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The Nature of Time

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Though used with precision, time is often called a mystery. The paradox is resolved by a theoretical conclusion: time is a general property of matter, described by the law that all isolated material changes occur (or would occur) in invariant ratios to each other. The law of time is a corollary of the first law of thermodynamics.

THE TIME PARADOX

The nature of time has been discussed and debated for thousands of years. Today, the discussion continues unabated.[1] Many scientists consider time to be a profound mystery. Remarks such as the following are frequent: "Our awareness of the flight of time . . . remains an ever-mysterious enigma" [2]; "Cosmic years, micro-micro-seconds—we use these terms, define them, but we cannot define time itself satisfactorily" [3]; "Time is instinctively known by us; and, like all things into which we think that we see deeply, it is mysterious. The scientist realizes his inability to touch reality in this field" [4]; "Introspective understanding of the flow of time is basic to all our physics, and yet it is not clear how this idea of time is derived or what status it ought to have in the description of the physical world" [5]; "Physical science has no way of deciding which clock goes at the supposedly 'correct' rate." [6]

Despite such sentiments, scientists usually have no difficulty using time in their work. It is significant, for example, that astronomers learned long ago to predict eclipses and other phenomena to the fraction of a second. The successful 1964–65 voyage of Mariner IV to photograph Mars required computations of high accuracy, and all those computations included time as a factor. Among the important results of the voyage were a better value for the ratio of the masses of Mars and the sun, probably improved values for the astronomical unit and for the mass of the earth–moon system, and increased accuracy in the ephemeris of Mars.[7] But it is taken for granted that the voyage did not add anything to our knowledge of time, and could not add anything. Everybody involved seems to know exactly what time is—or, at least, what to do with it in practice.

Our original clock, the rotating and revolving earth, has variations in its motion so large that astronomers have for some years been using the orbital motion of the moon as a standard because it is more accurate.[8,9] Now we have the possibility of an atomic clock, based on the hydrogen maser,[10] so accurate that "it gains or loses at the rate of a few seconds in 100 000 years." [11] The pertinent aspect of these statements is that we know how accurate our clocks are. We compare their readings with "perfect" time, which means that we know what "perfect" time is, whether we realize it or not.

Therefore, we have an odd situation. Time is often called a mystery, but is used as though it is anything but a mystery. The paradox is illustrated in a magazine article about atomic clocks[12] by Lyons, who, as chief physicist for the U.S. National Bureau of Standards from 1946 to 1955, led a group that developed the first atomic clocks. Lyons' opening sentence speaks of "the mysteries of time," but thereafter he writes with

[1] See, for example, (a) F. C. Haber, Science **152**, 632 (1966), a review of *The Voices of Time*, J. T. Fraser, Ed. (George Braziller, Inc., New York, 1966); (b) T. Gold and D. L. Schumacher, Eds., *The Nature of Time* (Cornell University Press, Ithaca, N. Y., 1967); (c) Edward M. Weyer and Roland Fischer, Eds., "Interdisciplinary Perspectives of Time," Ann. N. Y. Acad. Sci. **138, 2** 367 (1967).

[2] A. d'Abro, *The Evolution of Scientific Thought from Newton to Einstein* (Dover Publications, Inc., New York, 1950), 2nd ed., p. 221.

[3] H. Shapley, *Time and Its Mysteries* (Collier Books, New York, 1962), p. 6.

[4] P. E. Wylie, Griffith Observer **26**, 105 (1962).

[5] See T. Gold in Ref. 1(b), p. vii.

[6] See G. C. McVittie in Ref. 1(c), p. 866.

[7] R. K. Sloan, Sci. Amer. **214, 5,** 62 (1966).

[8] Sky and Telescope **25**, 27 (1963).

[9] W. Markowitz, IRE Trans. Instr. **I-11,** 241 (1962).

[10] D. Kleppner, H. M. Goldenberg, and N. F. Ramsey, Appl. Opt. **I,** 55 (1962).

[11] Sci. Amer. **207, 2,** 55 (1962).

