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GENERAL PROBLEMS OF METROLOGY AND MEASUREMENT TECHNIQUE

THE METHODOLOGICAL PRINCIPLES OF METROLOGY

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Methodological aspects are considered for theoretical metrology and the principles for determining basic concepts. The basic concepts in metrology are determined operationally, with the meanings established during the performance of sequences of experimental operations. Differences are pointed out in the definition of the same concepts in metrology and in theoretical physics.

Key words: *metrology methodology, basic metrology concepts, operational definition.*

Metrology methodology resembles the methodology of any other scientific discipline in formulating the concepts and in the definition of the scientific understanding structure, with methods of demonstrating and developing knowledge: the gnoseological principles of metrology. The methodology also determines a specific scientific discipline, particularly the role and place of metrology amongst other scientific disciplines. In our view, it is necessary to formulate the basic methodological principles of metrology for reasons familiar to metrologists. In [1], for example, the question is raised of the gnoseological principles of metrology. In [2], a form is given for the axioms in the basic metrology principles. It has been pointed out [3] that current metrology, both Russian and international, lacks an ideology (methodology in our terminology). On the one hand, metrology is an activity (it provides unified measurements) and at the same time is also a science concerned with the quantitative evaluation of physical quantities established during measurements and the setting up of the corresponding means of measurement. Here we consider the scientific side of metrology and methodological aspects associated with its concepts and gnoseological topics relating to the form of the specific scientific content.

The methodology of any science contains the principles for determining basic concepts. We consider the practice built up in metrology on the history of determining the standard for the unit of length: the meter. According to the decision of the First General Conference on Weights and Measures in 1889, the standard for the meter was a rod made from a platinum-iridium alloy with two scratches, the distance between which constituted one ten-millionth part of a quarter of the Paris meridian. The meter was reproduced by performing a series of instrumental operations with a comparator. In 1960, the General Conference on Weights and Measures confirmed a new meter, equal to 1650763.73 wavelengths of the orange line of krypton-86. The meter was reproduced by an interferometric method: counting that number of wavelengths and the fraction of the wavelength, with the construction of the krypton lamp and the excitation conditions for the orange line strictly defined. The procedure for reproducing the meter in both cases involved performing a certain sequence of experimental operations. These empirical procedures established the content of the unit of length concept. That method of introducing empirical concepts may be called operational.

In 1927, the physicist Bridgman [4–7] formulated operationalism as a system for generating concepts in physics having physical content, while at the same time it was intended as a philosophy, and he later became a Nobel laureate.

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Operationalism occurred as a philosophical response to the outstanding advances in physics at the start of the 20th century: the creation of special relativity theory (SRT) and general relativity theory (GRT), as well as quantum mechanics. These theories operated with a mathematical formalism more abstract than that used previously. To the extent to which this formalism became part of physical theory, it acquired a physical content, and the elements of the mathematical formalism became physical concepts. Traditionally, by physical concepts was meant the properties of physical objects established by experiment. Bridgman proposed a new interpretation: the content of a concept was determined not by the properties of an object but instead by the operations performed upon that concept: "The basic idea of operational analysis is fairly simple, namely: we do not know the significance of a concept until we have determined the operations that are used... in relation to that concept in a certain particular situation" [5].

New fundamental theories appearing at the start of the 20th century made it necessary to reconsider classical concepts in physics and methodological aspects. In these theories, there was a difficult problem of comparing theory with observations. Special relativity theory eliminated the concept of absolute time, which involved in particular reconsidering the concept of simultaneity. It was resolved operationally by the action of the observer in synchronizing clocks at different points, and the indication of a frame of reference in which lie the instruments and the observer. Quantum mechanics in its final form was formulated in terms of psi functions (Schrödinger's and Dirac's equations), which are not directly observed in experiments. A problem arose over the correct definition of an observed quantity. Bridgman's proposed operational definitions in many cases were useful for elucidating the experimental content of basic concepts in quantum mechanics. They for example eliminated certain paradoxes associated with a particle-wave dualism. For example, in application to electrons (neutrons, photons, and so on), the paradox is eliminated at once when a particular operational procedure is stated. For example, if a Geiger counter is used in the measurements, corpuscular properties appear in the experiment. If on the other hand an electron (neutron, photon, and so on) passes through an interferometer, then at the output one observes only wave properties of the particles. In the form of moderate operationalism, Bridgman's approach is used to elucidate the experimental content of certain basic concepts in quantum mechanics up to the present [8].

