The Dimensions of The Cosmos

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Preface

This book exists to address a problem most people don't recognize as a problem: understanding the magnitudes of the world around us. Humans have limited capacity to understand magnitudes intuitively. This problem is minimized in countries which adopted the metric system from the earliest days of its inception. However, the lack of numerical intuition is acute in the United States, one of only three countries on Earth* which does not officially use the metric system.

The proliferation of measurement units found in the US is often touted as a positive feature, rather than a confounding source of uncertainty. The US units for length include barleycorns (shoe sizes), inches (3 barleycorn), feet (36 barleycorn or 12 inches), yards (108 barleycorns, or 36 inches, or 3 feet), rods (surveying), chains (roadwork, surveying), miles (two versions) and leagues.

For weight there are two types of pounds, Avoirdupois and Troy, with 16 ounces in the former and 12 ounces in the latter. The Avoirdupois pound has an equivalent weight of 7000 (wheat) grains. Aspirin in the US is still often sold in 5 grain tablets. The troy pound has 5760 grains.

In the case of volume, the US has gills, pottles, pints, quarts, and gallons, with all their interrelationships. These Old English versions of weights and measures are different from the imperial variant used by the English, who are now metric and have given up almost all their pre-metric measures.

When one is allowed to choose from such a large number of measurement units, it only dilutes an understanding of magnitudes. In the pre-metric world, one chooses a unit, from the large number available, which is close the dimension to be measured, rather than having a fixed measurement system, which measures the object in relation to it. The original version of the metric system decreased the number of measurement units considerably, but

*United States, Liberia and Myanmar

because it was a product of its time, superfluous metric prefixes were introduced. The founders of the metric system could not completely escape the human impulse to embrace familiar complication over unfamiliar simplicity. More recent adopters of the metric system, such as Australia, have introduced considerable simplification. When the streamlined version of the metric system is used, the orderly grouping (in 1000's) produces a measurement continuum which offers a much more intuitive grasp of the magnitudes of our universe.

The modern metric system allows everyday people to use simple numbers for all their common tasks, instead of complicated fractions or less complicated decimals. It allows a person to grasp the measures of the everyday world in a streamlined manner, and efficiently tame and categorize numbers too large for humans to comprehend directly.

There has been no monograph produced for the general public, journalists, engineers, and scientists detailing the best usage of the metric system for expressing magnitudes. This work attempts to remedy this absence and provide entertaining vignettes.

The first chapter introduces the reader to the most streamlined and intuitive usage of the metric system. The following chapters are each divided into "metric worlds," each of which correspond to a metric prefix. I've provided tables of useful dimensional examples to be used as references for journalistic work, scientific work, student papers, and so on. This book may be read from beginning to end or if the reader prefers, read at random for pleasure. It is intended to be of use as a reference for writers and the general public.

The current expression of numbers in the US media is a tangled web of antique units, both metric, US pre-metric, and imperial. In general, periodicals appear to have no measurement policy, whereas a policy on English usage is considered of considerable gravitas. The eloquent expression of numbers is as important as polished prose. Understanding the amount of carbon entering our atmosphere each year with a clear numerical context is of paramount importance to an informed public. Often a concatenation of the premetric terms millions, billions, trillions, et cetera, are stacked onto metric values to produce narrative impact, at the expense of numerical context and understanding. What follows is meant as a guide for providing order, context and clarity when expressing numerical information.

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Chapter 1

The Metric System

The world of modern engineering and science expanded the range of human understanding from the microscopic to the macroscopic. There are no pre-metric measures of an appropriate magnitude that can describe the length of a virus, because before the invention of the microscope, it was unimaginable there was a world smaller than a poppy seed. There are no pre-metric (before 1795) measurement units to describe the size of astronomical quantities, as they were produced in a world before the invention of the telescope. Astronomical observations were limited to what one could see with the human eye. The stars were thought to be attached to a celestial sphere, which was the outermost of at least twenty-six nested spheres. The celestial model developed by the astronomer Claudius Ptolemy (90–168) estimated the distance to the stars as approximately 20 000 times the radius of the Earth. This is about 128 000 000 000 meters, or 128 Gigameters, which is miniscule when compared with the known universe.

Robert Hooke (1635–1703) witnessed the intellectual transformation created by the telescope and the microscope. In his classic work, *Micrographia*, published in 1665, he stated that the limitations of our senses could be corrected by:

> a supplying of their infirmities with *Instruments*, and, as it were, the adding of *artificial Organs* to the *natural* . . . By the means of *Telescopes*, there is nothing so *far distant*

> but may be represented to our view; and by the help of *Microscopes*, there is nothing so *small* as to escape our inquiry; hence there is a new visible World discovered to the understanding.

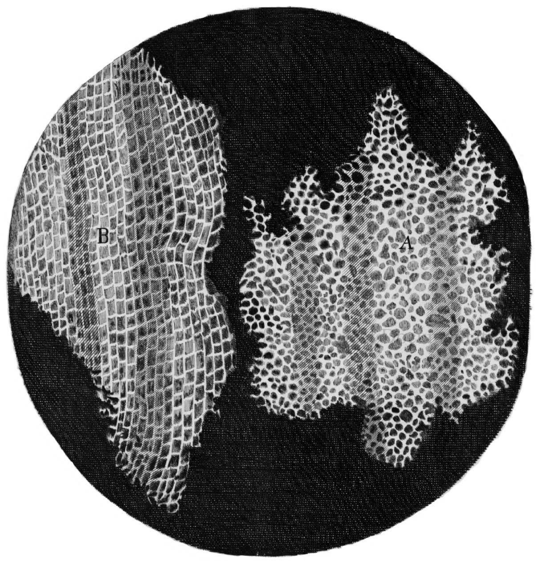

Figure 1.1: The illustration of cork from Robert Hooke's *Micrographia* where he first described the small openings he saw as cells.

