# Chapter 5

## Multiple Metric Systems & Metrology

James Clerk Maxwell (1831-1879) was quite possibly the most important scientist between Newton and Einstein.[1] He developed the "color triangle" which explains the limits of color reproduction. A modern version of this is known as a chromaticity diagram.

The stability of the rings of Saturn were a scientific mystery in Maxwell's time. A prize, known as the Adams Prize was offered as an incentive for physicists to solve this problem. Maxwell demonstrated that the rings could not be solid and must consist of separate bodies orbiting independently. The Mathematical explanation Maxwell developed won him the Adams Prize, in fact, he was the only one to submit a solution to the problem, which demonstrated its enormous difficulty. Photographs taken by Voyager 1 and Voyager 2 in the 1980s confirmed Maxwell's predictions.

Maxwell contributed to the kinetic theory of gasses which saw temperature as a manifestation of the average velocity of gas particles. A rise in temperature meant that the average velocity of the particles had increased. A decrease in temperature produced gas particles with a lower average velocity.

The scientific triumph, for which Maxwell is perhaps best remembered, is his development of Maxwell's Equations of electromagnetism. Maxwell gathered together four known laws of electricity and magnetism and integrated them together by adding a new mathematical term. The new set of equations predicted the existence of electromagnetic waves which would propagate at the speed of light. Heinrich Hertz (1857-1894) would later experimentally confirm Maxwell's theory. Maxwell did not live long enough to see the confirmation of his theory. The contemplation of Maxwell's understanding of light would lead Albert Einstein (1879-1955) to develop his famous equation $E = mc^2$. Energy is equal to mass multiplied by the speed of light squared.

In 1832 the German mathematician Carl Friedrich Gauss proposed a measurement system based on the use of the centimeter, gram and second for its base units. Maxwell and William Thomson (Lord Kelvin) augmented the system with electrical units in 1874. This became known as the centimeter-gram-second or CGS system of measures. The artifacts created by the French were the meter and Kilogram. Despite the notoriety of its developers, the CGS system contained inside itself vestigial pre-metric unit magnitudes. The use of the centimeter acts as substitute for an inch. Whether or not a unit which is the size of an inch should be included in a measurement system was never questioned, until industrial practice in the early 20th Century very slowly began to erode this medieval belief.

In 1901 Giovanni Giorgi (1871-1950) proposed a system whose fundamental units are the meter, Kilogram and second. This became known as the MKS system and would later replace the CGS system of units.

Despite the fact there were now two "metric systems," uncertainties remained about the definition of their base unit of length, the meter. Its length definition wasn't exactly scientific and readily accessible. James Clerk Maxwell in his *A Treatise on Electricity and Magnetism* sums up the situation with the meter in 1873:

> In...countries which have adopted the metric system, ...[the base unit] is the metre. The metre is theoretically the ten millionth part of the length of a meridian of the earth measured from the pole to the equator; but practically it is the length of a standard preserved in Paris, which was constructed by Borda to correspond, when at the temperature of melting ice, with the value of the preceding length as measured by Delambre. The metre has not been altered to correspond with new and more accurate measurements of the earth, but the arc of the meridian is estimated in terms of the original meter.

One can sense that Maxwell is satirizing the idea of a measurement unit based on the Earth, and exposes the "Earth based" meter as being essentially a defined artifact which is not exactly "universal."

Maxwell had his own viewpoint of how a universal standard of length might be created:

> In the present state of science the most universal standard of length which we could assume would be the wavelength in vacuum of a particular kind of light, emitted by some widely diffused substance such as sodium, which has well-defined lines in its spectrum. Such a standard would be independent of any changes in the dimensions of the earth, and should be adopted by those who expect their writings to be more permanent than that body.

Maxwell is suggesting that one use wavelengths of light emitted by an element as the basis for a length standard.[1] In his dryly humorous way, Maxwell points out that using light would be a scientifically based repeatable method. Should the Earth ever disappear, which was the current metrology "standard," it would still be theoretically possible to recreate the meter anywhere in the universe without it. Beyond Maxwell's "concern" that we might misplace the Earth, it was also understood that the Earth was cooling. As the Earth cools, one would expect it to shrink, which would in turn alter the length of the meter.[2]

This is when the eccentric and abrasive American-born Charles Sanders Peirce (1839-1914) enters the story. Peirce would be the person who would earn American metrology an equal footing internationally. His improved measurement techniques and precision measurements forged a path which was finally separate from British metrology, and made it self-sustaining.[3]

Charles Peirce was introduced to a spectroscope, which is a device that separates light into its constituent frequencies, by Joseph Winlock (1826-1875) of the Harvard Observatory. Spectroscopy was allowing scientists to identify the chemical elements which make up stars. The element helium was first identified as a yellow spectrum line seen during a solar eclipse of the sun in 1868—prior to its identification on Earth. I suspect researchers thought it would probably be a metal given the ium suffix. With the help of his father, Charles became head of the Office of Weights and Measures in 1872. Peirce traveled to Paris in 1876 and

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[1] Jacques Babinet (1794-1872) is credited as the first scientist to suggest, in 1827, that wavelengths of light be used as a measurement standard.

brought back brass meter standard number 49, which would be used for the calibration of American standards.

