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Beyond the Metre (Part II)

Richard S. Thompkins
Mississippi Bend Area Education Agency

Vincent N. Lunetta
University of Iowa

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Richard S. Tompkins
Metric Education Consultant
Mississippi Bend Area Education Agency
2604 West Locust Street
Davenport, Iowa 52804

Vincent N. Lunetta
Associate Professor of Science Education
University of Iowa
Iowa City, Iowa 52242

Introduction

This article is the second in a series discussing the wide spectrum of metric units. The first article dealt with some general aspects of the International System of Units (SI) and then went on to consider the metre, square metre, cubic metre and second. This article describes the SI unit of mass, and how units for velocity and acceleration are built using physical laws.

The Metre Per Second (m/s)

Speed is usually represented in terms of a distance traveled during some time interval. If it takes an hour to drive from Iowa City to Davenport, the automobile has maintained an average speed of 55 miles an hour.

A three-hour trip from Davenport to Des Moines does not imply a speed of "165 miles per three hours." By convention, the time portion is reported in terms of a single unit (the hour in this case). The distance must be reduced proportionately, giving "55 miles an hour" again. Average speed is defined to be "the average distance traveled within a time period of unit length."

A car speedometer does not indicate average speed. It measures speed from moment to moment. Its needle points at a number showing how far the car would travel if it kept going for an hour with the same *instantaneous* speed.

The SI unit for both average and instantaneous speeds is the *metre per second,* the pace of a pedestrian striding one metre each second. Over short distances a quick sprinter can run 10 times as fast.

Although the metre per second has a name built from other units, it accepts prefixes in a simple way. Adding "milli-" yields the *millimetre per second,* a unit useful for clocking snails. Earth satellites, on the other hand, travel many *kilometres per second.* Any needed prefixes latch onto the "metre" portion of the unit without confusion. Nothing has come of the Danish delegate's suggestion at the 11th General Conference of Weights and Measures (CGPM) to name the unit after the inventor of the bicycle.[1]

It is possible to write a formula for speed if the distance and time are known.

$$\text{average speed} = \frac{\text{distance traveled}}{\text{time to travel the distance}}$$

A beam of light, for example, will travel 3,000,000,000 m in 10 seconds. Placing these measurements into the formula gives

$$\text{average speed of light} = \frac{3{,}000{,}000{,}000 \text{ m.}}{10 \text{ s}}$$

Numbers are numbers and labels are labels. Grouping similar parts together,

$$\text{average speed of light} = \frac{3{,}000{,}000{,}000}{10} \frac{\text{m.}}{\text{s}}$$

Carrying out the division,

$$\text{average speed of light} = 300{,}000{,}000 \, \frac{\text{m}}{\text{s}} \text{ or } 300{,}000{,}000 \text{ m/s.}$$

The SI symbol for the metre per second has appeared automatically as a result of inserting the units, as well as the numbers, into the formula.

New speed units may be created by changing the time period involved. Canadian traffic signs, doing away with the second, proclaim speed limits in *kilometres per hour (km/h)*. The minute and hour, however, belong to the short list of non-SI units approved for use by themselves but unrecommended for combination with other units. Metrological purists would replace the kilometre per hour by the metre per second in order to increase the coherence of SI. The kilometre per hour does not relate to other units in decimal multiples. It is roughly the same size as the metre per second (1 m/s = 3.6 km/h). Why have two units when one will do? Furthermore, the kilometre per hour is harder to visualize in personal terms. A speedometer reading 120 km/h centers the mind of the driver on how long the whole trip will take. If he saw his speedometer indicating instead 33 m/s (the same speed), the driver might pause to think how far he will travel in the second or two it takes to react to a dangerous situation.

The Metre Per Second Squared (m/s^2)

A change in speed is an *acceleration,* which is expressed as the amount of change within some unit period of time.

$$\text{average acceleration} = \frac{\text{change in speed}}{\text{time interval}}$$

If a car, starting from rest, picks up speed for 10 seconds until it is traveling 50 km/h, the rule above indicates

$$\text{average acceleration} = \frac{50\ \text{km/h}}{10\ \text{s}} = \frac{50}{10}\ \frac{\text{km/h}}{\text{s}}$$

Carrying out the arithmetic, and recalling that the division signs in labels are read as "per," we find that the car's acceleration is 5 km/h per second. Each second it moves 5 km/h faster until, after 10 seconds, it is moving 50 km/h.