When examining a slice of cork with a microscope, Hooke noted irregular pores or cells, see Figure 1.1. This was the first observation of plant cell walls in the tissue of cork, and by extension the existence of plant cells. Hooke called the small enclosures cells because they reminded him of the cells in a monastery where monks resided. As Hooke and others began to examine this new microscopic world, they found themselves using objects of everyday dimension* to describe it. Forests, fibers, ropes, whiskers and other macroscopic objects became metaphors for this new found world below the scale of the everyday one.

*The word dimension is from a Latin word that means "to measure out."

Anton van Leeuwenhoek (1632–1723) used small single lens microscopes of his own construction to study this new world. In 1677, he was the first to discover one-celled animals, which are now known as *protozoa*. He called them "little animals." Leeuwenhoek estimated these living entities to be more than ten thousand times smaller than: "the animalcule .... called by the name of Water-flea or Waterlouse, which you can see alive and moving in water with the bare eye." Leeuwenhoek used a very small creature as a dimensional reference, because he was describing an object which outstripped the existing measurement units. An entire miniature world of new creatures with structures as nuanced as those found at human scale revealed itself. Leeuwenhoek discovered the existence of tiny insects, which nourished themselves on fleas. This lead to the proverbial notion of a "flea on a flea on a flea" which was originally expounded by Johnathan Swift (1667–1745).

Remarkably, in 1683, Leeuwenhoek is thought to have described microscopic forms which were almost certainly bacteria. Objects of this dimension were at the limit of the resolution of his lenses, and it would be over a century before others would again see and describe bacteria. Bacteria are on the order of 1 micrometer (1 μm) in extent. The smallest unit of length in the British Imperial system is the poppyseed, which is 2117 micrometers. The poppyseed, the smallest unit of measure available, is two thousand one hundred and seventeen times larger than the bacteria Leeuwenhoek viewed with his microscope. The smallest unit of measurement then available is completely inadequate to describe the bacterial world. Leeuwenhoek would resort to imprecise dimensional descriptions such as "eight times smaller than the eye of a Louse,". A grain of sand was also employed as a measurement touchstone. Leeuwenhoek estimated a course grain of sand to be about 847 micrometers.[†] He was the first to see individual red blood cells with his microscope. Leeuwenhoek used 100 red blood cells to estimate their size at around 8.5 micrometers[‡], which is

[†] 1/30 of an inch
[‡] 1/3000 of an inch

very close to the modern value of about 7.7 micrometers.[1]

It was Italian entomologist Agostino Bassi (1773–1856) who first suggested, and even demonstrated, animalcules (microorganisms) might be responsible for some diseases. The silkworm industry in Italy was under assault from a disease called *muscardine*, which would later be identified as a fungus. Bassi asserted microorganisms were not only the cause of diseases found in insect populations, but also those found in humans and animals. Bassi offered guidance for controlling the disease, which is credited for saving the Italian silkworm industry from ruin. Louis Pasteur (1822–1895) expanded on Bassi's work and was greatly influenced by it.

The idea that animalcules could be the cause of disease circulated as early as 1725, but remained marginalized for well over a century.[2] The microscope revealed the most ubiquitous and diverse life form on planet Earth, microorganisms. Until that time, they remained invisible, yet existed everywhere in the Earth's biosphere. It would not be the microscope, and the newly discovered world of the miniature which would generate controversy, but the telescope, and the newly revealed realm of the macroscopic.

The heavens were thought to be unchangeable and perfect, but in 1572 a new star appeared in the night sky, which challenged this ancient conception. Astronomer, astrologer and alchemist Tycho Brahe (1546–1601) noted this was a new star which had no previous record of observation.

In October of 1604, there was a second challenge to the ancient notion of a fixed and unchanging heavens, and it didn't require a telescope for observation either. It was visible to the unaided eye. This new star was noted by many, including mathematician, astronomer, and astrologer Johannes Kepler (1571–1630).

Both new stars were supernovas. The stars were not truly new. They were previously invisible to the naked-eye, and only the brightness of their explosions revealed their presence. The supernova of 1604 was spectacular. Brighter than any star in the night sky, and at its maximum brightness, was visible during the day for more than three weeks. Kepler's Supernova took place about 189 Exameters from Earth. Our galaxy has a maximum extent of around 1000 Exameters, (or about one Zettameter).

Before the telescope, astronomical observers like Tycho used their unaided eyes, with help from basic geometrical instruments, to study the night sky—but that would soon change.

Galileo Galilei (1564–1642) visited Venice in May of 1609. There he heard about a Dutchman who had invented a device which made far-away objects appear to be much nearer. It was called a "Dutch perspective glass." Today we know it as a telescope, but that word wasn't coined until a few years later. Galileo fit two 42 millimeter diameter lenses into the opposite ends of a lead tube, and found it magnified distant objects by a factor of approximately three. Galileo experimented with the design until he had achieved a magnification of about thirty-three. It was at this point, he used his new device to peer at the moon.[§] When he did so, he saw mountains, craters, and areas with smooth surfaces. Watercolor drawings of what Galileo saw are shown in Figure 1.2. This observation went against the 2000 year old notion of the Moon as an object of perfection, consisting of a substance unlike any found on Earth. There were no predisposed ideas about the microscopic world, but many had been formulated about the macroscopic.

