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LETTERS TO THE EDITOR

PARADOXES IN THE 1983 DEFINITION OF THE METER

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The general conference on weights and measures in 1983 defined the meter as the length equal to the distance traveled by a plane electromagnetic wave in a vacuum in a time of 1/299792458 second. This definition, from our point of view, contains a fundamental inaccuracy. We draw attention to the previous definition of the unit of length. According to the definition adopted at the 11-th General Conference in 1960, "the meter is a length equal to 1650763.73 wavelengths in a vacuum of the radiation corresponding to the transition between the $2p_{10}$ and $5d_5$ levels of the atom of krypton-86." The number of wavelengths in a vacuum can only be counted by an interferometric method and, consequently, the 1960 definition contains a clear indication on the procedure for reproducing the meter.

This clear and easily realized procedure for reproducing the meter is also given in the first international agreement on the meter, namely, the Metric Convention of 1875 (which functioned up to 1960), in which a standard of the meter in the form of a platinum-iridium rod with two lines was proposed. But the 1983 definition does not in fact contain a description of the measurement operations by means of which the unit of length can be established nor does it describe a method for reproducing it. To what does this lead? If we refer to the 1983 meter strictly in accordance with the literal definition, paradoxes arise.

Suppose the wavefront of a plane electromagnetic wave passes a point A at the beginning of the meter (we assume that it is situated at the first reference line of the platinum-iridium standard), while an observer-metrologist observes the point B at the end of the meter (at the second reference line) and records this wavefront. When the plane electromagnetic wave passes the point B, the observer-metrologist records the fact that the wavefront has passed the point B and no other. No metrologist can measure any distance from one such fact: to do this, two signals, which define the time interval and the spatial interval corresponding to it, are necessary. This is the first paradox in the 1983 definition of the meter.

The two signals required can be obtained if a mirror is placed on the propagation path of the electromagnetic wave, which reflects the wave in the opposite direction. In this case, the time interval between a signal released at the point A and reflected at the point B from the mirror defines twice the distance between the mirror and the observer. Clearly, the corresponding time interval is twice the value cited in the 1983 definition of the meter. If one clearly follows the 1983 definition of the meter (in terms of the velocity of light and the time interval), then, in principle, one can correct the 1983 definition by introducing a location method into it. However, an accuracy problem arises here.

The accuracy with which the meter can be reproduced by a location method is determined by the accuracy with which the time interval can be measured. High accuracy is achieved when using pulses with a sufficiently sharp leading (or trailing) edge and, consequently, with a wide frequency band Δf. This is the fundamental necessary condition for the accurate reproduction of the meter. Here a monochromatic wave is not suitable for accurate measurements.

The time interval in which an electromagnetic wave travels a distance of 1 m, there and back, is equal to $t = 6.67 \cdot 10^{-9}$ sec. The minimum error δt in measuring the time interval is determined by the bandwidth Δf: $\delta t \sim 1/\Delta f$. Assuming $\Delta f \sim f$, we obtain for the relative accuracy in reproducing the meter $\Delta L/L \approx \delta t/t \approx c/2Lf = \lambda/2L \sim 2.5 \cdot 10^{-5}$. The 1960 meter was reproduced with a relative error of $\delta L/L = 4 \cdot 10^{-9}$. Each new definition of the meter introduces an increase

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in the measurement accuracy. In this case, we obtain the opposite – a reduction in the accuracy. This is one more paradox in the 1983 definition of the meter.

In practice, the meter, as previously, is reproduced by an interferometric method using laser sources of electromagnetic radiation. The International Committee on Weights and Measures periodically publishes detailed recommendations on this theme [1, 2]. The outcome is that the definition of the meter does not correspond to practice.

But that is not the only point. There is also the conceptual aspect which touches on the definition of fundamental scientific ideas. In theoretical physics, for example, scientific ideas are revealed in terms of properties which are common for a set of similar physical objects. Abstracting from the particulars, theoretical physics proceeds to idealized ("metaphysical") objects – a point mass, an absolutely black body, an incompressible fluid, the psi-function etc. – and describes physical reality precisely in these terms. The transition from idealized ideas to measurable quantities, in general, is not simple. With the development of quantum mechanics and the special and general theories of relativity, this would seem to be a technical question of conversion into a nontrivial scientific problem. One of its solutions was proposed by Bridgman [3] and would lead to the fact that scientific ideas must be formulated in terms of experiment using rules (operations), describing the measurement procedure. Bridgman's methodology has been called operationalism. Shortly afterwards it was found that the theory cannot manage without metaphysical ideas and hence operationalism has not obtained wide acknowledgement. At the present time there has been increased interest in operationalism. In the "moderate" form, when only certain basic ideas are derived from realistic experiments, it is used as a new approach to interpreting quantum mechanics [4].