[12] H. Lyons, Sci. Amer. **196, 2,** 71 (1957).

complete clarity, and not one bit of mystery, about various atomic clocks, among them the cesium clock, whose accuracy today "is about one part in 10^{12}. This means that in 6000 years it would not gain or lose more than a second." [13] The work of Lyons and others implies the solution of the supposed mystery. He said,[14]

> The central problem of exact time measurement is to find some periodic cycle that never changes, or changes so little that the variation can be disregarded .... The atomic clocks offer great advantages. The motions of atoms and molecules, which can serve as "pendulums," are absolutely pure and regular. Their rates are inexorably fixed by the laws of the atomic world.

Now this is an overstatement and is not correct as it stands because, as we shall see later, there cannot be a periodic cycle that *never* changes. But the motions of atoms and molecules can be controlled to make them *nearly* "pure and regular," even though it is impossible for them to be "absolutely pure and regular." So with these qualifications, Lyons' statement does imply the solution we seek.

THE DERIVATION OF TIME

Matter is always undergoing change, and time is always associated with material change: physical change, chemical change, change of state, change of relative position. Ordinarily, we think of measuring any material change in units of time. This view is useful in practice, and is likely to remain the best practical way to think of time and to use it. Nor is there anything wrong with this way of thinking—provided we understand its origin and its limitations. Nevertheless, taken too narrowly, it presents a serious philosophical and logical difficulty. When we think of measuring material change in units of time, and when we assume that this view represents the whole of reality, we are left with an important question unanswered and unanswerable—what then is time? Time itself remains a mystery, something beyond matter, forever unknowable.

But consider the origin of this view. Our units of time (with the partial exception of the month) are derived from the motions of the earth. That is, man began *by expressing time in units of material change*, rather than the other way around. Each time unit—year, month, day, hour, second—is derived from material change, and has no other origin. Here, then, is the solution of all the supposed mystery. Matter exists, matter changes, and time is defined and measured in units of material change.

Richard Schlegel put it this way.[15]

> Does the world change because time moves on, or does time move on because there is change? The answer must be that time arises from changes.

In this fundamental view, time can be fully understood and fully described in terms of the known properties of matter. Moreover, since we can describe time in general, we can therefore establish units of time, each unit representing a specific quantity of material change, and we can then measure any other material change in units of time. Our practical way of using time has been given a firm material basis and no longer leads to mystery.

THE POSTULATE OF TIME

All experience in all ages points strongly to the validity of the postulate of time, the implicit assumption on which every use of time is based.

The postulate of time is that if any two changes experienced by matter are isolated (isolated, that is, from each other and from outside influences), the numerical ratio of those changes is a constant. The postulate can be stated another way: all isolated material changes occur (or would occur) in invariant ratios to each other. The word *isolated* is used here as it is used in experimental science, meaning that interfering factors are either reduced to negligible proportions or are controlled at known levels so that calculation can determine how things would stand without them.

The postulate of time is demonstrated on examination of any phenomenon of change. For example, it is well known that every radioactive element seems to have a specific rate of decay, and science can alter that rate only by applying great energy in an accelerator or in a nuclear explosion. Such a change of state is therefore isolated under ordinary conditions. If the changes

[13] Sci. Amer. **218, 6,** 60 (1968).

[14] See Ref. 12, p. 72.

[15] Richard Schlegel, *Time and the Physical World* (Michigan State University Press, East Lansing, 1961), p. 1.

of state of two different radioactive elements are compared, they are found to have the same ratio under all conditions except when their isolation is shattered. Radium 226 has a half-life of about 1620 years, carbon 14 a half-life of about 5730 years. Each half-life is a constant of nature, a property of matter. Or we can compare the properties of two substances used in atomic clocks, the resonance rate of the ammonia molecule, 23 870 129 235 Hz,[16] and of the cesium 133 atom, 9 192 631 770 Hz.[17] Each rate is a constant of nature, a property of matter. ["This (cesium resonance) frequency . . . is a fundamental constant of the atom." [18]] And the ratio between those rates is also a constant of nature, a pıoperty of matter.

When we say that radium 226 has a half-life of about 1620 years, and carbon 14 a half-life of about 5730 years, we are actually stating the time ratios between the decay of those two elements and the revolution of the earth about the sun. Similarly, we are stating the resonance rates of the ammonia molecule and the cesium 133 atom in terms of the rotation of the earth on its axis or of the revolution of the earth about the sun, depending on which of the older definitions of the second is used.

