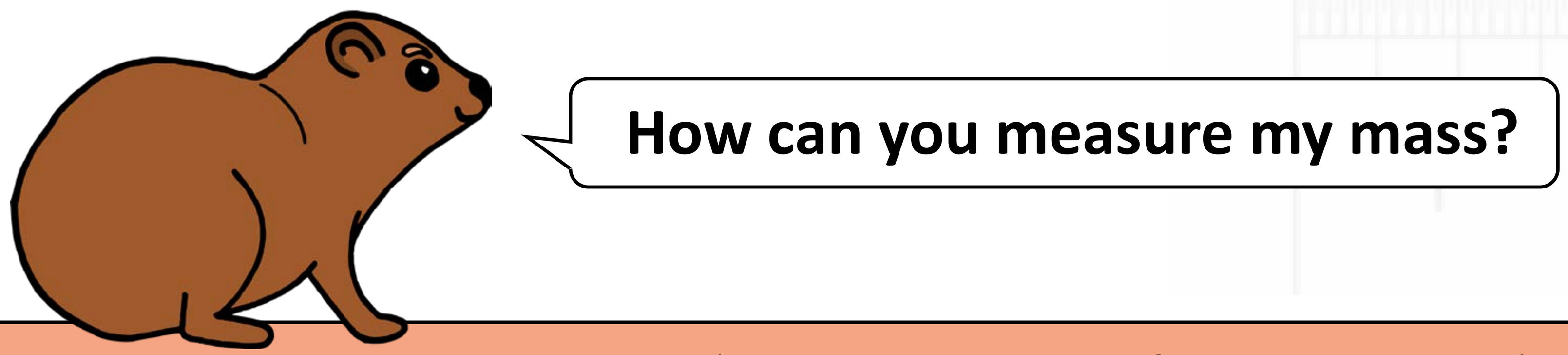
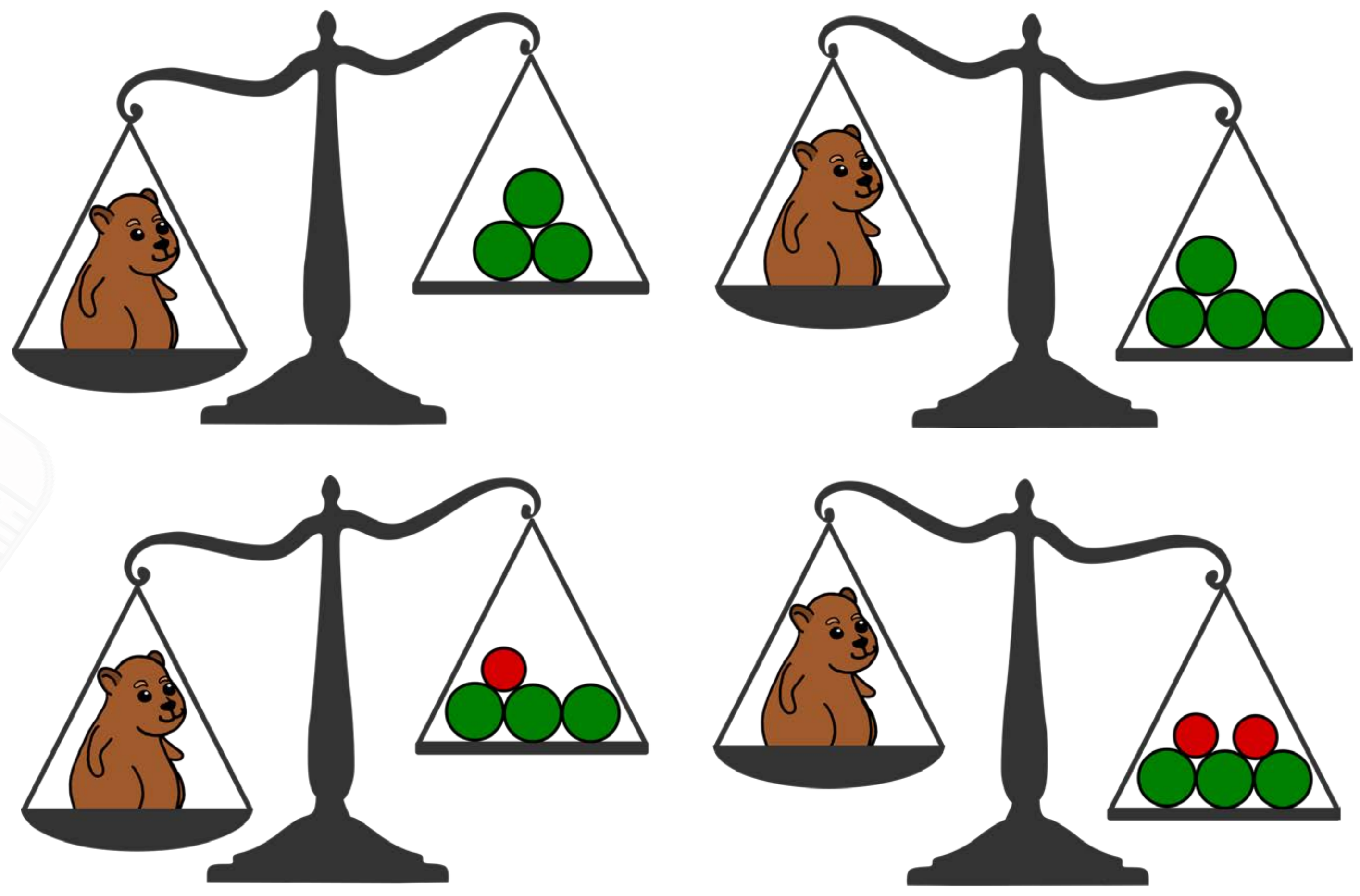
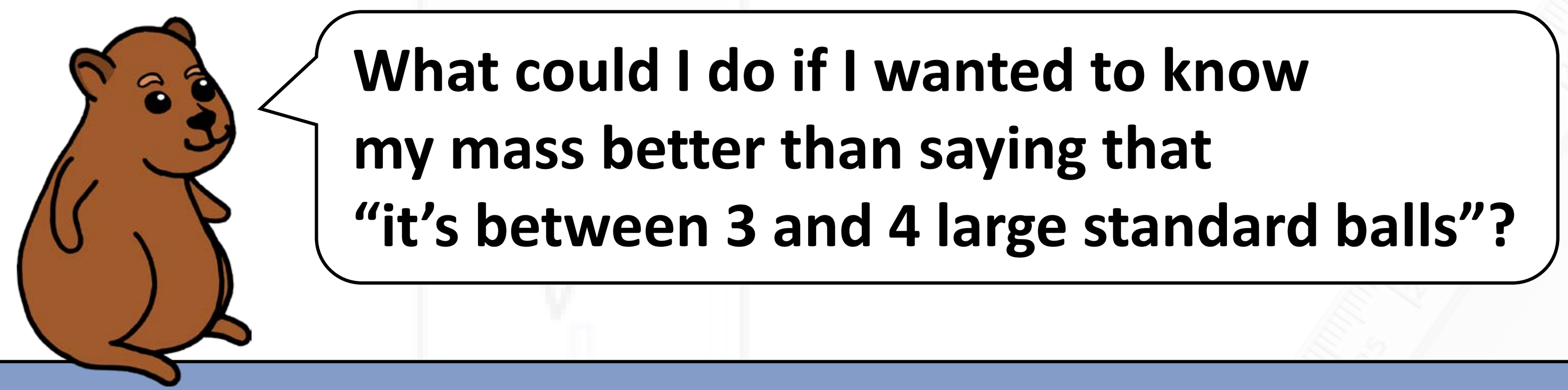
Measurement and the SI

