients grappling with measures of length (initially seeds), time (the lunar cycle in multiples of sunrise to sunrise, *i.e.* ‘the day’, with 365 days per solar cycle measured against the stars) and weight (based again on seeds and developed as a system by the Romans). Over 3000 years, the Chinese person’s foot nearly doubled in length, with a male foot and a female foot having their own units. The final section is on the Romans’ influence, with Julius Caesar introducing the leap year of 366 days. Also the pound weight is originally a Latin term, *libra pondo*. A preference for multiples of 12 appears, contrary to the previous emphasis of ten such as the Ten Commandments of the Bible and ten digits on our two hands.

Chapter 2 is on *Measurement in the early modern period*, defined as after the Romans and into the Middle Ages. This includes examples such as King Richard I’s iron rod standard length, distributed as copies to towns in England. A standardization of weights and measures was included in the law of Magna Carta in 1215. Tensions again surface (page 44) between imperial (based on 12) and metric systems (based on 10). By 1656 the first pendulum clock was built by Christian Huyghens, which led to the finding that the period of such a clock was different in French Guiana and Paris, explained by Newton as due to the Earth not being perfectly round. Accurate time keeping depended on the pendulum clock for 300 years until the quartz oscillator of the 1930s.

Chapters 3 and 4 are entitled *Measurement in the modern world (I and II)*. They focus on the themes of the attempts towards standardization between France, Great Britain and America and the measurements for a unit of length. They span the late 18th century and detail the surveying of the distance (1000 km) between Dunkirk and Barcelona, which took about seven years to complete. Section 3.7 describes the precision achieved of



about 4 m, only three times worse than modern GPS via our Earth satellites. We are reminded that France and Spain were at war during this time! There were also the major tensions of the French revolution and the poverty of the masses against the large budget for the metric survey. A glimpse of the strength of feeling is given on page 97: 'The Republic needs neither scientists nor chemists; the course of justice cannot be delayed.' The survey continued nevertheless and settled the size of the metre in 1798 as one 10 millionth of the Earth's quadrant (page 100). Also the weight of 10 cm³ of water was settled as a unit of weight. The interest of the new French Republic in decimal units applied also to 'time'. So for several years until 1795 time was divided into ten hours, including, of course, clocks; Fig. 4.1 shows a delightful time piece of the era divided into ten.

Chapter 5 is *Creating the language that is science*. We are taken back a hundred years in this chapter, to the role of Leibnitz (1646–1716) and 'finding a way to comprehend all of science . . . via base units'. This step back in time is logical as Leibnitz and others were wrestling with combining units to understand other quantities such as speed and acceleration. Table 5.1, page 123, lists the seven base units; length, mass, time, electric current, temperature, amount of a substance and intensity. The writing neatly shifts from history into tutorial mode here, explaining dimensional analysis, an important tool in physics to properly compare like with like.

Chapter 6 is *What was not in the original Metric System?* This to my mind is an odd title as it presupposes that John Wilkins in 1668 could have known all the base units of physics, just like that. But the chapter nicely explains energy and work done, even with an excursion into Einstein's $E = mc^2$, without needing a new base unit. This was not true, however, with electricity, which is a base unit with magnetism dependent on it. But a conundrum is subtly introduced; Faraday generated an electric current *from* a magnetic field. Then immediately there is a further conundrum; electromagnetic waves are light, and yet the seventh base unit is intensity, initially defined in terms of candela, candles. I offer the answer that the single unit electric charge is the more fundamental, whereas a single magnetic pole, a monopole, does not exist or rather has never been found.

Chapter 7 is entitled *Measurement in the age of scientific certainty*. This chapter considers how other countries, besides France, were coping with standards of measurement and their units, focusing on the early 19th century. An odd fact was that the British Weights and Measures Act of 1824 did not follow The Royal Society John Wilkins Report of 1668 but formally adopted yards, seconds and pounds weight. These 'imperial units' were already used anyway in British industry and, via its colonies, in many parts of the world. Nevertheless, Britain signed the International Metre Convention in 1884 and was duly presented with standard copies of the metre and kilogram. Concerns over the long-term stability of these copies led in May 2019 to the adoption of Quantum-SI without the need for such copies (artefacts). This momentous event thus led to the second edition of this book.