We have nearly always used the rotation or revolution of the earth as the denominator of time ratios because the earth, until a few years ago, was our most accurate clock. Now, when atomic clocks are more accurate than the earth or the moon, their readings are increasingly used as the denominators of time ratios when extreme accuracy is necessary.

Indeed, the world is changing over to a time system in which the second is defined in terms of an atomic resonance frequency. On 13 October 1967 the Thirteenth General Conference on Weights and Measures, meeting in Paris, formally abandoned the old astronomically derived definitions and decided that[19]:

> The unit of time of the International System of Units is the second, defined in the following terms: "The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the fundamental state of the atom of cesium 133."

Thus, science establishes every time scale in units of a specific material change, an almost completely isolated material change.

When we deal with time in practice, it is most convenient to use readings from a single clock (such as the earth) or a single type of clock (such as the cesium clock) as the denominator of all our time ratios. For instance, the resonance rates of the ammonia molecule and the cesium 133 atom are both stated initially in this paper in terms of the earth's rotation or revolution.

But we can directly compare the changes that ammonia and cesium undergo, the ratio of 23 870 129 235 to 9 192 631 770, eliminating the earth's rotation or revolution from consideration. This ammonia–cesium resonance ratio is a time ratio, a constant of nature, a property of matter, and it has nothing to do with the motions of the earth. In their paper on the determination of the cesium resonance frequency, Essen and Parry suggested an experiment to make this very comparison. They proposed[20]

> . . . a precise comparison between the cesium resonance frequency and that of the ammonia molecular resonance. This is of theoretical importance because the forces involved in the two transitions are of a different nature, and a comparison of the frequencies over long periods of time will be of interest.

Blaser and Bonanomi have conducted the experiment. Their paper reporting their work said of an ammonia maser and a cesium resonator[16]:

> In order to obtain a uniform base for the atomic times determined by the different standards, their frequencies have to be compared directly . . . . Such a comparison is of particular interest to prove the consistency of atomic and molecular frequencies produced by completely different devices.

The postulate of time is expressed by a simple equation. Compare any two rates of isolated material change, $\mathbf{c}_1/\mathbf{s}$ and $\mathbf{c}_2/\mathbf{s}$, each (for example) in terms of cycles per second. Find the ratio between those two rates.

$$c_1/s \div c_2/s = c_1/c_2 = K.$$

The time ratio $\mathbf{c}_1/\mathbf{c}_2$ compares two isolated

[16] J.-P. Blaser and J. Bonanomi, Nature **182**, 859 (1958).

[17] See Ref. 9, p. 239.

[18] L. Essen and J. V. L. Parry, Phil. Trans. Roy. Soc. London, Ser. A **250**, 47 (1957).

[19] Natl. Bur. Std. (U.S.) Tech. News Bull. **52**, 10 (1968).

[20] See Ref. 18, p. 68.

changes directly, without reference to the usual standards of seconds, hours, days, or years. Obviously this can be done with any pair of isolated changes, and any such time ratio is always a constant.

Schlegel, from whom I borrow the term *time ratio*,[21] observed[22]:

> The fact that there are cyclic processes which give rise to our time concept must be considered to be one of the major generalizations that we can make about the natural world. The fact that the various uniform cyclic processes do bear a constant frequency ratio to each other is a further general property of nature of the widest significance. This fact is related to what is sometimes expressed as the "uniformity of nature" or the "order of natural law." . . . The constancy is so universally found for a given ratio of cyclic frequencies that we confidently assume the constancy to exist everywhere in the universe. Further, we confidently and usually justifiably assume that noncyclic processes have a similar uniformity.

Clemence has discussed time ratios; he calls them frequencies. He said[23]:

> Another class of entities is based exclusively on time intervals.... A frequency . . . is the ratio of one unit of time to another and is, therefore, a pure number. When we say that there are 365.2422 days per year we are stating a frequency. When we say that the frequency of a particular alternating current is sixty cycles per second, we are stating the ratio of two units of time, the cycle and the second.

Clemence seems to suggest[24] the possibility that time ratios are not constants of nature, as I contend. He says, "There is no a priori reason for assuming them to be,"[25] and cites papers by Dirac[26] and Jordan[27] on the subject. Clemence says "Dirac's basic postulate was that the constant of gravitation is diminishing with the passage of time, at the rate of about a part in 10^{10} per year." Clemence considers the subject to be "an open question," and says that, "Eventually the question whether atomic time is accelerated on ephemeris time will be settled by experiment, by comparing the two time scales."