A measurement is an action that you take in order to know the value of a physical quantity for the first time, or to improve what you may already know about the quantity. This can be within the context of science, engineering, law, medicine or trade.



Every measurement requires you to make a comparison with the apparatus you are using for the measurement. For example you may use a balance to determine the mass of the dassie, and a set of "large standard balls" ●.





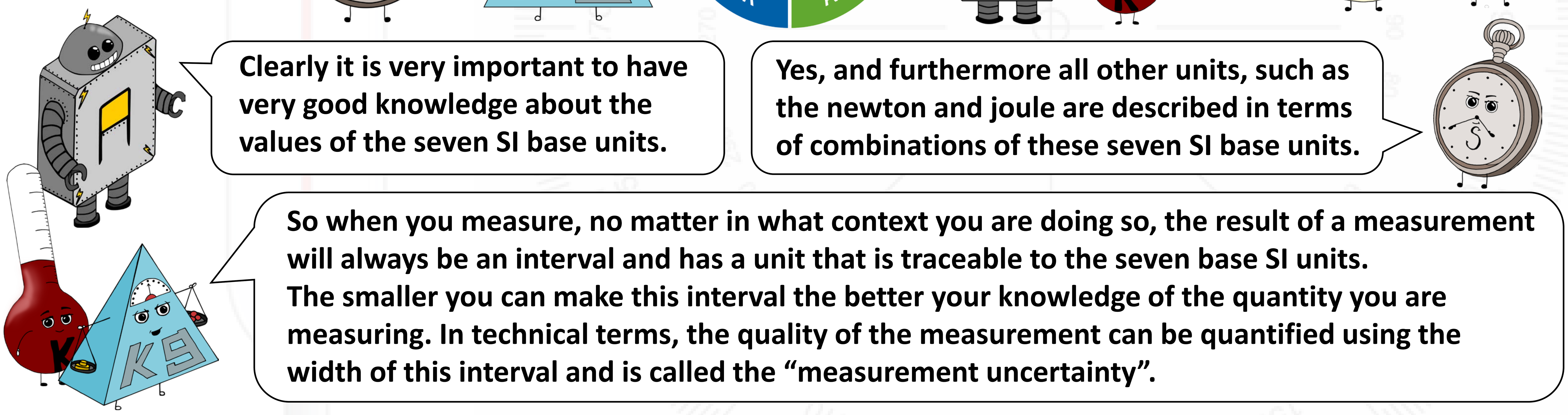
You could use a set of small standard balls as well ●. We say that the **precision** of the measurement has improved.