The idea of using light for a standard had been contemplated for some time, but there was a potential problem. Light is a wave, waves travel through a medium (water for water waves, air for sound waves). It was thought that light traveled through a medium, which they called aether. It was believed that the wavelength of light would be altered because of the Earth's rotation in the aether and from its solar orbit. This would be like the problem of a seconds pendulum having a different period depending on its latitude. Peirce was aware of this potential problem:

> [T]here may be a variation in wave-lengths if the aether of space, through which the solar system is traveling, has different degrees of density. But as yet we are not informed of such variation.

In 1887 the Michelson–Morley experiment failed to detect the aether. This caused a considerable scientific brouhaha, but the aether was not dead yet. It was too powerful of an idea. In the end, after repeated experiments failed to detect the aether, it was decided it must not exist, and light could be relied upon to be a universal standard for the definition of a meter.

The path Peirce would take to relate a distance to light would not involve counting wavelengths of light, this would occur later. It was known that a series of finely spaced lines on the surface of a transparent medium would split light into a number of different directions. An equation described the directions of these beams in terms of the distance between the etched lines. This transparent medium with a series of parallel lines is known as a diffraction grating. Peirce would attempt to use this known property of a diffraction grate to relate light and distance.

One can create light which is produced by a known element by placing its gas inside of an evacuated tube. When the gas within the tube is excited with electricity, the gas will emit light. We all know that when the gas is neon, we call it a neon light, or neon tube. Peirce chose to use sodium for his tube. Peirce attempted to calibrate the distance between the machined lines on a diffraction grating, back to his number 49 meter standard using the sodium light. Unfortunately, the lines on the diffraction grating had imperfections that made the lines a bit fuzzy, which limited the resolution. The distance between the lines on the diffraction grating would change with temperature, further decreasing the accuracy. The accuracy of the thermometer he used to monitor the temperature also introduced error. Peirce published his results in 1879. He had tied the meter to a wavelength of light by way of lines on a diffraction grating. He was the first to do this, but it was still not the method described by Maxwell, which involved counting wavelengths of light.

Albert Michelson (1852-1931) read Peirces publication and realized that the interferometer he and Edward Morley (1838-1923) had developed to detect the ether could be used for the precise measurement of wavelengths. An interferometer splits a single beam of light in two and then later recombines them so the two beams that meet are out of phase. This produces a series of light and dark interference patterns. A screw is attached to a mirror that can be used to move the mirror and count the number of light and dark oscillations. Michelson and Morley published this work in 1888. The original illustration is given in Figure 5.1

The first sentence of the paper is: "The first actual attempt to make the wave length of sodium light a standard of length was made by Peirce." The inaccuracies of his method are described and the advantages of an interferometer are discussed.

They determined that it would take the counting of 400,000 wavelengths to obtain a decimeter (100 mm). Michelson and Morley suggest in their paper:

> Probably there would be considerable difficulty in actually counting 400,000 wave lengths, but this can be avoided by first counting the wave lengths and fractions in a length of one millimeter and using this to step off a centimeter. This will give the nearest whole number of wave-lengths, and the fractions may be observed directly. The centimeter is then used in the same way to step off a decimeter, which again determines the nearest whole number, the fraction being observed directly as before.

In 1892 Michelson went to Paris to relate he and Morley's interferometer work. Unfortunately, Michelson discovered that his sodium light did not produce a single frequency line, but was actually a composite of two lines. This caused enough fuzziness to not allow for measurements