At present, we can determine a few time ratios with great accuracy, but we can determine them only empirically. Because time ratios are properties of matter, it is certain that adequate knowledge of atomic and molecular structure and function will eventually enable determination of many time ratios from theory. It is also certain that empirically-determined time ratios will help in investigations of atomic and molecular structure and function.

ISOLATION

In 1964, the International Committee on Weights and Measures adopted a temporary definition of the second, specifying the necessity that atoms of cesium 133 be "not perturbed by external fields"[28] as a condition of accuracy in an atomic clock. In nature, of course, a material change is never completely isolated, just as an element or a compound never occurs naturally in the pure state. But scientists can isolate a material change almost completely, just as they can purify an element or a compound almost completely. In an atomic clock, a change is almost completely isolated,[29] so that its rate is almost uniform. Moreover, the men who build an atomic clock know, with only a minute error, how much their clock readings vary from "perfect" time, which means they know what "perfect" time is, in practice at least.

David Bohm's discussion of isolation[30] is pertinent here.

> In observations and experiments, an effort is made to choose conditions in which the processes of interest are isolated from the interference of contingencies. Although no such effort can lead to a complete avoidance of contingencies, it is often

[21] See Ref. 15, p. 5.

[22] See Ref. 15, p. 8.

[23] See G. M. Clemence, in Ref. 1(a), p. 412.

[24] See Ref. 1(a), pp. 412–413.

[25] I contend there is a most compelling reason for assuming them to be constants of nature: the first law of thermodynamics. See the section of this paper titled, *The Definition of Time.*

[26] P. A. M. Dirac, Phil. Trans. Roy. Soc. London, Ser. A **165**, 199 (1938).

[27] P. Jordan, Z. Physik **157**, 112 (1959).

[28] Compt. Rend. des Séances de la Douzième Conférence Générale des Poids et Mesures, Paris, 6–13 Octobre, 1964, p. 93.

[29] See Ref. 12, p. 76, for a description of how cesium atoms are controlled to isolate those with the proper resonance. A beam of atoms "is sent through a magnetic field which acts to select only atoms in certain energy states."

[30] David Bohm, *Causality and Chance in Modern Physics* (D. Van Nostrand Company, Inc., Princeton, N. J., 1957), pp. 2, 4–5.

> possible to obtain a degree of isolation that is good enough for practical purposes. If, then, the predictions based on our hypotheses are consistently verified in a wide range of conditions, and if, within the degree of approximation with which we are working, all failures of verification can be understood as the results of contingencies that it was not possible to avoid, then the hypothesis in question is accepted as an essentially correct one . . .. Even where contingencies are important . . . one may *abstractly* regard the causal law as something that *would* apply if the contingencies were not acting.

THE DEFINITION OF A CLOCK

A clock is a physical system (natural or man-made) that isolates, to a considerable degree, a change experienced by matter. The accuracy of any clock depends on the degree of isolation. A clock that would completely isolate a material change would be a "perfect" clock and would keep "perfect" time.

When we isolate a material change in a clock, we do so on the assumption (the postulate of time) that any other change similarly isolated would occur in an invariant ratio relative to the change in our clock. All such ratios are constants of nature—they are time constants, time ratios.

Any one of the infinite number of changes occurring in nature would provide "perfect" time if completely isolated in a clock. Any isolated change can be expressed in terms of any other isolated change to form a time ratio.

Any material change is isolated to some extent, and to that extent it is a clock, however crude. Animals and plants are biological clocks. Hamner has pointed out[31] that "this behavior (as a clock) results not only from responses to physical conditions of the environment but involves an innate capacity to meter the passage of time." [32]

Rarely, an individual musician (Mozart, for example) has "absolute pitch"; on hearing a note, he can identify it on the scale. In effect, he can tell the vibration rate of any note he hears, the number of cycles per second. He is, therefore, a rather accurate biological clock.

[31] See K. C. Hamner, in Ref. 1(a), p. 281.

[32] It is of minor importance here, but Hamner's phrase "meter the passage of time" could be construed to mean that time is something separate from the material changes occurring in a biological clock, a view rejected as incorrect in the final section of this paper.