Clearly no matter how small we are able to practically make our standard balls, the knowledge we have about the mass of the dassie (or any other physical measurement) will always be limited to an interval (between two values) and will never be exact (a single value). This is a very important feature of **all** measurement: our knowledge can never be perfect (is always between two values).

The other important issue is how the **unit** of the measurement is defined and by whom. In the example above the unit was "the standard ball." Throughout history a huge number of standard units (for many different quantities) were created, often based on physical artefacts such as someone's foot or nose!

For example, shown alongside are a few drawers from a "cabinet of weights" used in the 19th century. Since each city had its own measurement system, you needed to choose the appropriate weights from the collection when trading with a particular city. This made trade very complicated.

As a consequence of there being many different units in use around the world, in 1875 a number of countries agreed to the "Convention of the Metre" which declared a standard set of units for length, time, and mass, the so called Metric System. Units for electric current, temperature, luminosity, and amount of substance were introduced in later years to form the International System of Units (SI). Nearly all the countries in the world have signed the Convention of the Metre, agreeing to use the SI with its seven base units and derived units, for science, engineering, and trade.



The seven SI base units are all precisely defined by a group of international experts. Each country is responsible for the implementation of the SI through their own national metrology institute. In South Africa this is the National Metrology Institute of South Africa (NMISA).