When Galileo used his telescope to observe stars, they remained points of light, and did not reveal themselves as discs, which some saw as evidence for their being located at a very large distance. The magnifying effect of the telescope concentrated light, and because of this, it revealed stars which are invisible to

[§]British astronomer, mathematician and ethnographer Thomas Harriot (1560–1621) focused his attention on astronomy after viewing Halley's Comet in 1607. He used a telescope to view the Moon on July 26, 1609. On that evening, Harriot made drawings of the Moon's surface, and became the first astronomer to make a drawing of a celestial body using a telescope. This was about four months before Galileo made his drawings. In 1610 he also noticed sunspots. Harriot's work was not published in his lifetime, and was lost to history until recent times. In 1970 a crater on the moon was named for him.

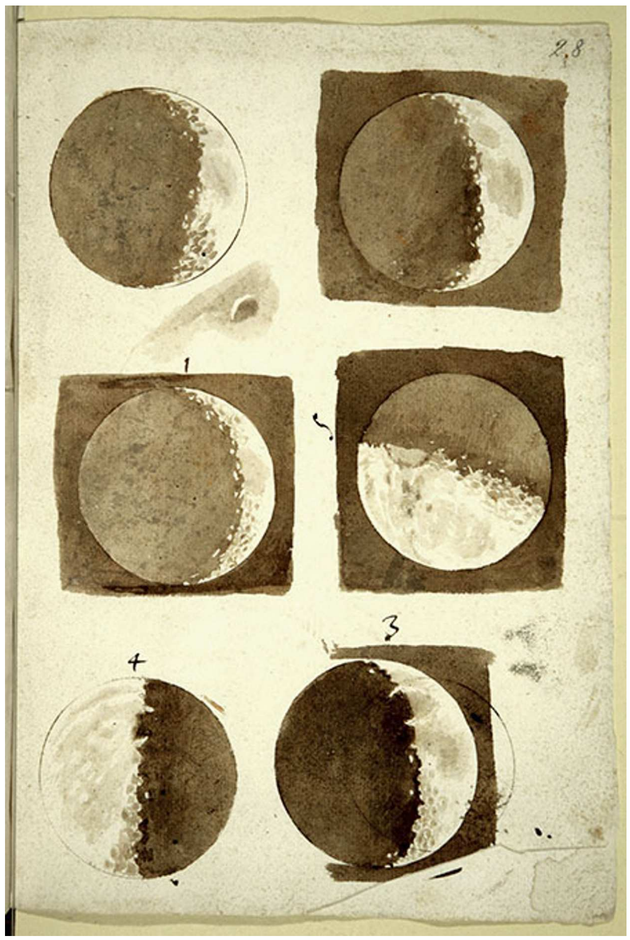

Figure 1.2: Galileo's watercolor images of the moon (1609)

the unaided eye. When viewed through Galileo's telescope, the glowing fog of the Milky Way became a countless tapestry of individual stars. The known planets sharpened into discs when viewed with the new optical device. Could it be there were a "plurality of worlds" and the stars might be other suns?

When Galileo observed Jupiter on January 7th of 1610, he noted three glinting dots of light near the planet. Almost a week later, a fourth sparkle of light appeared. The new objects were given the name satellites. When Galileo published his observations that year, it generated a Mega-brouhaha. German astronomer Simon Marius (1570–1624) used a Dutch telescope to confirm (and claim priority over) Galileo's discovery, which punctuated the controversy.

When the telescope revealed dark spots on the Sun, this was more than the orthodox authorities of the time could tolerate, especially after Galileo published a work which was clearly in favor of the Copernican view of the solar system. It was not the size of the universe which precipitated the reaction, but its content. The observations made with the telescope did not directly challenge the orthodox dimensions of the sky at the time, only its aesthetics. It would not be until the 19th century, with the measurement of stellar parallax, that the astonishing dimensions of the universe would begin to take shape. The scientific importance of the telescope and the microscope are memorialized in our evening sky. The constellations Microscopium and Telescopium are Latin words which respectively mean microscope and telescope in English.

The largest traditional British unit is the league, which is generally defined as approximately three miles or 5.6 Kilometers.[¶] The distance from the Sun to Neptune is 4503 Gigameters (4 503 000 000 Kilometers). The development of the microscope

[¶]The Jules Verne novel *20,000 Leagues Under the Sea* refers to the distance traveled by the group, and not depth below the surface of the sea. The book actually employes a metric league, defined as 4 Kilometers. The total distance traveled is thus 80 000 Kilometers. The circumference of the Earth is very close to 40 000 Km so the crew went around the Earth an equivalent of two times.

and telescope in the sixteenth and seventeenth centuries expanded the known world by factors which were not easily described using pre-metric units. The only way to understand the extent of our modern world in a succinct, compact and intuitive manner, is to use the modern metric system, also known as The International System of Units or "SI."

The pre-metric world possessed an almost uncountable number of measurement units, which were impossible to master in their entirety. No letter of the alphabet is spared. There were almuds and arpents, batmans and bozzles, caldrons and coombs, diras and dorons, ells and eimers, firkins and fardos, gabs and gantas, hellers and hemias, immis and issarons, jeribs and jitros, kalvars and kandys, lamberts and leas, mahuds and manos, nagels and noggins, occas and oggas, packens and pagodas, quadras and quartos, ratals and rattels, sacs and sagas, tablas and talents, uggas and unglees, varas and vers, wakeas and wangs, xestes and xiches, yings and yots, as well as zarfs and zayoots.

