THE MEASUREMENT OF TIME INTERVALS

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Introduction.

One item on the agenda of the Tenth International Conference of Weights and Measures, held in October, 1954, at Paris, was the definition of the unit of time. Formerly the specification of the mean solar day was precise enough for practically all the needs of physicists, but in recent years progress in the accurate measurement of intervals of time has resulted in the need for a more exact standard. It was for this reason that the discussions on an international level took place in Paris.

The Nature of Time.

As is well known, practically all physical quantities can be measured by reference to units of mass, length and time; symbolized in the theory of dimensions by the letters M, L and T. Time, however, differs from the other two members of this trinity in that we cannot construct tangible standards to represent the unit. At the National Research Laboratories, Ottawa, for instance, standards of length and of mass, representing their respective units to a high degree of precision, can be shown to a visitor, but he will not find the corresponding standard second kept in a vault.

We are conscious of the lapse of time as events occur and immediately pass into memory but we cannot add or subtract discrete portions of time in the way we do with quantities measured by their mass or their length. Much philosophic discussion has taken place regarding time and its relation to the length dimension, and this relation is important in the principle of relativity. While such discussions are interesting, it seems they seldom reach any useful conclusion. My personal feeling is that our conception of the world around us is so conditioned by our own minds that our concepts are really a jumble, on the one hand, of impressions that arise from something existing apart from us, and on the other, of secondary mental effects aroused by those impressions Just as, in the theory of atomic physics, it is affirmed that certain conditions are forever unknowable because the mere operation of observing them destroys their character, so it seems quite possible, on a larger scale, the human mind cannot form a completely objective concept of the world of which it necessarily forms a part.

However, if we cannot hope entirely to unravel the external world by scientific means, we are at least constantly finding additional details to add to our picture of it. One very old-fashioned, but still fruitful, method to this end is the making of increasingly accurate measurements of physical quantities. In such operations the physicist can utilize time still in the guise of something flowing continuously past him, with great success. He is usually concerned with intervals which are of short duration but which must be measured in terms of an accepted unit to a very high order of precision.

The Unit of Time.

Accurate measurements can only be made when we have available precisely defined standards to represent the units we adopt. As the precision of a measurement increases so it becomes more and more difficult to find a complete and satisfying definition of the appropriate standard. Time, flowing continuously, or so appearing to our minds, naturally requires as a standard some series of events which recur at regular intervals. Thus, quite early in history, water or sand passing through an orifice provided a means for evaluating small time intervals. Astronomers satisfied their requirements by utilizing the period of the axial rotation of the earth. As the stars are at a very great distance, the sidereal day became the reference standard, while the deduced mean solar day* was used for many non-astronomic purposes owing to its convenience

* The period of rotation of the earth with respect to a fictitious sun which would give a solar day of uniform duration throughout the year.

The duration of the sidereal day is determined by recording the transits of stars across the meridian, and thus finding the error of the observatory clock. The transit instrument may be considered as a glorified upper portion of a surveyor's transit theodolite and is subject to the same sources of error, e.g. collimation deviation, horizontality and irregularity of the pivots, temperature effects, etc. and elaborate measurements are necessary to evaluate the corresponding corrections as closely as possible. The right ascensions and proper motions of the "time" stars utilized have been found from extensive operations which are somewhat the universe of the time observations.

More recently the zenith tube has come into favor for time determination. It depends on a lens having a mercury surface below it at a distance of about one-half the focal length and a small photographic plate near the node. In this instrument a slight tilt of the lens thus produces negligible error. Short traces of the image of a star passing close to the zenith are registered on the plate and can be correlated with clock indications. Apparently each observatory must employ its own set of "time" stars according to its latitude.

Clocks.

It goes without saying that the observatory clock fills a very important role as a secondary standard in time measurement For many years the pendulum clock held its own and showed a remarkable series of improvements in accuracy as successive inventors contributed their ideas. First of all, escapements were improved so that the necessary external impulse, which sustains the pendulum swing, produced a minimum of disturbance. Later, the slave pendulum was introduced, leaving the free pendulum with very little work to do, and a remarkable degree of constancy in rate was achieved.

In an observatory, several clocks are likely to be used, mounted on piers in an air-conditioned vault. But even with the best design of mounting, precise measurements have shown some small coupling between the different pendulums. It is customary for the interiors of pendulum clocks in observatories to be maintained at low, constant pressures.

Piezo-Electric Clocks.