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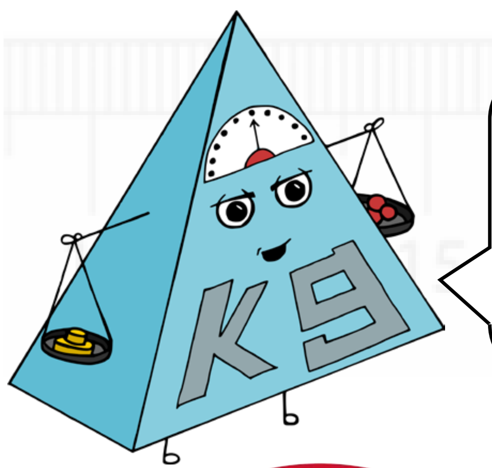
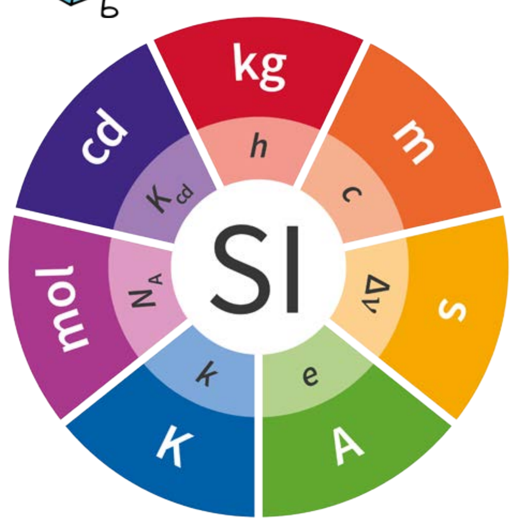
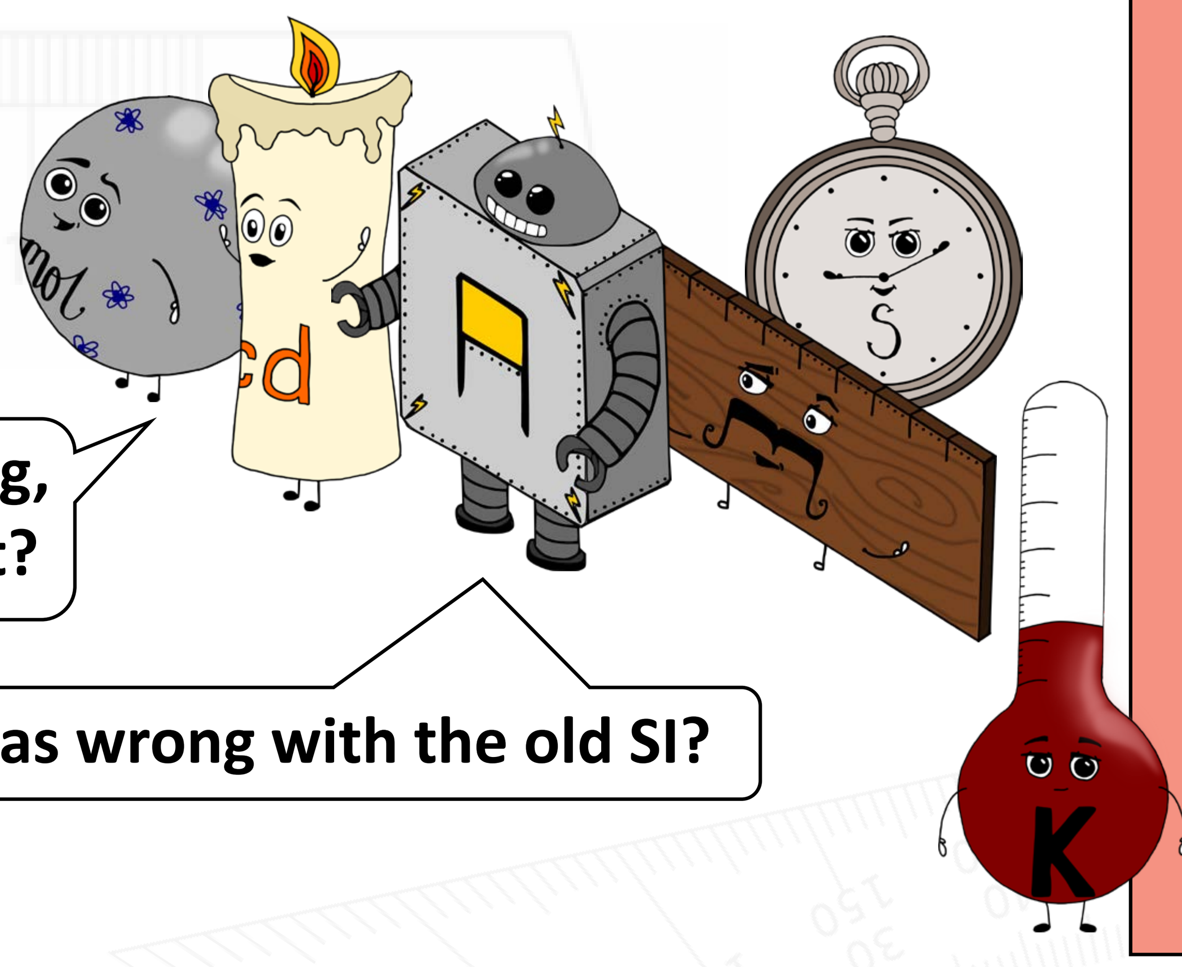
Revision of the SI units



Did you know that we have been revised?

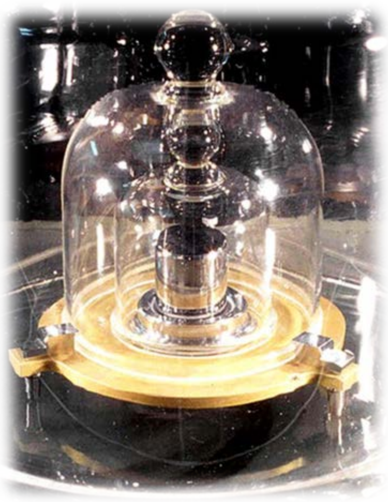




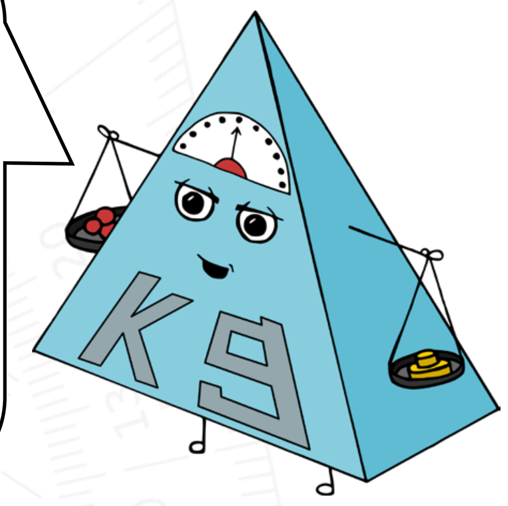
That is amazing, is it important?

