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Introduction: The fundamental constants of physics, precision measurements and the base units of the SI

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This is a short introductory note to the texts of lectures presented at a Royal Society Discussion meeting held on 14–15 February 2005 and now published in this issue of *Philosophical Transactions A*. It contains a brief resumé of the papers in the order they were presented at the meeting. This issue contains the texts of all of the presentations except those of Christophe Salomon, on cold atom clocks and tests of fundamental theory, and Francis Everitt, on Gravity Probe B, which were, unfortunately, not available.

Keywords: fundamental constants; metrology; SI

Accurate and reliable measurements are the foundation for international trade, high-technology manufacturing, human health and safety, the protection of the environment, global climate studies and many other aspects of today's world. Precision measurements allow the essential tests of scientific theory upon which all of these depend. At this discussion meeting, a comprehensive review was given of the practice of precision measurements, the present state of our knowledge of the fundamental constants and their increasing use as the basis of the International System of Units, the SI. The meeting ended with a presentation on the broader role of metrology in today's society.

The fundamental constants of physics play an increasingly important role in measurement science (metrology). This was foreseen by Maxwell, who in his famous statement during his Presidential address to the British Association for the Advancement of Science in 1870 said:

> If, then we wish to obtain standards of length, time, and mass which shall be absolutely permanent, we must seek them not in the dimensions, or the motion, or the mass of our planet, but in the wavelength, the period of vibration, and the absolute mass of these imperishable and unalterable and perfectly similar molecules[1]

[1] See Quinn & Kovalevsky (2005) in this issue for an extended extract from this speech.

One contribution of 14 to a Discussion Meeting 'The fundamental constants of physics, precision measurements and the base units of the SI'.

At the time, science and technology did not allow Maxwell's precept to be implemented, but now it does. In the first article, Barry Taylor (2005) gives an account of how we reach a consistent set of the best values for the fundamental constants of physics which are now the building blocks for today's metrology. He describes the complex interlinking relations between many of the constants that on the one hand allow multiple ways of using them as standards but on the other allow fundamental tests of theory to be carried out by using experimental measurements to test their mutual consistency. He describes in some detail how the latest (2002) CODATA Adjustment of the constants was carried out.

Maxwell made his statement before, of course, Planck developed his theory of quantization of energy and before quantum mechanics, so that many of what we know today as the fundamental constants were unknown to Maxwell. In the paper that follows, Peter Mohr (2005) goes into more detail on the relations between modern physical theory and the fundamental constants. He shows that at a very basic level they are part of modern physics. He then examines how far the recent CODATA Adjustment depends on theory and to what extent it depends on particular assumptions and how reliable these are and whether or not the outcome of the Adjustment can give information on the consistency of theory. He gives some examples.

The constancy of the fundamental constants is taken as a given in practical science and metrology but the possibility of some time variation of the constants, particularly the gravitation and fine structure constants, is predicted by certain of the candidate theories for unification of the forces of nature. John Barrow (2005) reviews the properties of some of these theories for the variation of the gravitation and fine structure constants in the light of the various cosmological models therein. He discusses the recent data consistent with a time variation of the fine structure constant obtained from quasar observations.

In their article, Hänsch *et al.* (2005) give an account of recent advances in the spectroscopy of the hydrogen atom. Among the important techniques used have been laser-cooling of atomic gases, Doppler-free two-photon spectroscopy and, more recently, femtosecond laser frequency combs. The last of these are particularly associated with him and his group in Garching and have revolutionized the precise measurement of optical frequencies and are sure to be central to future optical clocks that will allow a redefinition of the SI second. Recent measurements of the 1S–2S two photon transition have reached unprecedented accuracies and open the way to ever more stringent tests of the fundamental laws of physics, including laboratory tests of the time variation of the fundamental constants.

