Is direct measurement of time possible?

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Abstract. Is direct measurement of time possible? The answer to this question may depend upon how one understands time. Is time an essential constituent of physical reality? Or is what scientists are talking about when they use the symbol 't' or the word 'time' an human cultural construct, as the Chief of the USA NIST Divisions of Time and Frequency and of Quantum Physics has suggested. Few aspects of physics do not reference activity to time, but many discussions within either view of time seem to use one same, largely traditional, language of time. Briefly considering the question of measurement, including from a formal measure-theoretic point of view, clarifies the situation.

1. Introduction
There is a thread in physics which raises questions about whether time as traditionally understood actually is or is not an essential aspect of physical reality, a fundamental constituent of the universe. There are a variety of interpretations of how the universe may be "timeless", but discussions of time metrology are not a prominent feature of them.[1]

Modern standardized time metrology involves exquisitely complex physical apparatus.[2] But one might think that an aspect of the world considered so fundamental as time would be accessible more directly than that. In the historical development of the concept and use of time, simple direct observation of readily apparent features of the world were considered sufficient to tell time.[3] Those features even now perhaps have not been entirely superseded—the present standard definition of the “second” is the current iteration of a sequence of refinements tracing back to pre-atomic science and folk culture.[4]

With the rise of science and technology since the European Renaissance and especially Galileo, the uses of time changed along with the increasingly fine scale at which time metrology operates.[5] As a comparison, matter, too, is ordinarily understood to be a fundamental aspect of the world albeit of a different kind, and the atomic theory of matter has existed since at least the Ancient Greeks.[6] But conceptions of the essential nature of matter were profoundly changed when increasingly refined experiments accessed increasingly smaller physical scales. The understanding of atoms came to include component entities which at first were not directly observable. Milliken’s 1909-11 oil drop experiments produced an early direct or nearly so measurement of electrons, and his 1916 paper on the photoelectric effect continued with direct or nearly so measurements relating the atomic electron and the light photon. Now, based on complexly mediated experimental techniques and interpretations, the Standard Model presents a systematization of additional sub-component entities, and even the dynamics of atomic
components and processes are becoming observable.[7] However, modern time metrology, despite its subtlety and fineness, has not found any substructure of time.

So if time metrology, as sophisticated in complexity and in fineness of scale as it now is, has not produced a clear answer to the question of whether nature is timeless or not, perhaps going back to basics will help. Consider the question: “Is Direct Measurement of Time Possible?”.

2. “Direct”

By “direct measurement” is meant measurement made with systems the components and values of which do not involve chains of subcomponents and of reasoning and interpretation to provide results. A canonical simple example for measuring space is a measuring tape. A child can assess its surroundings and an adult can build a house using only a measuring tape to identify spatial extents. It is a spatial object which one can directly handle and move at will, and can reuse in different spatial locations and situations without alterations. Other objects are directly compared to it. One merely extends the tape and holds it directly beside some other spatial object to tell directly the length of the other object. No theoretical interpretation is necessary, nothing intervenes between measuring tool and measured object. One holds the tool and sees the value, whether measuring an object or an empty spatial extent.

To make the contrast explicit, a toy example of non-direct would be measuring a spatial object (a) visible in a mirror, by walking around the room until (b) some other object—a chair, say—exactly obscures the mirror image, then (c) measure the chair, and finally (d) use trigonometric relationships to calculate the original object’s length from the chair’s size and from relative positions of things.

If a time dimension exists, it is not like a spatial dimension. No formally organized direct physical manipulations, the usual concomitants of measurement, are available. One cannot stand beside a temporal object and see all of it, nor cut it in half, nor separately manipulate halves, nor move pieces around, nor assemble a temporal object from various temporal pieces. There are no Cuisenaire® rods showing a temporal parsing which matches a number system, like those spatial objects for children do.[8] Though numbers are used as time values, the only inherent physical operation is increase; and there is no control over that.