What was wrong with the old SI?

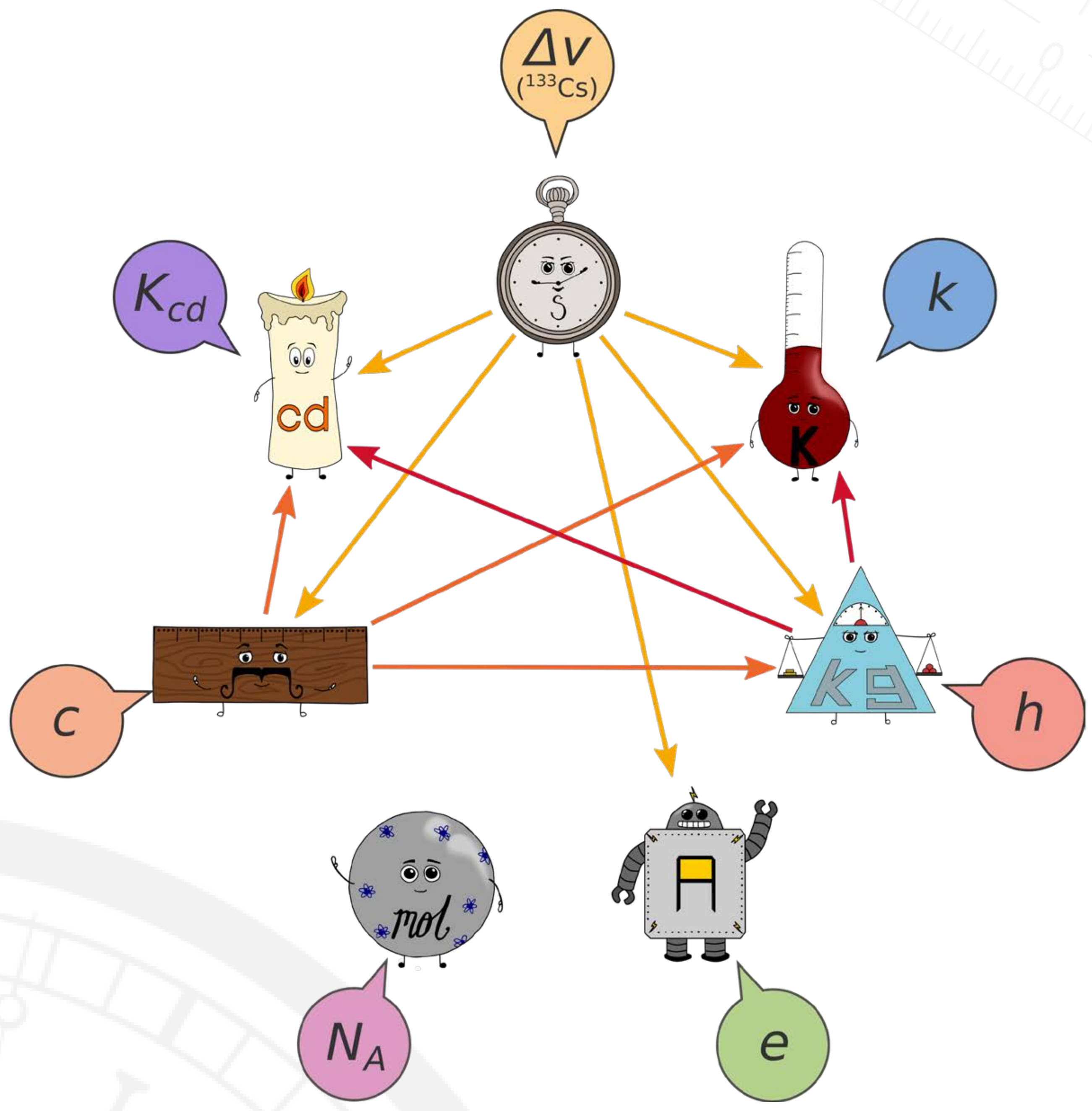
On 16 November 2018 member states of the Convention of the Metre agreed at the 26th General Conference on Weights and Measures to a revision to the international measurement system that underpins all global science and trade. On World Metrology Day, 20 May 2019, the SI unit system underwent the most significant change since its conception. The revised system means that measurements are not linked not to physical artefacts or atomic material properties, but to the unchanging fundamental properties of nature itself.