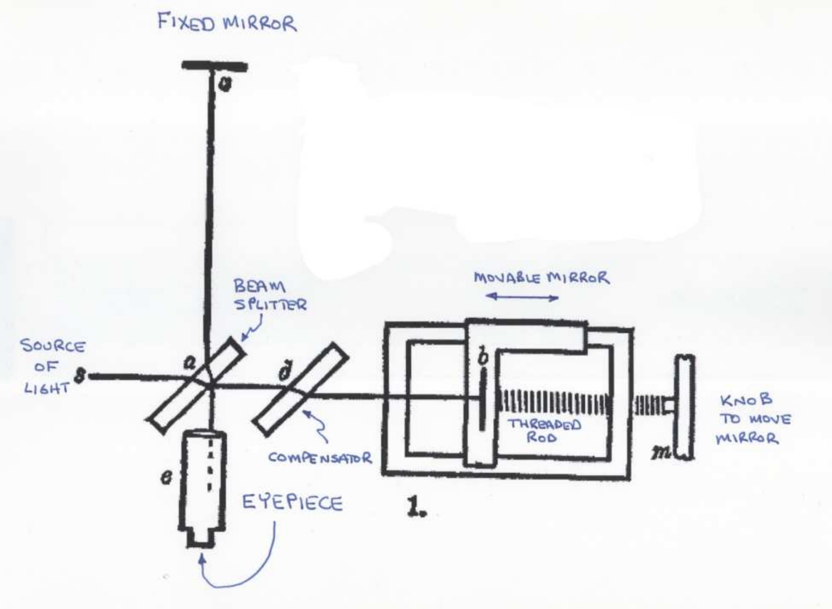

Figure 5.1: Original illustration of Michelson-Morley interferometer. The source of light passes through a half-silvered mirror. This beam-splitter allows half of the light to pass directly through the glass plate, and reflects the other half toward the fixed mirror. The direct beam passes through a compensator which is the same thickness of glass as the beam-splitter. Its purpose is to equalize the path lengths of the light. This light reflects from a mirror which has an adjustable micrometer attached so that it may be moved in and out. The two beams recombine and arrive at the eyepiece where one sees concentric light and dark fringes. These may be used to count the number of wavelengths of light as the mirror moves.

which were as precise as he needed. Michelson tried both mercury and cadmium and settled on the latter.

In the 1906 book *Outlines of The Evolution of Weights and Measures and The Metric System*, authors William Hallock and Herbert Wade, state that Michelson used “three different kinds of light, viz. the red, green, and blue of the cadmium spectrum, he determined the wave-length of each or the number of times this wave-length was contained in the standard meter.”

Hallock and Wade can hardly control their enthusiasm and excitement at this technical breakthrough:

> The accuracy of this work is almost incredible, as the variation in measurements was only about one part in ten million. . . . here is an absolute measurement which gives the length of a standard in terms of a natural unit, under conditions reproducible at any time. This, of course, gives a permanent check on the integrity of the meter, as in the event of the international prototype being damaged or destroyed. . .

It was decided by the participants, that pursuing a method of tying the natural phenomenon of light to the meter was to be undertaken. French physicists Charles Fabry (1867-1945) and Alfred Perot (1863-1925) made improvements to Michelson and Morleys interferometer, and were able to obtain a precision near that of their artifact standard. Improvements to the interferometer continued.

A survey of candidate elements was undertaken to find the best one for use as a new standard for the meter. This uncovered the fact that various isotopes of the elements were emitting light at different wavelengths which caused blurred lines. The search was on for elements that were heavy and had few isotopes. This work continued throughout the 20s and 30s. World War II delayed progress, but by the 1950s enough improvements had been made to schedule a re-definition of the meter in 1960. By international agreement the meter was defined in terms of the wavelength of light emitted by the krypton-86 isotope. The meter became equal to 1 650 763.73 wavelengths of the orange-red emission line in the electromagnetic spectrum of the krypton-86 atom in a vacuum. The meter was now a length available to all countries without respect to an artifact or geography.

Despite the fact that Peirce, Michelson, and Morley, all American scientists, were instrumental in achieving the dream of a universal meter available to all, America did not convert to the metric system or metric lengths for their everyday lives.

Engineers and scientists involved in metrology may have made considerable strides in developing a unique and reproducible length for the meter, but how best to arrange those units was still up for debate in the early twentieth century. Between World War I and World War II the French created a variant of the metric system called the meter-tonne-second (MTS) system. Yet another throwback to pre-metric nomenclature, which is used to this day, is the word *tonne* as a substitute for the Megagram. The pre-metric unit, the ton, had at least two variations known as long and short tons. The word is derived from the word tun which was the volume of a large sized barrel.

The third metric system should have more properly been called the meter-megagram-second system or MMS. This new version of the metric system was created in response to a perceived need by industry for it. It was adopted by the Soviet Union in 1933, and abolished there in 1955. It was a legal system in France from 1919 until 1961. The international collaboration of scientists had produced a new measurement system, but clearly, there was considerable fumbling and experimenting to discover the most expressive and efficient way to use it.

A fourth metric system was in use by meteorologists, which was known as the decameter-tonne-second system, or DTS system.[4] A decameter is 10 meters, and part of the archaic prefix cluster around unity which complicates metric usage. Once again the cultural inertia of continuing to use a "metric unit" named after the non-metric ton continued with the creation of this alternative system. It would have been more properly called the decameter-Megagram-second system (DMS).

It looked like there might not be a consensus, and multiple incompatible metric systems might exist. The CGS system had about four variations which encompassed electromagnetic units. The MTS system existed well into the mid twentieth century, as did the MKS or meter, Kilogram, second system. Considerable incompatibilities existed between them. Surprisingly an international consensus for a single version the metric system overcame desires for tribalism, and the system unified itself into what we now call SI.

# References

[1] Mahon, Basil *The Man Who Changed Everything* John Wiley & Sons 2003

[2] Raymond T. Birge “On the establishment of fundamental and derived units, with special reference to the electrical units. Part I”, *American Journal of Physics* 3: pp 102-109

[3] Robert P. Crease *World In The Balance*, W.W. Norton, 2011, Chapter 9

[4] Charles B. Clapham *Metric System for Engineers*, Chapman& Hall, LTD 1921 page 106