Science writer Isaac Asimov (1920–1992) wrote about engineering and scientific subjects which ranged from the smallest to the largest of dimensions. He also wrote about the need for the metric system, and lamented its absence in the United States. Dr. Asimov noted in his 1962 essay *Pre-Fixing It Up*:[1]

> All other sets of measurements with which I am acquainted use separate names for each unit involving a particular type of quantity. In distance, we ourselves have miles, feet, inches, rods, furlongs, and so on. In volume, we have pecks, bushels, pints, drams. In weight, we have ounces, pounds, tons, grains. It is like the Eskimos, who are supposed to have I don't know how many words for snow, a different word for it when it is falling or when it is lying there, when it is loose or packed, wet or dry, new-fallen or old-fallen, and so on.
>
> We ourselves see the advantage in using adjective-noun combinations. We then have the noun as a general term for all kinds of snow and the adjective describing the specific variety: wet snow, dry snow, hard snow, soft snow, and so

> on. Whats the advantage? First we see a generalization we did not see before. Second, we can use the same adjectives for other nouns, so that we can have hard rock, hard bread, hard heart, and consequently see a new generalization, that of hardness.
>
> The metric system is the only system of measurement which, to my knowledge, has advanced to this stage.

The metric prefixes themselves provide an intuitive set of relative magnitudes, expressed in literary form. A word expression in metric is immediately translatable into an exact numerical equivalent. The value one hundred twenty four micrometers or forty five point three Megameters can be immediately translated into 124 x 10^{-6} meters or 45.3 x 10^{6} meters seamlessly.

I've devoted much of my life to reading books written by Isaac Asimov. They have enriched my life and were always engaging. I would immediately purchase each new book he wrote, and devour its contents. It seemed it was not possible for Dr. Asimov to write a less-than-perfect book, but there was one published in 1983 I did not use my meager funds to purchase. The book is *The Measure of the Universe*, and it examines the world from the microscopic to the macroscopic. Many years later I wondered if I had been too quick to judge this book, and purchased a copy.

Dr. Asimov's book uses the idea of a ladder, as a metaphor, with steps to describe each change of dimension. He labeled each section STEP 1, STEP 2 and so on, with metric values below each of these rubrics for reference. Asimov used magnitude steps which are the square root of two to divide up the magnitudes of our universe. This produces a disjointed perception of the size steps and unnecessarily multiplies their number. In turn, this proliferation acts to decrease an intuitive understanding of magnitude. Asimov decided to use the "re" spellings of metre and litre, rather than the Americanized versions, meter and liter. While the former are the accepted spellings for SI, the latter are more psychologically palatable for Americans.

Asimov's book embraces many useful SI practices, but is a singular work, as he only employs them within it, and does not adopt modern metric usage for the rest of his writing.[†] The most important SI style change he embraced, may well be the use of thin spaces instead of commas for parsing numbers in triads. In other words, a number like 100,000,000 would be written in this manner: 100 000 000, without commas. This seems like a rather small, and unimportant change, but when one fully embraces the metric system, it encourages the eye to automatically separate the sets of zeros, and they may easily be "counted out" in triads, and assigned an appropriate metric prefix.[‡] The largest number associated with a current metric prefix is:

1 000 000 000 000 000 000 000 000

When the eight magnifying metric prefixes are memorized, and become a part of everyday life, each group of three zeros immediately has an assigned meaning:

$$1\ \underbrace{000}_{\text{Yotta}}\ \underbrace{000}_{\text{Zetta}}\ \underbrace{000}_{\text{Exa}}\ \underbrace{000}_{\text{Peta}}\ \underbrace{000}_{\text{Tera}}\ \underbrace{000}_{\text{Giga}}\ \underbrace{000}_{\text{Mega}}\ \underbrace{000}_{\text{Kilo}}$$

Each word prefix has a single letter symbol associated with it, which makes the metric system even more symbolically compact for expressing magnitudes:

$$1\,\underbrace{000}_{\text{Y}}\,\underbrace{000}_{\text{Z}}\,\underbrace{000}_{\text{E}}\,\underbrace{000}_{\text{P}}\,\underbrace{000}_{\text{T}}\,\underbrace{000}_{\text{G}}\,\underbrace{000}_{\text{M}}\,\underbrace{000}_{\text{K}}$$

Each of these metric prefixes are used to magnify the set of metric system base units. The base unit of length in the metric

[†] The singular exception to this is his book *The Ends of the Earth*. It uses metric exclusively throughout, but not thinspace triad separators.

[‡] At the time of the creation of the metric system in France, financiers and businessmen were increasingly separating whole numbers in sets of three with commas between. This made them easier to read. The triad grouping was adopted, but the comma was thought to be inelegant and confusing. Laplace and Lagrange stated: "..., it is hoped that the use of a comma to separate groups of thousands will be abandoned, or that other means be used for this purpose." Other means were adopted, which is the small space between groups of thousands.

system is the meter. A Kilometer is 1000 meters, a Megameter is 1 000 000 meters, a Gigameter is 1 000 000 000 meters and so on.