The development of the thermionic tube has resulted in another type of clock coming into prominence in recent years. If a specially selected piece of quartz is placed between two conducting plates, there is a small dimensional change when the electric potential between the plates is varied. Utilizing this phenomenon aided by electronic circuits, a quartz crystal can be maintained indefinitely in a condition of vibration at, or close to, its natural period for such vibrations, and thus we have a clock. Such clocks, for short intervals of time are probably the most accurate so far invented. Needless to say, as in the case of mechanical clocks of high precision, they require great ingenuity in their installation and operation and a standard quartz clock is just as elaborate as, and perhaps needs more careful housing and attention than, its mechanical predecessors. However, piezo clocks are becoming the standard time-keepers in observatories as well as serving as frequency standards for radio wave propagation.

As a crystal may be vibrating at 100,000 cycles a second and electronic circuits permit quite small fractions of a single cycle to be detected, it is readily seen that the physicist has at hand the means for measuring small time intervals with a precision unattainable with chronographs and allied devices governed by a mechanical clock.

The Precision of Time Measurements.

Here we encounter a difficulty which began to show itself even as mechanical clocks tended to reach their ultimate degree of refinement. No one has yet constructed a clock which will remain as regular over a period of years, or centuries, as does the earth. On the other hand, the errors inherent in the observation of star transits, small perturbations in the inclination of the earth's axis or in its actual period of rotation, etc. are such that, in the aggregate, they may well exceed the variations of a crystal clock, when the interval of time in question consists only of several days. There has also to be considered the gradual slowing of the earth's rotation due to tidal friction, etc.

Hence we have, on the one hand, clocks which cannot be expected to keep accurately in step with the flow of standard time for, say, a century, or even for several years, but which for much shorter periods maintain an extremely steady rate, and, in contrast, a rotating earth whose mean period of rotation over a long interval of time can be determined with great accuracy, but which for most time intervals of importance in physics, is less precise than the clock, even though we must use the earth as the ultimate reference standard.

A few figures may illustrate the situation. Physicists think they can detect a change of 1 in 10^8 or 10^9 of the frequency of a first-order quartz clock during a short time interval. A day as 86,400 seconds and 1 in 10^8 is therefore approximately 0.001 second per day. I do not think any observatory could be sure of measuring the duration of a day even through a week or more, to this precision. Moreover, according to astronomers, the mean solar day has varied by as much as 1 part in 10^7 during the interval 1870 to 1950. The mean solar day is therefore insufficient as a standard for measuring time intervals to a high precision, and in both physics and astronomy there has, for some years, been an evident need for a more precise definition of the standard of time.

The solution to the problem proposed by Mr. A. Danjon, Director of the Paris Observatory and President of the International Committee on Weights and Measures, is to adopt the duration of the tropic year 1900 as the standard for time measurements. According to Danjon the duration of this year (whose mid instant was noon on 1 January, 1900) was 31,556,925.97474 seconds. The duration of a year centered at any other date is obtained by subtracting 0.5303 x t seconds from the standard (t is the elapsed time in Julian centuries counting from noon 1 January 1900) Danjon states that, on this basis, the tropic year centered near midnight on 29 March, 1895, would contain exactly 31 556 926 standard seconds. He recommends the use of this figure in calculations where the reciprocal of the second is referred to the tropic year.

Time measurements based on the proposed standard would have the benefit of a well-defined unambiguous unit, but, presumably, in work of the highest order of precision physicists might have to wait for months, or even years, before applying final corrections to their observations. Only after the reduction of considerable data affecting perturbations, etc., so far as I can see, would the astronomers be able to assure the physicists that the time supplied to them had been finally adjusted to the standard.

It is almost certain that Danjon's proposal will be officially approved by the International Committee on Weights and Measures, which was authorized by the Tenth Conference to sanction an international standard as soon as the International Astronomical Union approved certain small amendments to the original figures approved by the Union.

An Alternative Standard of Time.

It would, of course, be a great advantage if a natural time standard could be discovered which had a very much shorter period than the earth (say a small fraction of a second) and which could be readily available in any laboratory with the confidence that its frequency was always the same. This is analogous to the present situation in length measurement, where light-waves, corresponding to definite atomic radiations, permit accurate length measurement without recourse to the International Metre. As in the case of lengths, so, with such a natural oscillator, very precise experiments could establish, once and for all, the duration of a single cycle in terms of the fundamental standard of time.

For these reasons attempts have been made to utilize the frequencies associated with the radiation emitted or absorbed by certain molecules, where these frequencies are low enough to permit the employment of electronic circuits in conjunction with them. So far the experimental difficulties in developing a natural time standard along these lines have proved to be very great, but we cannot affirm that the goal is unattainable.

One advantage of the "natural" clock would be to give physicists more confidence when accurately measuring short intervals of time. There can occur small frequency changes in the case of man-made piezo crystals, and if, say, the duration of one second is being measured, it is difficult to ensure nowadays that the crystal frequency has remained absolutely constant throughout the interval. An effect based on atomic properties of which we have no reason to doubt the constancy is not so likely to be irregular in this respect.