The development of methods to cool and trap atoms with laser light not only led to a Nobel Prize for Steve Chu, Claude Cohen Tannoudji and Bill Phillips but also opened the way to cold atom clocks and a whole new range of experimental physics at ultra-low temperatures. It led in due course to the achievement of Bose–Einstein condensation (BEC) which itself gained a Nobel prize for those who first accomplished it. In their paper, Dunningham *et al.* (2005) describe the particular properties of a BEC that are of interest for precise experiments. These are principally that the atoms are extremely cold (temperatures of picokelvins) and that they have laser-like coherence properties.

The International system of Units, the SI, was set up by the 11th general Conference on Weights and Measures in 1960. In his paper, Christian Bordé (2005) examines how discoveries in quantum physics since 1960 have revolutionized measurement science. He takes a radical look at how our present unit system is set up and makes suggestions on how we might take advantage of the new understanding of nature brought about by quantum physics to redefine some of our base units to link them more closely to fundamental constants and to produce a system more appropriate to modern science.

The 1985 Nobel Prize for physics was awarded to Klaus von Klitzing for his discovery of the quantized-Hall effect. This, together with the Josephson effect, for which the discoverer also received the Nobel Prize, has revolutionized electrical metrology. In his paper, Klaus von Klitzing (2005) describes the very large amount of work on the quantum-Hall effect that has taken place since its discovery and future prospects for metrology.

A further review of the implications of the macroscopic quantum effects, the Josephson and quantum-hall effects and single-electron tunnelling, for electrical metrology was given by John Gallop (2005). He summarized the very different physics behind the Josephson and quantum-Hall effects and single electron tunnelling, reviewing the present state of development in all three. Implications for the future are also considered, especially relating to ultra-low temperature, nanoscale and truly quantum mechanical versions of the standards.

The discussion was by no means all related to quantum metrology. In his paper, Richard Davis (2005) gives an account of the various methods now being pursued that might lead to a new definition of the kilogram linked to atomic or fundamental constants. Principal among these are the watt balance and the X-ray crystal density method using silicon. Although none of them are yet quite at the level of accuracy sought, it is highly likely that within a few years the present artefact representation of the kilogram will be replaced. This is a subject at present under lively discussion within the metrology community.

The Newtonian constant of gravitation, G, appears in the 2002 CODATA Adjustment with an uncertainty of 1.5 parts in 10^4, by far the largest uncertainty of any of the fundamental constants of physics. Clive Speake (2005) presents the role of the gravitational constant in the framework of classical and quantum gravitational theory and goes on to describe the key problems that confront experimentalists who attempt to determine G. These include criteria for the selection of the detector of the gravitational torque from the point of view of random uncertainties due to read-out noise, thermal and vibrational noise. An important aspect of precise determinations of G is the control of systematic effects (type B uncertainties) such as those due to uncertainties in absolute calibration of the gravitational torque, density homogeneity of source masses and length metrology. He describes some current experiments.

The last of the technical papers presented here is by Felicitas Arias (2005). The provision of an accurate time scale for the world requires, first of all, a sufficient number of atomic clocks to provide a stable and continuous time reference (a flywheel) together with a small number of primary caesium frequency standards to link it to the SI second, then a means of comparing the readings of all these clocks around the world and finally an appropriate algorithm for calculating a mean time scale. She describes the role of the International Bureau of Weights and Measures in organizing and collecting the data from these clock comparisons and doing the calculation to establish International Atomic Time (TAI) and then Coordinated Universal Time (UTC). With the likelihood of more accurate atomic clocks becoming available in the near future, she describes the possibilities for an increasingly accurate time scale and the challenges that must be met to achieve this and meet the most demanding practical requirements, notably in the field of satellite navigation.

The final paper in this issue is a general one (Quinn & Kovalevsky 2005), that traces the development of metrology since the time of the French Revolution and the creation of the metric system and describes how world metrology is organized today and gives examples of applications of metrology showing how it concerns us all in many aspects of our daily life.

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