As mentioned above, SI speeds are more correctly expressed in metres per second. Converting the final speed of the car and using the formula again gives

$$\text{average acceleration} = \frac{13.9\ \text{m/s}}{10\ \text{s}} = \frac{13.9}{10}\ \frac{\text{m/s}}{\text{s}} = \ \ \frac{\text{m/s}}{\text{s}}$$

What do the labels mean this time?

It may help to write out the words

$$\frac{\text{metres per second}}{\text{second}} \quad \text{or} \quad \frac{\text{metres/second}}{\text{second}}$$

This indicates that a distance in metres has been divided by seconds (to obtain the speed) and now has been divided by seconds again (to give the acceleration). The symbols can be treated as if they were fractions

$$\frac{\text{m/s}}{\text{s}} = \text{m/s} \div \text{s} = \frac{\text{m}}{\text{s}} \div \text{s} = \frac{\text{m}}{\text{s}} \times \frac{1}{\text{s}} = \frac{(\text{m})(1)}{(\text{s})(\text{s})} = \frac{\text{m.}}{\text{s}^2}$$

This is the label for the *metre per second squared*, the SI unit of acceleration. It has simply fallen out of the acceleration formula, once SI units were inserted. This is another instance of coherence.

Some geophysicists measure the acceleration of falling objects in terms of the cm/s^2, which is christened the *gal*. This well-intentioned honor to Galileo, the Italian scientist and science popularizer who was first to analyze motion mathematically, will probably disappear because the gal is not coherent with SI units.

Units for other physical quantities can be built from those discussed so far. Changes in acceleration are measured in metres per second cubed (m/s^3), for example, and river flow rates in cubic metres per second ($\text{m}^3\text{/s}$).

The Kilogram (kg)

Unlike the second and the metre, the troublesome *kilogram* is still officially defined in terms of an actual object, a cylinder of platinum-irridium alloy 39 mm high and wide which sits in a vault at the International Bureau of Weights and Measures (BIPM).[2]

In order to change the definition from this prototype to a natural standard reproducible in the laboratory, the kilogram should be defined in terms of a certain number of atoms of a particular kind. Unfortunately, measurement scientists can weigh the prototype to an accuracy of only a few hundredths of a milligram.[3] Until this precision is improved, kilograms the world over will be based on the prototype. Accidental damage to the prototype kilogram, such as happened to British standards during a fire in 1834, would be metrologist's nightmare.[4]

The kilogram is the fundamental SI unit of mass. The history of the term "mass" stretches back to the Greek word for bread. Isaac Newton first ascribed to it the meaning physicists use: "I call mass the quantity of matter."[5]

Aside from the word "massive," we rarely encounter mass in everyday speech. Instead we use the term "weight" to refer to the quantity of matter in a steak we admire at the supermarket. A spring scale measures how much steak is purchased. But such a scale actually indicates the pull of gravity of the steak. It would show a different weight on the moon, where gravity pulls the meat less strongly. Buying a pound of hamburger on the moon using a terrestrial spring scale would get you six times as much hamburger as on earth. The scale reading will even vary slightly from place to place down here. A hamburger patty may change weight infinitesimally between Ackley and Zwingle.

Does "weight" mean a quantity of matter, or what the spring scale measures? To clarify the situation, the physicist takes the latter view and defines "weight" to be the pull of gravity on an object.[6] If the object is moved around the universe, the gravitational pulls on it vary and its weight in the physicist's sense is not constant. The quantity of matter in it does not change. Its mass in kilograms is constant. The kilogram does not measure what the physicist means by "weight."

On the other hand, most Americans use "weight" to mean the amount of material in an object, not the pull of gravity on it. Lunar weightwatchers will not sleep easier on the moon although the bath scale reads 85 percent less than back home. A fat person is still fat anywhere in the universe. Space travel will not make hamburger cheaper. "Weight" commonly means what the kilogram measures.