It is important to note the prefixes become applicable after the first digit to the left of the each triad brace appears. In other words The first three zeros may are interpreted as Kilo only when one or more digits appear to the left of the first three placeholders (zeros in this case). This is true for the next three digits which represent Mega and so on. For instance the number 123 456 meters, when expressed in Kilometers becomes:

$$\overbrace{123}^{\text{Integer Part}} \quad . \leftarrow \text{(decimal separator)} \quad \underbrace{456}_{\text{decimal Part}} \quad \text{Km}$$

or 123.456 Kilometers. The last three digits inform us the first three digits should have the prefix Kilo. The decimal separator tells us the last three digits are the decimal part of the decimal notation.

The speed of light in a vacuum is 299 792 458 meters per second. We see the 299 792 is the integer part if we wrote this number in Kilometers/second, but we have another three digits, which can move us to the next prefix. The integer part for expressing the value in Megameters is 299, and as there are no more digits to the left we can settle on Mega for a prefix. Therefore we can write this value as 299.792 458 Mm/s. It is an interesting metric coincidence that for most engineering work (and much scientific work) the speed of light is approximated as 300 000 000 meters per second. This can be written as 300 000 Kilometers per second or 300 Megameters per second. The most compact form is 300 Mm/s or 300 x 10^6 meters per second. We will see how rounding and expressing metric values as whole integers has great utility for comparing the magnitudes of numbers.

The original metric system was instituted in 1795, and had only three magnifying prefixes: deca, hecto and kilo. These increasingly magnified a base unit by factors of ten. A decameter is 10 meters,

VALUES OF UNITS.

UNIT OF LENGTH.

Myriametre..........	10,000	Metres.	
Kilometre...........	1,000	"	
Hectometre..........	100	"	
Decametre..........	10	"	
Metre..............	1	"	
Decimetre...........	0.1	"	or $\frac{1}{10}$ of a metre.
Centimetre...........	0.01	"	" $\frac{1}{100}$ " "
Millimetre...........	0.001	"	" $\frac{1}{1000}$ " "

The Metre is equal to 3.280899 feet nearly; or to 39.37079 inches.

The unit of Itinerary measure is the Kilometre, which is equal to 0.62138 miles.

Figure 1.3: Metric system table from *The Metric System of Weights and Measures* (1872)

a hectometer is 100 meters, and a Kilometer is 1000 meters. This choice reflected the dimensions experienced by ordinary people in the late 18th century. A spacing of ten between prefixes *appeared* to be of utility and, when compared with the cacophony of existing units, greater simplicity.

The word million was not invented until 1300. Prior to this time, the largest number in general use was the myriad, which was Greek for 10 000. When Archimedes expressed his calculation for the number of poppy seeds in the universe, he resorted to using myriads and myriads for the result. When Galileo first looked at the night sky with a telescope, he suddenly saw a large number of stars invisible to the unaided eye. He used the vernacular of the day to describe what he had found: "stars in myriads, which have never been seen before," . . . "and which surpass the old, previously known stars in number more than ten times." [3] The early metric system included the prefix myria, which was used to create a myriameter (10 000 meters). Figure 1.3 is a table reproduced from an 1872 monograph by Fredrick A.P. Barnard (1809-1889) which illustrates the metric prefixes as envisioned in the 19th century. Factors of ten were thought to be the best choice at that time. When Isaac Asimov wrote *The Measure of The Universe* in

1983, the magnifying prefixes Mega, Giga, Tera, Peta and Exa had been added (all in increments of 1000). Not until 1991 were Zetta and Yotta adopted as further magnifying prefixes for use with the metric system.

In 1795, there were only three reducing prefixes defined by the metric system: deci, centi and milli. They reduced base units by a factor of ten each. A decimeter is 0.1 meter, a centimeter is 0.01 meter, and a millimeter is 0.001 meter. Again a choice of ten was implemented, and the smallest dimension, a millimeter, is smaller than a barleycorn, and encompassed a magnitude that people of the 18th century could directly experience with their eyes. This choice of ten for the magnifying and reducing prefixes would prove to be an anthropocentric complicating factor in the later development of the metric system. This anthropocentric allure lead the originators of the metric system to include primitive atavistic prefixes based on two. Here is a translation of the original section of the 1795 French metric decree defining the prefixes double and demi:

> 8. In weights and measures of volume, each of the decimal measures of these two types shall have its double and its half, in order to give every desirable facility to the sale of divers items; therefore, there shall be double liter and demiliter, double hectogram and demihectogram, and so on with the others.

The use of these halving and doubling prefixes was still in play into the late 19th century. This is seen in Figure 1.4 The figure is from a book published by the American Metric Bureau in 1877. We see double and demi used throughout the illustration. There are double and demi deciliters, double and demi centiliters, double and demi hectograms. When defined in terms of milliliters the quantities become obvious integer values: Double Deciliter (200 mL), Deciliter (100 mL), Demi-Deciliter (50 mL), Double Centiliter (20 mL) and Centiliter (10 mL). Thankfully, these prefixes were purged from metric usage.

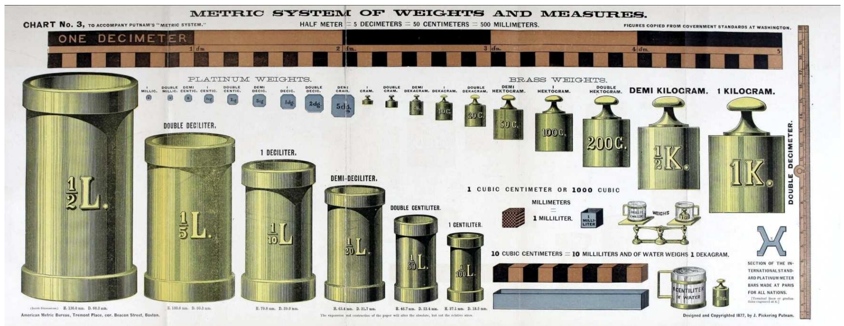

Figure 1.4: *The Metric System of Weights and Measures* J. Pickering Putnam, American Metric Bureau, 1877.