Examples also occur in classical physics of dualism in physical concepts. For example, a given physical quantity (electric field in a homogeneous dielectric) can have two aspects in accordance with the measurement conditions (operational measurement procedure): as a field strength and as an induction. For example, if an extensive narrow slot is cut in a homogeneous dielectric and an instrument is placed at the center of it, it will measure the strength of the electrostatic field, which is equal to the strength $\mathbf{E}$ in the insulator when the slot is oriented parallel to the $\mathbf{E}$ vector. If on the other hand the slot is oriented perpendicular to $\mathbf{E}$, the instrument will measure the strength equal to the field induction $\mathbf{D}$ (in a gaussian unit system). The same applies to the magnetic field in a magnetic material [9]. In that case, statement of the particular method of measurement allows one to avoid a formal paradox.

Bridgman proposed to extend operationalism to the whole of physics. Very soon however it was established for example that theoretical physics cannot be fitted into the framework of operational concepts. It is based on fundamental abstract concepts and quantities and involves a system of idealized concepts, often very far from reality. In theoretical astronomy, for example, the Sun is considered as a material point within which the Earth together with its satellite the Moon can locate freely. In general relativity theory, the idealized object is an abstract four-dimensional set of coordinates and instantaneous time (an object of criticism by Bridgman). Theoretical physics considers properties common to a set of homogeneous physical objects or phenomena and is abstracted from details, and it sets up idealized objects and concepts such as black body, incompressible liquid, material point, psi function, absolute space, absolute time, curved (Riemann) space-time, and so on. It describes physical reality in these abstract idealized terms, which are theoretical concepts according to Carnap [10]. We prefer the term metaphysical. The definition of metaphysical in philosophy is frequently used in the context of outside experiment or beyond experiment, and relates to judgments not based directly on sense perceptions and experiment. That concept is found already in Kant: "if physics examines nature, and we can adapt our understanding of nature only via experiment, then the science that is based on it will be called metaphysical. This is knowledge that lies as it were outside the area of physics on one side of it" [11]. That concept is used in that context here. In terms of such abstract theoretical (metaphysical) concepts and objects that are not directly observed, one formulates the laws of theoretical physics: Maxwell's equations, the kinetic theory of gases, Schrödinger's equation, general relativity theory, and so on. One can say that theoretical physics by virtue of its abstraction is to a substantial extent metaphysical [12].

We differ from Bridgman in restricting the sphere of operationalism to metrology. This corresponds to the tradition in metrology of determining metrological concepts operationally. Metrological concepts are empirical ones and relate to observed and measurable quantities. Empirical concepts are used in formulating empirical laws (Ohm's law, the gas equation, the Josephson effect, and so on). The laws of theoretical physics are formulated as noted above in theoretical (metaphysical) concepts, which use metrology indirectly. The relationship between theoretical concepts and metrological (empirical) ones is established by correspondence rules [10], such as the expression of a temperature in terms of the mean kinetic energy of the molecules, or current density in terms of the number and speed of the electrons and so on.

In 1983, the tradition of operational definitions in metrology was broken: the General Conference on Weights and Measures defined the meter as the distance traveled by a planar electromagnetic wave in vacuum in a time of 1/299792458 sec [13–16].

This definition is not operational, and it is impossible in principle to put the unit of length strictly into correspondence with the letter of the definition. The matter is as follows. We follow strictly the definition of the meter of 1983 and consider that the front of the planar electromagnetic wave passes through point A at the start of the meter (we consider it as lying at the first scratch on the platinum-iridium measure), while the metrologist observes point B at the second scratch at the end of the meter. When the electromagnetic wave attains point B, the metrologist records the fact of passage of the wavefront through it as a time mark and nothing more. No metrologist using one time mark alone can estimate the distance passed by the wave, as this needs two signals or two marks defining the time interval, and after multiplication by the velocity of light as the corresponding constant. The situation could be corrected if the metrologist at point B possesses a mirror, and can move to point A. In that case he could observe at point A the instants of starting off and arrival of the reflected signal to estimate the doubled distance between points A and B, after which division by 2 gives the required unit of length: a meter. However, the 1983 definition did not envisage such a procedure.