In order to simplify the transition to metric terminology for those to whom it is unfamiliar, the use of "weight" to mean mass may be grudgingly permitted. The use of "mass" is certainly more correct. The distinction between mass and gravitational attraction is important to understanding how the world works. Students capable of grasping the ideas of pull and amount can master the key concepts if the teacher uses this terminology consistently.

To make matters worse, there is no English word meaning "to measure the mass of." We seem to be stuck with "weigh" as a verb in both gravitational pull and mass senses.

The General Conference of Weights and Measures (CGPM) has come down on the side of the physicists. In SI, "weight" officially means gravitational pull and not mass.[7] Of course, by its own definition, the panel's name should be the General Conference of Masses and Measures.

Unlike a spring scale, which measures the pull of gravity on an object, a pan balance truly measures mass. It uses gravity only to compare objects of known mass with objects of unknown mass. Equal masses will balance anywhere in the universe.

A kilogram contains a thousand *grams*. Even though the gram is the unit without a prefix, the kilogram is the fundamental SI unit and is used to build other units. No prototype gram sits in the BIPM's vaults. No rule officially defines the gram in terms of some physical procedure.

A 1795 law originally defined the gram in natural terms. It was to be the mass of a cubic centimetre of water at the temperature of melting ice.[8] The French academecians soon recognized the convenience and precision of prototype standards, however, and in 1799 set out to produce such a standard of mass. They chose the kilogram for greater accuracy, and the prototype finally delivered differed from the mass of a cubic decimetre of water by only 28 parts in a million. But a century later this tiny discrepancy precipitated a scandal.

The Third General Conference of Weights and Measures (CGPM) officially defined the litre to be the volume occupied by a kilogram of water, the kilogram being defined by the prototype. But such a mass of water would have a volume of 1000.028 cm^3. The litre no longer equaled the cubic decimetre! The conference had created a second system of volume measurement competing with the cubic metre and its decimal multiples. For years, students had to puzzle out the distinction between the litre and cubic decimetre. In 1964 the General Conference of Weights and Measures (CGPM) relented and restored the litre's original definition and dropped it from the catalog of official SI units. A litre today is exactly one cubic decimetre. It does not weigh exactly one kilogram because of the tiny error in 1799.[9]

From time to time there have been movements to change the kilogram's name to some prefix-free form. One thousand grams was originally called a grave, but the term fell into disuse. Given the widespread acceptance of the kilogram, any change seems unlikely.

Household metric standards can help with learning to estimate metric masses. A straight pin weighs about 0.1 g, a dollar bill about 1 g, a nickel 5 g, and a flashlight battery 100 g.

The 1978 U.S. government budget was about $450 billion.[10] If this money were spent in dollar bills, what would its mass be?

A cubic metre of water defines the *tonne* (t), another unit of mass. The tonne served as a foundation unit of the French legal system of measures before the adoption of SI. It weighs as much as a million cubic centimetres of water — one megagram (Mg) — and roughly matches an American long ton. Its unusual spelling distinguishes it from the many varieties of customary tons, and purists pronounce it to rhyme with "don."[11] While we are unlikely to run to the store to buy a millitonne of sugar, this hefty unit is helpful in certain calculations. To determine the mass of water in a swimming pool 60 m long, 30 m wide, and 10 m deep, first compute the volume of the pool in cubic metres. Each of these has a mass of a tonne.

Units smaller than a gram turn up occasionally. The diamond industry somehow convinced the Fourth General Conference of Weights and Measures to adopt the *carat*, equal to 0.2 g. Its use today is "deprecated."[12] Medical workers often employ the *milligram (mg)*. To visualize this tiny mass, imagine a dollar bill cut into 1000 pieces. Interesting exercises using milligrams can be based on comparisons of human nutritional requirements from the *World Almanac* with the labels on canned goods.

Summary

This article has discussed the metric units of velocity, acceleration and mass. The next article in this series will describe the units of force, pressure and density.

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