In 1983, there were five more metric reducing prefixes, which Dr. Asimov used in his book *The Measure of the Universe*: micro, nano, pico, femto, and atto. In 1991, zepto and yocto were added to the reducing prefixes.

When a new system is invented, it takes time to realize how to best use it in the most efficient and intuitive manner possible. Prefixes above Kilo and below milli were added using factors of 1000, not 10. It was gradually realized, the ten-based prefixes were not very useful, encouraged the introduction of errors, and could be set aside.[4] These prefixes only reflected a perceived need for units corresponding to earlier pre-metric ones, but in practice were found to unnecessarily complicate metric measurement usage. This set of four prefixes: centi, deci, deca, and hecto are *atavistic* prefixes. The adjective atavistic, implies something is a throwback, or exhibits primitivism.

The atavistic prefixes have slowly been purged from general usage. Researchers don't use centiliters or hectoliters in medical research, the milliliter is an effective and simple unit for expressing volume. Why this is the case will be explained later. The deca prefix is the only accepted metric prefix which has a *two letter* prefix symbol (da). Ten decaliters is written as 10 daL, and is the odd-person out in the world of metric prefixes. Here we will not use the atavistic prefixes.

The desire to retain the centimeter is often voiced with visceral passion by many people. They cannot imagine the world without it. The centimeter has slowly been understood to not only be unnecessary, but also causes confusion and complication for those who use it. Isaac Asimov had this to say about the matter in his 1983 work on measurement:

> The prefix "centi" (SEN-tih), symbolized as "c," represents a hundredth of a basic unit, from the Latin "centum" meaning "hundred." A "centimetre," therefore, is a hundredth of a metre. The prefix is not commonly used, except in "centimetre," and its use is falling off even there. [7]

The reason for this retreat from centimeters, is that for most practical everyday purposes, millimeters allow people to use integers without the need for any decimal arithmetic. In other words, one can use simple whole numbers to describe lengths without the need for a decimal point.

In Australia, and the UK, building plans are dimensioned using only millimeters as their small metric unit. Centimeters are strictly *not allowed* for use in Australia's building code.[§] This strikes most people in the United States as untenable, and possibly worthy of ridicule, but it actually simplifies the drawings. A doorway can be written as 800 millimeters without a decimal point. The distance between studs is 600 millimeters. Six hundred was chosen because it can be divided evenly by 24 different numbers: 1, 2, 3, 4, 5, 6, 8, 10, 12, 15, 20, 24, 25, 30, 40, 50, 60, 75, 100, 120, 150, 200, 300 and 600.

The numbers used to construct a metric house are all *simple* numbers with whole number (integer) values. A millimeter is also small enough, any construction actually done to this dimension

[§]A more complete list of countries which use the millimeter as their unit for construction: Australia, Bangladesh, Botswana, Cameroon, India, Kenya, Mauritius, New Zealand, Pakistan, South Africa, United Kingdom, and Zimbabwe. The neglected United States metric building code also calls for millimeters only, eschewing centimeters.

is also very accurate. It has been estimated Australian construction costs are about 10–15% less than those associated with US construction because we do not use the metric system.

It was discovered that using centimeters for construction leads to the excessive use of decimal points in computations. This in turn produces dimensional errors, which translate into scrap and waste. When a window is 820 millimeters, it is a simple integer value and uses three symbols: eight, two and zero to represent the distance. When expressed as centimeters, it is 82.0 centimeters. The centimeter expression requires four symbols: eight, two, decimal point, and zero for the *same* exact distance. Any arithmetic involving centimeters introduces a decimal point, which shifts around, providing an extra opportunity for error. The introduction of a decimal point also requires more cognitive recognition.

Accepted international metric building codes specify the centimeter is not to be used in any way. It is not to be written down, and no calculations are to be made with centimeters—period. Square meters are allowed for the area of a roof, and if you have a long enough driveway, Kilometers may be used to describe its length.

Isaac Asimov also understood this trend. In 1983 he wrote:

> The prefix "milli" (MIL-ih), from the Latin "mille," meaning "thousand," is symbolized as "m," just as "metre" is. A millimetre is therefore symbolized as "mm." Increasingly "milli-" is replacing "centi-" and "deci-" in use. We are approaching the point where 1 centimetre will routinely be referred to as 10 millimetres, and 1 decimetre as 100 millimetres. This is even more true where these prefixes are used for any basic measure other than "metre." [8]

Mathematician Carl Friedrich Gauss (1777-1855) was an enthusiastic promoter of the metric system. He used the second as defined by astronomers for time, and the millimeter for his metric unit of length. According to the SI Brochure, in 1832:

> Gauss was the first to make *absolute* measurements of the Earth's magnetic field in terms of a decimal sys-

> tem based on *three mechanical units* millimetre, gram, and second for, respectively the quantities length, mass and time.[9]

When Australia underwent its metric switchover in the 1970s, the people there took away four main lessons from their experience.¶

The first lesson is that one should not allow the use of dual scale instruments. In other words, all rulers need to be graduated with millimeters only. Rulers should not have inches on one side and millimeters on the other. The availability of the old units of measurement allows people to continue with their old ways, and ignore metric. This book will not make comparisons using pre-metric units, which are still ubiquitous in the United States. The best way to understand metric sizes is to use metric sizes alone. There will of course be comparisons using familiar objects like coins, golf balls, or houses.