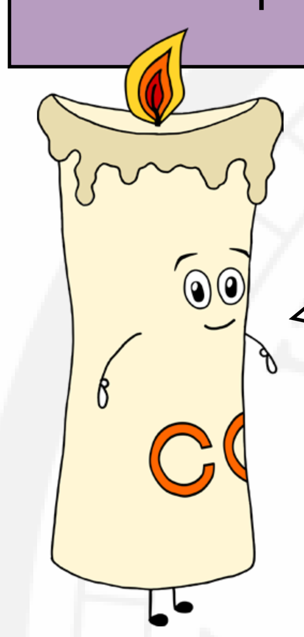
Some of the units used to have reference to physical artefacts, the most famous being the International Prototype of the Kilogram (IPK), which was held in a vault in Paris. The problem with using a physical artefact to define the unit, is that it is subject to changes in properties over time. Since the creation of the IPK in 1889 variations in environmental conditions caused the mass to change, so the definition of the kilogram was linked to something that was unstable over long periods of time.



Scientists have now found an improved and much more reliable way of defining the units. The definition of the units is now completely separate from the technologies used to realise the primary reference standards for the seven SI base units. This means that scientists can measure the seven SI base units with ever increasing accuracy and precision, as more advanced experiments and technologies are designed and implemented.



In the revised SI the new definitions are based on seven of the most important fundamental constants of nature which are now known to a very high precision. Each of the constants is linked to one of the seven SI base units (as shown alongside). After the SI base units are realised through experiment using modern technology, then every single measurement can be linked by a sequence of inter-comparisons (is “**traceable**”) to the one or more of the seven SI units.



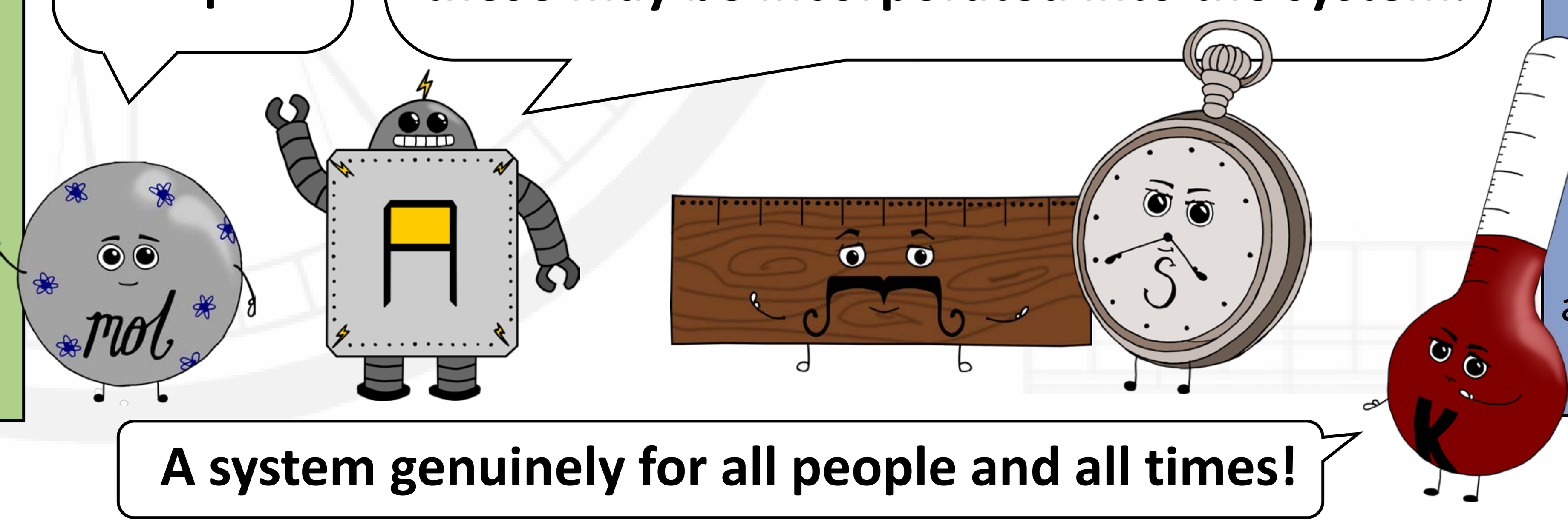
I have heard that one of the ways being developed to realise the reference standard for the kilogram is using a “kibble watt balance”, a simple version of which can be built in a school science laboratory. The example shown alongside was constructed at NMISA. The balance uses precise measurements of electrical properties (current, voltage) and a combination of physical constants to define the quantity we call mass.

The famous physicist Max Planck made this extraordinary statement in 1927 about linking the measurement units to constants of nature, that “they will necessarily retain their validity for all times and cultures, even extra-terrestrial and nonhuman.”

