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Nature is Exact!

In my first undergraduate year, I had to do a practical experiment involving a soap film stretched over a circular aperture. A small pressure difference across the film distorted it into a portion of a spherical surface, which could form an image of a needle placed at its centre of curvature. The quality of this image astonished me – it was as good as that of the best lens. I remarked on this ability of a simple bubble to form a surface correct to within a wavelength of light to my college tutor. "Ah!" he said, "you see, nature is exact." So, instead of giving my old job description as "establishing the SI as the basis of all measurement," which does not sound the most exciting task in the world, I could have said "finding out whether nature is indeed exact, and to what extent we can use its exactness," which sounds more interesting.

Progress has conformed to a sort of Moore's law over the decades. A hundred years ago, a little better than one percent was thought good enough for electric standards and measurements, but this rapidly shrank to a few parts in a million in the 1960s. This relied on, for example, the more-or-less reproducible voltage of the chemical mix in a Weston standard cell. This voltage was not accurately predictable, but in a good-quality example it could, metrologists thought, be relied on to remain constant to 0.1 parts in a million over several years. Their faith in this was established by inter-comparisons they made between sets of some tens of cells kept at a very constant measured temperature and bolstered by occasional inter-comparisons with the mean of similar sets maintained by their peers in other national laboratories. And then, Brian Josephson at Cambridge predicted theoretically that electron-pairs tunnelling through a thin insulating barrier between two superconductors would generate discrete voltage increments when the junction was irradiated with microwaves of a single frequency.

The first practical Josephson devices were simply drops of tin-lead solder in which a niobium wire was embedded. Niobium has a natural thin oxide coating, and so the resulting dry joint constituted a primitive Josephson junction, but the production was decidedly *hit or miss*, mostly miss. Metrologists' sense of humour improbably christened them as *Superconducting Low-inductance Undulatory Galvanometers*, or SLUGs for short, because that is just what they looked like. Nevertheless, these decidedly ugly-looking devices when irradiated with microwaves of precise frequency υ and compared with others were good enough to demonstrate the beautiful exactness of the Josephson equation, $h\upsilon = 2e_J V$, where h is Planck's constant, e_J is believed to be the electron's charge and V is one of the stepped differences of voltage across the junction. Later, technology reliably produced thousands of vacuum-deposited junctions in series, creating voltages up to 10 volts, and their back-to-back comparison revealed a 1 part in 10^{16} exactness rivalling that of the *one second in the life-time of the universe* time-keeping of atomic clocks.

Metrologists immediately put the exactness of Josephson voltage sources to good use as a great improvement over standard Weston cells to maintain national standards of voltage. This revealed a classic example of a *Zanzibar unit*. For readers unfamiliar with this fable, with deep and sincere apologies to the citizens of Zanzibar, I repeat the story. Once upon a time, a metrologist took a vacation on this remote and tiny island. He was intrigued by a loud explosion every day at midday and tracked it down to an old sea-captain who had taken upon himself the role of time-keeper for the island. The metrologist asked him how he kept his time-keeping accurate. "I have a good watch," the captain replied, "and once a week I go to the other side of the island and re-set it by the master clock in the jeweller's shop window." Later, the metrologist's persistence sent him into the jeweller's shop to ask the jeweller how he ensured the accuracy of his master-clock. "That's easy. I set it by the cannon that the old sea-captain lets off precisely at noon." It should have come as no surprise to the keepers of the Weston cell volt in the various countries when the advent of the Josephson-maintained volt told them that their unit had been steadily getting smaller at the rate of about 0.3 parts in a million per year. The realisation that something similar could also be happening to the kilogram, because its supposed constancy is only verified by comparing it with its siblings, provides much of the drive for basing it on the exact physical constant h.

In 1980, following the theoretical observation of Klaus von Klitzing, metrologists at the German metrological laboratory

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Physicalische Technische Bundesanshtalt established to within a few parts in a million that the ratio of the transverse voltage to the current flowing through a conducting cryogenic atomic monolayer was always an integral $1/i$ fraction of h/e_H^2 where e_H is again believed to be the charge of the electron. This exactness has subsequently been narrowed down to better than a part in a billion, in the diverse monolayer in a MOSFET, a gallium arsenide semiconductor, and most recently graphene, despite the monolayers being far from perfect in that they have various impurities and contributing regions. This is because the exactness is contained in each individual conducting electron. This quantum Hall effect provides a standard of resistance far superior to the age-affected and temperature-dependent standards made from resistance wire.

The Meissner effect in superconductors enables us to make an exact flux linkage between two coils so that if no remnant flux is detected, the cancellation of the ampere-turns of the coils means that the currents in them are in the exact inverse ratio of their numbers of turns. Flux cancellation is detected by a third coil, often just a single turn, incorporating a Josephson junction. As a detector of flux quanta φ_o, with present technology, it has a sensitivity of up to 10^{-6} φ_o. The resulting instrument is called a cryogenic current comparator and has become a standard instrument for comparing currents to help set up basic SI electrical standards in national measurement laboratories.

In the energy of interaction E of two linked toroids, one that is a closed ring of magnetic flux Φ and the other a circulating current I, the details of the toroids being irrelevant, is exactly $E = I\,\Phi$. It is surely another of the beautiful equations of physics, just like $E = mc^2$. It also has direct application in the Watt balance presently involved in a redefinition of the kilogram.

These examples, and there are many others, exhibit exactness to the limit set by the available technology of the time. Sometimes, in other instances, deviations have been found which generate fundamental advances in our understanding, such as general relativity, or quantum field theory, which arose from unexpected anomalies in the spectrum of atomic hydrogen, and exactness is restored with accompanying increased understanding. So, we should not merely accept what has been discovered so far in setting up standards of measurement but seek to advance the investigation of nature's exactness in all its manifestations. The greatest interest now is in seeking to know whether the parameters e, e_J, and e_H are in fact identical, all being exactly the charge of an isolated electron. This can be established by comparing a Josephson voltage with the voltage across a quantum Hall device when a current of a counted number of electrons per second passes through it. At the moment, electrons can be counted with great difficulty to an accuracy which is only a little better than a part in a million, whereas *exact* in this instance would now be defined as being better than a few parts in a billion. Watch this space; electron-counting to this accuracy is under development.

In the film about the stories of Hans Christian Anderson starring Danny Kaye, he looks at a looper caterpillar. This insect is commonly called an inchworm because it moves around flowers by looping its body to bring its back legs up close behind its front legs, then stretching its body forward and repeating the process over and over. Against a chorus of children in the village school who are mindlessly repeating a multiplication table to learn it by rote, he sings:

Inchworm, inchworm measuring the marigolds,
Seems to me you'd stop and see how beautiful they are.

We metrologists miss so much, if we are just inchworms.

For Dr. Kibble's contact information and bio, please follow this link: http://ieee-ims.org/publications/immagazine.