From our point of view, the methodology of operationalism corresponds quite adequately to the basic principles of metrology [5]: metrology considers the physical quantities in relation to their quantitative estimate, which can only be obtained by measurement. Hence, concepts are metrologically defined uniquely and strictly in terms of the corresponding measurement procedures. Whereas in theoretical physics one studies "the distance traversed by light in a time t," metrology is interested in how this distance can be measured using some measurement operation which can give it a quantitative estimate. The 1983 definition of the meter rests on idealized (metaphysical) ideas of theoretical physics, replacing metrological (operational) concepts. In our opinion, this is incorrect.

The 1983 definition of the meter became possible due to two prominent achievements – the development of highly stabilized lasers and the radio-frequency bridge, which enabled the optical band of laser radiation to be related to the radio-frequency band. The most important property of this bridge is the conservation of the monochromaticity of the line in the transition from one frequency band to another. Using this property, it became possible to measure the frequency f of laser radiation accurately, and from the formula

$$\lambda f = c_0, \tag{1}$$

where c_0 is the velocity of light in a vacuum, it was possible to determine its wavelength λ. Here the tempting possibility arises of considerably increasing the accuracy with which λ is determined. Thus, if the velocity of light is taken as the accurate value by definition, then, by formula (1), the determination of the wavelength of any source reduces to measuring the frequency of this source. As is well known, of all forms of measurement, maximum accuracy is achieved in frequency measurements. Agreement on the new status of the velocity of light as the fundamental physical constant with an exact fixed value has enabled the accuracy in reproducing the meter (by an interferometric method) to be increased considerably – by two orders of magnitude. Thanks to the measurement of wavelength by a frequency method, it has become possible to determine wavelengths relatively easily in essentially any laser source. As a result, whereas the 1960 definition of the meter was reproduced solely in terms of a single line of electromagnetic radiation (krypton), now one can use a practically unlimited number of radiations to reproduce the meter. The recommendations of the International Committee on Weights and Measures [1, 2] contain a vast list of radiation lines for which the values of the frequency and wavelength have been accurately determined and which are recommended for use to reproduce the meter.

Nevertheless, the International Committee also recommends [2] that the meter (and any distance l) should be determined in terms of the time interval and the velocity of light from the well-known formula

$$l = c_0 t. \tag{2}$$

As already pointed out, such a reproduction of the meter is only possible by a location method and only using essentially non-monochromatic radiation. It therefore gives rise to a contradiction with the practical realization of the meter and with those experimental achievements (the invention of laser and the radio-frequency bridge), which have enabled new monochromatic radiation technologies to be developed.

In our opinion, the unit of length – the meter – must be determined from the position of operationalism, resting on the interferometric measurement procedure. One must choose Eq.(1) and not Eq. (2) as the fundamental relation between the measured quantities. It is precisely Eq. (1), where c_0 is an exact quantity, which enables the wavelength of the radiation to be expressed in terms of its frequency and, in the final analysis, enables one to obtain high accuracy in reproducing the meter. The simultaneous use of both equations (1) and (2) in the 1983 definition of the meter is artificial and excessive.

Following from the above discussion, we propose the following definition of the meter.

The meter is a length, equal to the number N of wavelengths λ of electromagnetic radiation in a vacuum; the number N is equal to the ratio of the frequency f of this radiation, expressed in hertz, to the number 299792458 so that

$$1\ \mathrm{m} = N\lambda = \frac{1}{299792458}\left(\frac{f}{1\,\mathrm{Hz}}\right)\lambda,$$

where the frequency f and the wavelength λ are related to one another by Eq. (1), in which c_0 = 299792458 m/sec.

This definition clearly rests on the interferometric method of measurement and in this respect is similar to the 1960 definition of the meter. But, unlike it, in this definition the wavelength of the source of electromagnetic radiation is not fixed, while the velocity of light is assumed to be an exact specified quantity.

Note also that agreement to give an exact value to the velocity of light is equivalent to choosing velocity as the fundamental physical quantity, the unit of which is exactly equal to the velocity of light. Distance in this case becomes a derived physical quantity. In this connection, we must make a comment in connection with the fairly popular idea, namely, "a single standard of time and length." In practice none of these standards can be replaced by the other, and the procedures for reproducing the standard of time (the second) and the standard of length (the meter) are different. From the point of view of operationalism, this corresponds to two independent metrological concepts, and there is no basis for combining them into a single concept.

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