Further, in the case of time actually there are no recognizably temporal objects of any kind to which to have a direct relation. Neither is there anything like an empty extent of time. Although various spatial objects have been used during the historical development of the time concept as markers within various conceptions of time, they are merely spatial, even if motion is involved.[9]

As a source of indirect but pertinent evidence about the issue, consider humans, the dominant species on Earth. Humans evolved able to live in climates from hot tropics to icy Arctic. They evolved able to kill mastodons to eat, to kill lions to avoid being eaten, to kill three-dimensionally spatially motile birds in flight, and to kill each other, with only wood and stone tools. That human species as well as myriad “lesser” creatures have evolved binocular parallax vision and skin sensory receptors, and are able directly to sense spatial distances and lengths.[10] In the battling competitions of “nature red in tooth and claw”, one would expect that over many millions of years some organ would have evolved to sense time directly, and would be known as such. But there seems to be no such evolved feature. This is a modern statement of Poincaré’s point: “We have not a direct intuition of the equality of two intervals of time. The persons who believe they possess this intuition are dupes of an illusion.”[11]

3. Formal Measurement Theory

The actual doing of measurement can be very complex. But in measure-theoretic terms, the formal essence of measurement is matching members of one set, considered to be the measured, to members of another set, considered to be the measure.[12]
More thoroughly stated, consider a set A of empirical phenomena distinguishable from all other phenomena, and a set of relations R over the elements of A. Together (A,R) form a relational system of which A is the domain. (A,R) is taken as data, found rather than constructed in the same way that a collection of people and their relative physical heights is considered to be found data for the purpose of measuring them. There is another relational system (B,S), with domain B and relations S, which is a cultural construct. That is, the choosing and pairing of B and S to be (B,S) and the use of (B,S) for measurement is an agreed arrangement specified—a shared choice made—by people and as such is an human cultural construct, a tool to be used for a purpose, in this case for measurement. A system of measurement is a mapping from (A,R) to (B,S), and also is a cultural construct.

To be considered science, and certainly to be a physical science, (B,S) is generally required to be a mathematical relational system, with B numbers and S some n-ary mathematical relationships. In terms of these basics, much of the activity of mathematical physics consists of identifying appropriate number systems to be candidate Bs and suitable mathematical relationships S among the members of each Bi. And experimental science’s focus is to find whether an A of interest is partitionable according to some R in a way mappable to some (B,S). Note the distinction that whatever may be the raw uninterpreted result of an experimental run, or whatever mathematics may be involved in arriving at final relations among numbers, only the final output number for a phenomenon, comparable to other final output numbers, is the measure or more properly the “measured value”.

A measuring tape gives the (A,R) \rightarrow (B,S) mapping directly, including its visible final value output. In quantum physics for example the situation is less clear. Wigner’s classic 1963 paper “The Problem of Measurement” is concerned with how theory is involved in the data collection and interpretation complexities of experiment, and how that relates to measured results. Formal measurement theory as discussed here was first proposed in 1957, and Wigner’s article shows no obvious awareness of it. So it is an interesting exercise, which will not be done here, to go through Wigner’s article and identify what relates to (A,R), what to (B,S), and what to mapping.[13]

When experiment gives satisfactory results, A and and its characterization in terms of R are talked about as though they are reality. By the scientific method, measurability justifies vocabulary. “Heavenly spheres ”used to be considered real, now they are poetry and orbits instead are reality.