Is the new system perfect? Can it adapt?

The system will be under continuous improvement as experiments reach higher and higher precision. As we discover new science, or new fundamental constants, these may be incorporated into the system.

Measurement in every aspect of our lives, from everyday activities, to science and engineering, to medicine, to trade and industry, all of it, now has reference to a scale defined by nature. Seven of the fundamental constants are now at the heart of physical measurement.



A system genuinely for all people and all times!

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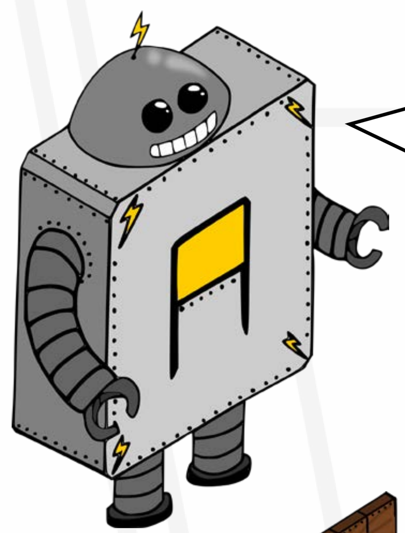
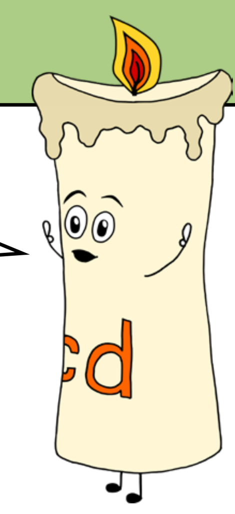
The SI and the constants of nature

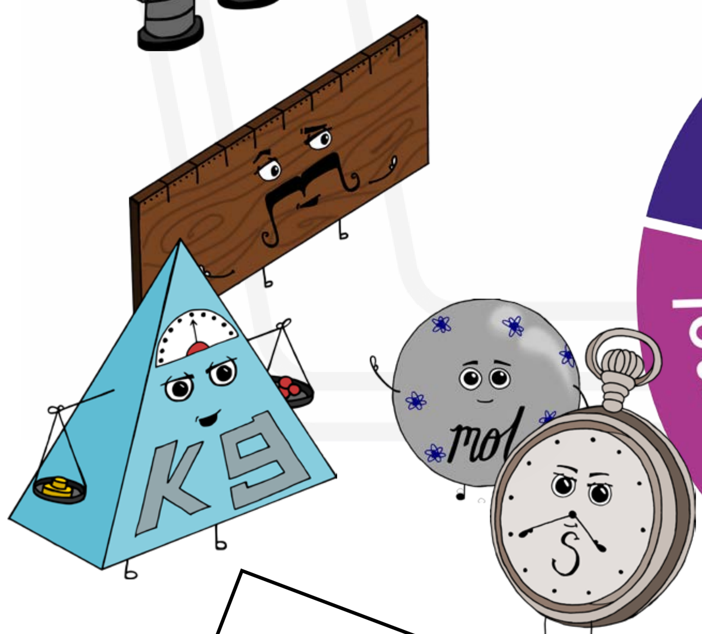
The fundamental physical constants are quantities that are both universal in nature (in other words identical throughout the universe) and are unchanging with time. These constants are a consequence of the fundamental theories of physics and may be measured with great precision nowadays.



Wow, so the laws of the natural universe are the same everywhere?

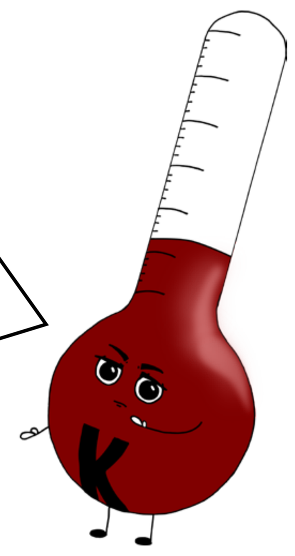
The fundamental constants underpin all of science by providing scale to the physical laws of the universe. Experiments can be designed to confirm theoretical models of physics which describe the way in which nature works. It is amazing that scientists have been able to make measurements across the length and time scales of the universe.



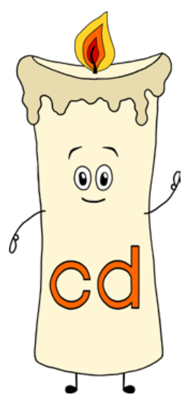


Do you mean that experiments are the key to science?