The second lesson learned was whenever possible, a person should use metric units which produce simple whole numbers. The use of millimeters by the Australian construction industry allows them to do their work entirely without decimal points. When milliliters are used for volume, they also produce whole number values for cooking, mixing chemicals, or household products. One will see a recipe with 100 milliliters of milk, but never need one with 100.5 milliliters. This is also true for grams. They are small enough that one might need 50 grams of butter, but never need an accuracy of 50.5 grams for a successful recipe. Using millimeters, milliliters, and grams allows the average person to simplify all the measurements they encounter in ordinary life.

The third lesson learned was, in order to preserve a continuity of understanding, a person does not need to immediately switch metric prefixes at a prefix boundary. For instance when measuring wine or other liquids, just because you have measured more than

¶This group of four rules are informally referred to as *Naughtin's Laws* after Australian metrication expert Pat Naughtin who promoted them before his death in 2011

1000 milliliters does not mean you immediately should write the volume as 1 liter. If you have containers with 300, 500 and 750 milliliters, and the next is 1000 milliliters (a popular size used for Australian wines), leave the larger value to preserve psychological continuity and maximize intuitive magnitude comparison. The side of a house in Australia is written as 23 000 millimeters without switching to 23 meters. This is done to preserve continuity of measure in a person's mind. It also allows a drawing to assume all its dimensions are millimeters, which simplifies the drawing further by only using dimensionless whole numbers. If a drawing has 1250 on it, one can assume the value is in millimeters. The use of a space as a triad separator, and the idea of "counting out" prefixes, allows a person versed in metric to immediately see 23 000 mm as millimeters or 23 meters interchangeably.

The fourth lesson learned was to eschew the atavistic prefixes. The use of hecto, deca, deci, and centi are discouraged.

When metric prefixes are embraced with the above rules (as Asimov pointed out) they become analogous to word modifiers. The simple word water is enhanced with modifiers like: hard water, cool water, brackish water, still water, sweet water, boiling water, murky water, or blue water. The absence of the metric system in the US impoverishes our ability to express weights and measures, and acts as a barrier between ourselves and important scientific knowledge. The use of our current measurement vernacular does not allow the average person to evaluate numbers associated with global warming, peak oil, available drinkable water, or other important and limited resources.

The modern metric system (SI) provides a measurement language which allows a person to express a dimension in words, in a manner which is exact, and may be immediately translated into Hindu-Arabic numbers. For instance, I can state the Earth is one hundred fifty Gigameters from the Sun; this value, stated only with characters of the alphabet, can immediately be represented numerically in meters, without computation, as 150 x 10^9 m or 150 000 000 000 m.

Metric Astronomy Distances

Metric Length		Astronomical Dimension
Megameter	(Mm)	Planet
Gigameter	(Gm)	Solar System
Petameter	(Pm)	Distance to Nearest Stars
Exameter	(Em)	Distance to Farthest Stars
Zettameter	(Zm)	Size of galaxies and Diameter of Local Group
Yottameter	(Ym)	Farthest Galaxies/End of Observable Universe

Table 1.1: Metric Distances and Their Related Astronomical Objects

The metric prefixes are immediately understood as a solidly defined number *or* as a descriptive expression. When writing down figures for astronomical distances, one can use Kilometers, Megameters, Gigameters, Terameters, Petameters, Exameters, Zettameters and Yottameters. Unlike the medieval measures[‖] used in the US, metric values form a seamless overlapping continuum of lengths, which also provide exact information about celestial objects. Table 1.1 has a list of metric distances and astronomical objects with which they are associated. The purpose of this book is to familiarize Americans with the rainbow of metric prefixes and each "world" of measurement they represent.

When the metric system has been completely and effectively implemented and taught in the US, our children will grow up with a numeracy which dwarfs that of the pre-metric world.

The metric system is also succinct and compact when used to express the size of numbers. Table 1.2 has a list of the magnifying metric prefixes, their associated descriptive word in English, numerical value, and exponential expression.

The number of letters used for the English words which describe their respective numbers is much larger than the equivalent

[‖] The US gallon is derived from the Winchester Wine Gallon, and the bushel is from the Winchester Bushel. These were both defined in the 10th century. The US inch was originally based upon the barley corn inch which was legally defined in the 14th century.

Metric Magnification Prefixes & US English Words

Prefix		US Word		Number	10^n
Kilo	(K)	thousand	(1000)	1 000	10^3
Mega	(M)	million		1 000 000	10^6
Giga	(G)	billion		1 000 000 000	10^9
Tera	(T)	trillion		1 000 000 000 000	10^{12}
Peta	(P)	quadrillion		1 000 000 000 000 000	10^{15}
Exa	(E)	quintillion		1 000 000 000 000 000 000	10^{18}
Zetta	(Z)	sextillion		1 000 000 000 000 000 000 000	10^{21}
Yotta	(Y)	septillion		1 000 000 000 000 000 000 000 000	10^{24}

Table 1.2: Metric Magnifying Prefixes and English Word Equivalents

metric prefix word. The prefix word may be further reduced to a single prefix symbol. This makes for an elegant description of metric sizes. For instance, 160 Exameters could be written as 100 quintillion miles. The metric description uses twelve symbols, and the English description nineteen, but with a metric prefix symbol, it can be reduced to five symbols: 160 Em. There is no commonly accepted abbreviation for 100 quintillion miles. Many Americans would probably opt for 100 billion billion miles, which is even longer.

