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Introduction

Metrology is the science of measurement including all theoretical and experimental aspects, in particular the experimental and theoretical investigation of the uncertainty of measurement results. According to Nobel Prize winner *J. Hall*, "metrology truly is the mother of science" [1].

Metrology, actually, is almost as old as mankind. As men began to exchange goods, they had to agree on commonly accepted standards as a base for their trade. And indeed, many of the ancient cultures like China, India, Egypt, Greece, and the Roman Empire had a highly developed measurement infrastructure. Examples are the Nippur cubit from the third millennium BCE found in the ruins of a temple in Mesopotamian and now exhibited in the archeology museum in Istanbul and the famous Egyptian royal cubit as the base length unit for the construction of the pyramids. Yet, the culture of metrology got lost during the Middle Ages when many different standards were in use. In Germany, for instance, at the end of the eighteenth century, 50 different standards for mass and more than 30 standards for length were used in different parts of the country. This of course had been a barrier to trade and favored abuse and fraud. It was then during the French revolution that the *French Académie des Sciences* took the initiative to define standards independent of the measures taken from the limbs of royal representatives. Instead, their intent was to base the standards on stable quantities of nature available for everyone at all times. Consequently, in 1799, the standard for length was defined as one 10 million part of the quadrant of the earth, and a platinum bar was fabricated to represent this standard (*Mètre des Archives*). Subsequently, the kilogram, the standard of mass, was defined as the mass of one cubic decimeter of pure water at the temperature of its highest density at 3.98 °C. This can be seen as the birth of the metric system which, however, at that time was not generally accepted through Europe or even in France. It was only with the signature of the Meter Convention in 1875 by 17 signatory countries that the metric system based on the meter and the kilogram found wider acceptance [2]. At the time of this writing, the Meter Convention has been signed by 55 states with another 41 states being associated with the General Conference on Weights and Measures *(Conférence Générale des Poids et Mesures, CGPM)*. At the General Conferences, following the first one in 1889, the system of units was continuously extended. Finally, at the 11th CGPM in 1960, the present SI (*Système International d'Unités*) (see Section 2.2) with the

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kilogram, second, meter, ampere, kelvin, and candela as base units was defined. The mole, unit of amount of substance, was added at the 14th CGPM in 1971. Within the SI, the definition of some of the units has been adopted according to progress in science and technology; for example, the meter was defined in 1960 on the basis of the wavelength of a specific emission line of the noble gas krypton. But then, in 1983, it was replaced by the distance light travels in a given time and by assigning a fixed value to the speed of light in vacuum. Likewise, the second, originally defined as the ephemeris second, was changed by the 13th CGPM and defined via an electronic transition in the Cs isotope 133. Thus, today, the meter and the second are defined by constants of nature. At present, efforts to newly define the system of all units shall be based on constants of nature [3–7]. In fact, in this context, single quanta physics has a decisive role as will be outlined in this book.

We shall begin with introducing some basic principles of metrology in Chapter 2. We start in Section 2.1 by repeating some basic facts related to measurement and will discuss in particular the limitations for measurement uncertainty. The SI, in its present form, is summarized in Section 2.2 together with the proposed new definitions.

Chapter 3 is entitled laser cooling, atom clocks, and the second. Here, we describe the realization of the present definition of the second based on the hyperfine transition in the ground state of ^{133}Cs employing laser-cooled atoms. We further describe recent developments of the so-called optical clocks, which have the potential for higher accuracy and stability than the present microwave clocks and will definitely lead to a revised definition of the second in the foreseeable future.

Chapter 4 is devoted to superconductivity and its utilization in metrology. Because of its prominent role for electrical metrology, we give an introduction to superconductivity, the Josephson effect, magnetic flux quantization, and quantum interference. By means of the Josephson effect, the volt (the unit for the electrical potential difference) is traced back to the Planck constant and the electron charge as realized in today's most precise voltage standards. Magnetic flux quantization and quantum interference allow the realization of quantum magnetometers (superconducting quantum interference devices) with unprecedented resolution and precision.

The underlying solid-state physics and the metrological application of the quantum Hall effect are discussed in Chapter 5. In Chapter 6, we describe the physics of single-electron transport devices and their potential for realizing the unit of electrical current, the ampere. The ampere is then traced back to the charge of the electron and frequency. Finally, the so-called metrological triangle experiment will be described.

Chapter 7 is then devoted to the envisaged new definition of the kilogram based on the Planck constant. In particular, we will present the watt balance and the silicon single crystal experiment for a precise determination of the Planck constant and the realization of the newly defined kilogram.

The envisaged new definition of the kelvin and various experiments to determine precisely the value of the Boltzmann constant are discussed in Chapter 8.

In Chapter 9, finally, we take an even further look into the future of the SI when we discuss the prospect of single-photon emitters for a possible new definition of radiometric and photometric quantities, for example, for (spectral) irradiance and luminous intensity.

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