4. Time

“For that is what time is: a number of change in respect of the before and after. So time is not change but the way in which change has a number.” Time “measures change”. (Aristotle, Physics)[14]

“[T]ime is an abstraction, at which we arrive by means of the changes of things. ... [Absolute time] is an idle metaphysical conception.” (Mach, The Science of Mechanics)[15]

“My own personal opinion is that time is a human construct.” “[B]ut what time really is, is a question that I can’t answer for you.” (Tom O’Brien, Chief of United States NIST Quantum Physics Division and of Time and Frequency Division)[16]

In dim prehistory, awareness that things change and some changes are vital and should be kept track of—eg when planting season begins—was a shared experience, and that brought vocabulary. The primitive origins of modern timekeeping, recognizing divisions within natural cycles and counting repetitions of natural events, required more vocabulary.[17] By now, time vocabulary is traditional and well-established, including its implicit reification of time as a thing real in the same sense the rest of the physical world is real. But traditional vocabulary
can mislead. Textbook and even theoretical discussions still use time vocabulary, including “spacetime”, in ways reifying an understanding that time is self-substantial and has various characteristics. Yet experimental practice in science uses time values simply as a more or less arbitrary uniform comparator in describing dynamic processes.

Historically, replicable scientific timekeeping became possible with the Galilean pendulum, and the low friction pivot isolating its periodicity from local disruptive influences. In the attoworld of modern science, atomic clocks provide highly granular timekeeping standards, with continual improvements based on increasingly sophisticated understanding of light phenomena.[18] These modern types are founded on light frequencies, which are believed to be constant when isolated in the same way that—and because—light speed is constant. In the USA the NIST Division responsible for this is named “Time and Frequency”, but frequency is more basic. The system depends technologically on accurately comparing and counting atomic transition cycles and light frequency cycles.[19]

But time is not “measured”. Rather some atomic transition cycle is chosen as a canonical unit of activity—informally, as a “tick”—; some number of sequential ticks is observed in coordination with some number of cycles of light; and that sequential existence is said to mark out what is to be considered one second of time. That is, seconds of “time” are generated, and are asserted as a reference to which to compare activity of other things. This “time” is merely a simple counting number, a culturally agreed upon reference counter usable anywhere, with zero being arbitrarily assignable at any point, exhibiting a mathematical elegance or pure numericality suiting it to be the ubiquitous ‘dt’ of ‘dx/dt’.

5. Conclusion
The answer to the title question seems to be that the question itself is wrong. “Time” is not an entity to which the operations of measurement, direct or indirect, apply. Instead it is a widely shared cultural construct, based in social activity in which the system of standard time values provides an universal, neutral, non-perturbing reference parameter for use measuring dynamics of other things. The effect is not unlike Newton’s absolute time but without reifying it as “absolute” or as “true”, keeping only the “mathematical” and “abstract” and using technology and social organization to refine “vulgar measures” into the functional analogue of an absolute.[20] The idea of time can be reduced to pure counting and as such is an epitome of abstraction, limpid in comparisons, available and effective as parameterization.

Formally, very often the measurement task in physical science is to find a mapping, not \((A,R) \mapsto (B,S)\) but \(((A,R),(C,T)) \mapsto (B,S)\), where \(C\) is a set of clock timestamps and \(T\) is relations among them. Deciding how \((A,R)\) and \((C,T)\) are to be put together and compared is an aspect of experimental design. But \((C,T)\) is supposed to be uniform in all experiments or at least relatable from experiment to experiment. The reason why the title’s question is wrong is that \(((C,T),(C,T)) \mapsto (B,S)\) is undefined—the measuring tape cannot be combined with nor compared to itself to measure its accuracy.

The traditional time vocabulary is well-established because in many social contexts “now”, “then”, “until”, “before”, “after”, etc are all useful, efficient references to complex configurations of spatial objects. However, in science it would be desirable to remove the realness or reification presumption while keeping the aptness for parameterization, leaving all reification to apply only to physical clocks. For example it could be possible to clarify the scientific time vocabulary by making small adjustments. One low-effort start might be to substitute the phrase ‘time value’ many places where ‘time’ ordinarily would be used; use ‘timekeeping’ rather than ‘time’ in many discussions in Special Relativity; and in almost all contexts, to stop referring to “measuring time”, perhaps using the not unusual phrase ‘counting time’. Change is possible—in scientific publication equal use of ‘she’ and ‘he’ for the neutral personal reference has become common.
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