Yes, no matter how clever you are, or how important you are, or how fancy your ideas are about the way nature works, if your ideas are not supported by the measurement results from experiment then they are wrong. It's as simple as that. That is the way science works. The relationship between experiment (observation and measurement) and ideas (theories) is critical.

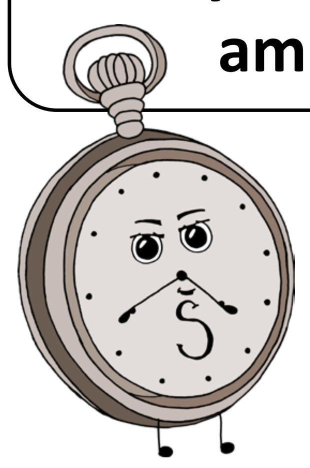


We heard that the SI have been redefined in terms of fundamental constants. How does that work?



First you need to be able to measure the fundamental constants precisely. As they are universal and unchanging, every measurement in every laboratory in the world, or on the moon, or even in another galaxy will give consistent results. Seven fundamental constants have been chosen and are linked to the seven base SI units as shown in the table. Once you can realise the seven SI base units through experiment, then every single quantity in measurement has traceability to the SI.

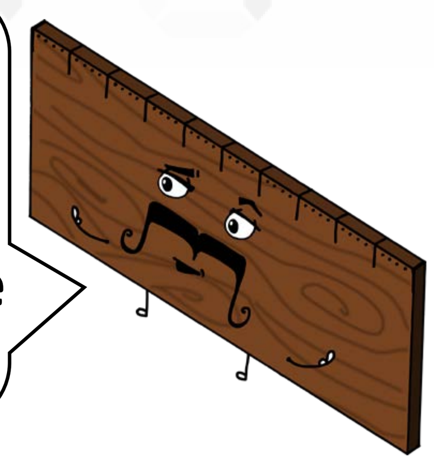
That sounds confusing… can you explain how I am defined?



Atomic energy levels are fixed by the configuration of individual atoms and are unique for every isotope. One particular configuration has been chosen as the defining constant for the second as it can be measured to high precision. The transition frequency of the caesium-133 atom $\Delta\nu(^{133}\text{Cs})$ is known to be 9192631770 Hz, i.e. per second.

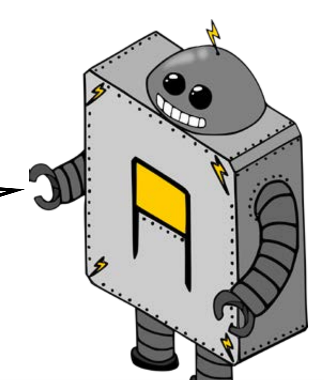
$\boldsymbol{\Delta\nu}(^{133}\text{Cs})$ = 9 192 631 770 **s**$^{-1}$ (Hz) unperturbed ground state hyperfine transition frequency of the caesium-133 atom	The transition of an electron between energy levels in a ^{133}Cs atom emits radiation with this unique frequency.
c = 299 792 458 **m** s^{-1} speed of light in vacuum	The ultimate speed limit! This is the maximum speed at which all conventional matter can travel.
h = 6.626 070 15 × 10^{-34} **kg** m^2 s^{-1} (J s) Planck constant	Relates the energy carried by a photon to its frequency.
k = 1.380 649 × 10^{-23} kg m^2 **K**$^{-1}$ s^{-2} (J K^{-1}) Boltzmann constant	Relates the average kinetic energy of molecules in a gas to its temperature.
e = 1.602 176 634 × 10^{-19} **A** s (C) elementary charge	The magnitude of the electric charge carried by a single electron.
$\boldsymbol{K_{cd}}$ = 683 **cd** kg^{-1} m^{-2} s^3 (lm/W) luminous efficacy of monochromatic radiation of frequency 540 × 10^{12} Hz	Describes exactly how bright a source of light is for a specific frequency (or colour) and power.
$\boldsymbol{N_A}$ = 6.022 140 76 × 10^{23} **mol**$^{-1}$ Avogadro constant	The number of particles (atoms, molecules, objects, etc.) in one mole of any substance.

Does that mean that I rely on the second to be defined?



For the metre, the speed of light in a vacuum c is used. The metre is then defined as the length of the path travelled by light in vacuum during a time interval of 1/299792458 seconds. The definition of the second is then used from its constant $\Delta\nu(^{133}\text{Cs})$, in combination with the speed of light c, to realise the metre.

Each of the seven SI base units is thus constructed from one or more of the seven constants.



No matter where scientists are from or what language they speak, physics is defined and communicated by a set of mathematical principles, physical theories, and base units defined by nature itself!

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