THE DEFINITION OF TIME

My argument is that all experience, especially the precise work done in the last few years, confirms the validity of the postulate of time. That being so, we are entitled to assert with some confidence that the postulate is more than a postulate: It is a law of physics.

We are entitled to include the law in the definition of time: Time is a general property of matter, described by the law that all isolated material changes occur (or would occur) in invariant ratios to each other.

The law of time is a corollary of the first law of thermodynamics. The proof of this is that, given two isolated material changes, their numerical ratio must be a constant, else the first law of thermodynamics would be violated.

These statements assume, of course, that the first law of thermodynamics is strictly correct, and that the constant of gravitation does not change.

Every material change involves motion and energy, so the law of time is a law of motion and energy, and is in strict harmony with all other laws of motion and energy.

To illustrate this concept consider the rotating earth as a clock, and the rotating Mars as another clock. Their rotations are fully explained by the Newtonian laws and the energy law. Their isolation from other large astronomical bodies is sufficient to make them very accurate clocks. The ratio of their rotations is very nearly a constant—a time constant, a time ratio. The variations from constancy are fully explained both qualitatively and quantitatively, qualitatively by the fact that the isolation of the two planets is not (and cannot be) complete, quantitatively by the laws mentioned above. Applying those laws to the variations from constancy, we can calculate what the time constant would be if the two planets were completely isolated (which, incidentally, is a fundamental way of stating the fact that there are variations in their motions). True, there remain minute residual variations that are as yet unexplained, but celestial mechanics assumes, on the basis of experience, that the residuals, too, can be fully accounted for by classical laws.

The law of time is also an extension of the laws of quantum mechanics, as we can infer from Lyons' words quoted previously.[14] "The motions of atoms and molecules . . . are . . . pure and regular.

Their rates are inexorably fixed by the laws of the atomic world." Essen, referring to atomic clocks, spoke[33] of

> . . . another event . . . regularly repeated in nature. This is the radio wave generated by an atom when its electron arrangement is changed slightly from one stable condition to another. The frequency of the wave is defined by one of the most fundamentally important relationships in physics and is simply proportional to the difference in the energy of the atom in the two states.

Emphasis must be given to the statement that time is *a property of matter*, just as elasticity, viscosity, and mass are properties of matter. Emphasis is necessary because most of the confusion about the nature of time originates in mystic notions that time is absolute, something beyond matter, outside of matter, independent of matter, higher than matter, notions that time "flows" by itself without reference to matter, notions that we compare material changes with a spooky beyond-the-blue-horizon "Time" sitting on Mt. Olympus with the other gods.

There is nothing mystic about mass; it is a property of matter. Viscosity is a property of matter, and has no other existence. Elasticity does not exist separately from matter; it is a property of matter, nothing else.

These statements are also true of time. Time is a property of matter—that is all it is. If there were no matter, there would be no mass, no viscosity, no elasticity—and no time.

EXACT MATERIAL TIME

As noted above, a clock would keep "perfect" time if it could completely isolate a material change. Here "perfect" time means what is usually meant by the phrases "absolute" time, "abstract" time, or "ideal" time. Such phrases, while they have a certain validity, are nevertheless unsatisfactory because each can be construed—and is often construed—to mean that time is independent of matter. Their ambiguity tends to perpetuate a mystery that should not be a mystery.

For this reason, it would seem that science needs a term or phrase which clearly denotes what time really is. The name *exact material time* would be useful. Its definition is simply that a clock completely isolating a material change would keep exact material time. The reason for the word *exact* is obvious. The reason for the word *material* is that we need to learn and remember an important fact—time is a property of matter, and does not exist except as a property of matter.

Really, the concept of exact material time is a familiar one, even though it may not have been presented in these words before. When we say of the cesium clock that "in 6000 years it would not gain or lose more than a second," [13] we mean that we are comparing its readings with exact material time. We should say so.

ACKNOWLEDGMENTS

To a considerable degree, this paper is based on the work of Richard Schlegel[34] and is a development of it. I thank Schlegel, Clayton Van Lydegraf, and Sherwood Parker for their clarifying and corrective criticisms.

[33] L. Essen, Phys. Today **13**, **7**, 28 (1960).

[34] See Ref. 15, Chap. 1.