This abstract definition of the meter has occurred because its authors diverged from metrology and abandoned the metrological identification of their science and entered a foreign scientific discipline: theoretical physics, which employs a different methodology. Although it operates with the same concepts as metrology (mass, space, time, and so on), it gives them a different metaphysical meaning. The concept of the velocity of light is also metaphysical, which plays a key role in the definition of the 1983 unit of length. In theoretical physics, that concept is a characteristic of the electromagnetic field, which elucidates its nature and essence, namely that perturbations in the electromagnetic field, no matter what their frequency, propagate in vacuum with a constant velocity. According to the theory, the velocity of electromagnetic waves (the speed of light) has the same value in all inertial frames of reference. That velocity is measured and even the particular numerical value is not important to the theory. The authors of the definition of the meter of 1983 used the concept of the velocity of light taken from theoretical physics. On it, they formulated the theoretical concept of the unit of length, in accordance with this as a metaphysical concept it cannot be measured in practice (does not have an operational content).

In 1983, there were two outstanding scientific discoveries: highly stabilized lasers (sources of monochromatic radiation) and the radio optical bridge (based on nonlinear diodes with MIM structure), which linked the optical range of laser radiation to the radio-frequency one, which radically improved the interferometric method. On the one hand, instead of the krypton lamp with a coherence length for the orange line of about half a meter, it became possible to use a new light source: a laser with almost ideally monochromatic radiation, whose coherence length attained hundreds of kilometers. On the other hand, the radio optical bridge enabled one to measure the laser frequency in the unit for the cesium standard of time and frequency. The length λ and frequency ν are related to the velocity of light c by $\lambda\nu = c$. If c is represented as an exact quantity free from error, then knowing the frequency one can determine the wavelength, and then one calculates the necessary number of wavelengths to arrive at the unit of length: the meter. The error in determining the 1960 meter was governed by the width of the orange krypton-86 line. As that line is unsymmetrical, there is a problem in the determination of the meter: from the maximum of the line or from the center of gravity. Narrower lines from laser sources with accurately known wavelength eliminated this dilemma and opened up good scope for improving the accuracy in reproducing the meter by the interferometric method.

The definition of the meter adopted in 1983 lies however outside these advances. If one modifies this definition by introducing a location procedure, then instead of a planar monochromatic electromagnetic wave (according to the definition) one would use an electromagnetic radiation pulse with a steep front, i.e., one would go to a technology other than interferometry, which at present has not been developed. An attempt to realize that meter with existing facilities would lead to a catastrophic fall in the accuracy [17].

The operational requirement for basic concepts in metrology was violated in the definition of the meter of 1983, but the tradition of operational definitions was maintained. The International Committee of Weights and Measures that took the nonmetrological definition of the meter but at the same time recommended [15, 16, 18] that the meter should be reproduced by interferometry, thus maintaining precedence for the definition of 1960 and incorporating new technologies in radio optical measurements. The accuracy in reproducing the meter increased at once by two orders of magnitude. A difference from the definition of 1960 was that a single source (krypton lamp) was replaced by a list of recommended laser sources providing monochromatic radiation, which from time to time has been updated by the Consultative Committee on Length.

Recent scientific discoveries (laser 1959, Josephson effect 1963, quantum Hall effect 1980) and new technologies in measurements in metrology have made it possible to define afresh the seven basic units linked to fundamental constants. The 1983 definition of the meter is one of the first such. It is related to the velocity of light, whose value is fixed. The next in the queue is the definition of the unit of mass, which in one of the forms will be linked to Planck's constant with a fixed value [19, 20]. The correct formulation of new definitions should incorporate the specific features of the methodology based on the operational definition of basic metrology concepts.

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