When the atavistic prefixes are removed, there is only one metric magnifying prefix symbol which is lower case. It is k for kilo. In order to make the expression of metric prefix symbols more consistent, I will use a capital K rather than the lower case k.

The magnifying prefixes (sans the atavistic ones), with their English word equivalents, numerical expression, and exponential engineering notation are presented in Table 1.2. With the exception of the first magnifying prefix Kilo, the remaining magnifying prefixes all end in *a*: Mega, Giga, Tera, Peta, Exa, Zetta, and Yotta.†

Capital letters signify magnification, and lower case letters sig-

†One can use the ending *a* as a memory device for *a*bove, signifying it is a magnifying prefix.

nify reduction. For example Km, Mm, Gm, Tm, Pm, Em, Zm and Ym are all symbols which magnify a meter, and are emphasized as such with upper case symbols. In the cases of mm, μm, nm, pm, fm, am, zm and ym, all these symbols reduce a meter, and are symbolized with the lower case prefix symbols.[‡]

It will be considered optional to write numbers which are 9999 or less without a space, or, if desired, with one: 9 999. When one encounters a number which is 10 000 or larger, we will express those numbers with a space separator.

When tables contain values that are 9999 or less, the thinspace separator will be suppressed. When a table has values that are 10 000 or more, numbers less than this value will contain a thinspace for readability of the metric triads.

Metric Reduction Prefixes & US English Words

Prefix		US Word	Number	10^n
milli	(m)	thousandth	0.001	10^{-3}
micro	(μ)	millionth	0.000 001	10^{-6}
nano	(n)	billionth	0.000 000 001	10^{-9}
pico	(p)	trillionth	0.000 000 000 001	10^{-12}
femto	(f)	quadrillionth	0.000 000 000 000 001	10^{-15}
atto	(a)	quintillionth	0.000 000 000 000 000 001	10^{-18}
zepto	(z)	sextillionth	0.000 000 000 000 000 000 001	10^{-21}
yocto	(y)	septillionth	0.000 000 000 000 000 000 000 001	10^{-24}

Table 1.3: Metric Reducing Prefixes and English Word Equivalents

Table 1.3 has the reducing prefixes with their equivalent English words, as well as their decimal expression and exponential expression. The reducing prefixes all have lower case symbols, which reminds one they are reducing prefixes rather than magnifying prefixes. The decimal expressions also have separation by threes so they may be "counted out" if necessary. This grouping decreases the chance one will get lost when parsing a long

[‡]Once can use the ending *o* as a memory device for bel*o*w, signifying a reducing prefix.

string of zeros and assign an incorrect metric prefix. It is much like the importance of spaces between words, which today we take for granted. There was a time when ancient manuscripts *did not use spaces between words.* Manuscripts were a continuous script of letters. The important addition of blank space between words in a text was a later innovation, which apparently, was not immediately obvious.

Table 1.3 also shows the longest English word equivalent for a metric symbol is a tie between quadrillionth and quintillionth. Each use thirteen letters as compared with up to five letters for their metric prefix, or one letter for a metric prefix symbol.

The reducing prefixes mirror the magnifying prefixes with the first reducing prefix ending with an i, but all the rest end with an *o*: micro, nano, pico, femto, atto, zepto, and yocto. One can recall which prefixes are which as a's are above, and o's are below unity.

The word descriptions of metric quantities which magnify will be capitalized, and those which reduce, will be lower case. For example 125 Mm will be written out as 125 Megameters or one hundred twenty five Megameters, but not 125 megameters. Magnifying examples are: 200 Megajoules, 400 Kilopascals and 700 Terameters. The word descriptions of metric quantities which use reducing prefixes will be in lower case. This comports with convention, so words like micrometer, milliliter, nanojoule, picofarad and so on will all be written without capitalization. This practice is especially helpful to provide context for unfamiliar prefixes. For example: attometer, Zettameter, zeptometer, Yottameter and yoctometer.

Why is measurement important? There is only *one idea* which reveals, connects, and confirms the scientific world is mathematical, *it is measurement.* Measurement is often cognitively assumed, and becomes psychologically invisible despite its overwhelming importance to our understanding of the Universe.

Isaac Asimov was the master of science writing, but his book about the world great and small is one of the few which seems a candidate for a new perspective. I have done my best to follow Dr. Asimov's lead, but in a way I believe is more elegantly structured. I hope you find the following scientific collages entertaining, and useful for understanding the sizes of our world.

References

[1] Isaac Asimov *Adding A Dimension*, Doubleday, New York, 1964, Page 58

[2] Catherine Wilson *The Invisible World*, Princeton University Press, Princeton NJ, 1995, Page 141

[3] Marjorie Nicolson *Science and Imagination*, Great Seal Books (Cornell University Press), New York, 1962 printing, Page 14

[4] Herbert Arthur Klein *The Science of Measurement*, Dover, 1988, Page 122

[5] Laura J. Snyder *Eye of The Beholder*, W.W. Norton, New York, 2015, Page 200

[6] Laura J. Snyder *Eye of The Beholder*, W.W. Norton, New York, 2015, Page 249

[7] Isaac Asimov *The Measure of The Universe*, Harper & Row, New York, 1983, Page 58

[8] Isaac Asimov *The Measure of The Universe*, Harper & Row, New York, 1983, Page 60

[9] SI Brochure, The International System of Units (SI), 2019, Appendix 4, page 205