Chapter 8 is *A true universal language: the SI*. This chapter explores further the field of electromagnetism and then gives a

first description of the old SI and the Quantum-SI (Figures 8.1 and 8.2 neatly summarize these). The author evocatively captures the mood of the respective ages by comparing, for the unit of length, one quadrant of the Earth versus that calculated from the helium–neon laser's red light frequency and the speed of light.

Chapter 9 is *20th century confusions and refinements in measurement*. This chapter explores a number of issues such as different governments' adoption of the metric system, or avoidance of it, and the threats of the World Wars to the standard unit artefacts held in Paris (manufactured by Johnson Matthey in Britain, chapter 10) and their evacuation. The measurement refinement theme continues the narrative of earlier chapters.

Chapter 10 is *The birth of the Quantum-SI*. A new way forward to the Quantum-SI was needed because the mass of the international kilogram varied. By comparing the masses of six copies against the one held in Paris, changes of up to 60 µg were recorded between 1889 and 2014 (Figure 10.2). The 'creation of the Quantum-SI was to remove the need for artefacts' (page 205). The rest of the chapter describes the moves of the international bodies involved to evolve the SI and introduces the 'Kibble balance' apparatus, named after its inventor Bryan Kibble. It works via the Lorentz force and Faraday induction, balancing a given mass.

Chapters 11 and 12 are on *The base units of the Système International d'Unités (I and II)*. Table 11.1 compares the seven base units before and after 20 May 2019. This transition dispenses with artefacts held in a vault in Paris and instead introduces measurements which can be made anywhere in the world. The means for new units of length and mass were touched upon in earlier chapters (as above), and now also temperature is to be expressed in terms of Boltzmann's constant. This meant no longer relying on water of a defined isotopic composition. For the unit of luminosity, the candela, you will just have to buy the book to learn about the (truly bizarre) internationally agreed definition of a standard candle! Part II, focuses on the base unit of 'time'. This refers to the caesium clock but with the intrinsic difficulty that the atom of caesium involved must be at rest and at 0 K, impossible to achieve in practice. It concludes with describing efforts to realize a clock accurate to one second spanning the age of the universe. Such clocks would improve navigation precision with a Global Positioning System (GPS).

Chapter 13 is entitled *The new Système International d'Unités*. As the author states on pages 288–289, beginning a wrap up of his book, 'The new definitions seek to improve the new SI, without changing the value of any units, thereby ensuring continuity with existing measurements . . . This was the culmination of decades of research.' Indeed the CODATA Data Prize for 2018 was awarded to the CODATA Task Group 1 on Fundamental Constants in recognition of this outstanding achievement (<https://codata.org/events/codata-prize/codata-prize-2018-codata-task-group-on-fundamental-constants/>). On page 289 is also the delicious statement that the SI includes 'constants (with values) obtained by experiment' and thereby with a precision of constancy which we can therefore not be

certain of. Section 13.5 highlights the role of X-ray crystallography in the most precise determination of Avogadro's number. This needs an ultrapure silicon single crystal, both isotopically and with the fewest possible defects, originally developed for ever more dense computer memories and CPU.

Chapter 14 is entitled *For this is science*. This chapter takes a philosophical stance: 'scientists' questions drive the technology and so push the measurement horizon' (page 307).

In summary, I think this book is excellent, not least because it can be read by people from diverse educational back-

grounds. There is some repetition of key topics in places but I imagine that this is to allow for different levels of expertise of the readers, especially in their physics. Certainly I felt that my degree in physics allowed me to appreciate the fine details. One criticism is that I would have liked a subject and also a names index. That said, the contents' listing is very detailed. I recommend this book because it brings all of us to the coal face of our very being as an intelligent species, challenging us on how we measure and what it all means in so many different ways, from the practical to the philosophical. I congratulate the author.