The manifold definitions of time

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We are unable, using our five senses, to feel time, nor, using our intelligence, to define it, because we stand inexorably within time. We achieve a representation of time through evaluation of changes in ourselves and in our environment. This is made possible by memory functions. What if time only existed as a construct in our minds, and what if the absence of this construct made our mode of thinking uncomfortable to us? If our two major tools for constructing our world, feeling and reasoning, are of little help, then the study of time, ie, chronology, might exist as a list of scientific hypotheses, and remain, to some extent, a philosophical question—an enigma that has been approached by thinkers for more than two millennia. In this review, various fields of knowledge are discussed in relation to time, from philosophy and physics to psychology and biology. We discuss the differences between Chronos and Tempus, respectively the time of physicists and that of psychologists.

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Introduction

What, then, is time?

If no one asks me, I know what it is.

If I wish to explain it to him who asks me, I do not know.

Saint Augustine¹

An initial issue regarding time is that, in our Western mode of thinking, we have retained Heracleitus' metaphor of time being a river which we never can enter twice, because it never remains the same. This is one the main assertions or principles attributed to Heracleitus (~510--~450 BC): "all things flow and nothing stands."² Marcus Aurelius (121–180) completed the metaphor when he wrote: "Time is like a river made up of the events which happen, and a violent stream."³ And Salvador Dali (1904–1989) more recently expressed the same idea in his famous painting of soft melting pocket watches. The idea of the passage of time is indeed strongly embedded in our culture.

The message of Heracleitus is that everything passes, therefore not only time, but we ourselves, also pass. Everything changes constantly, and it is the world that flows. The term "the past" in itself contains the idea of flow. In the case of the river, we know (and have done

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since Galileo's time) that gravity makes it flow. The use of this river metaphor to describe time leads to the illogical idea that the past might be located at a higher position than the future.

A second issue regarding time is its unicity, ie, whether there is only one time or a variety of times. E. T. Hall (1914–2009),⁴ studying various cultures, created the concepts of monochrony versus polychrony, which he illustrated with examples of waiting in line: in Northern countries, everybody patiently waits in line, while in more Mediterranean areas one sees several people being served simultaneously in the markets. For thinkers and researchers in general physics, from Galileo to Einstein, monochrony rather than polychrony is the accepted principle. They criticize polychrony, seeing it as a metaphor, because it includes versions of time that cannot be measured. However, as of the last few years, scientists in particle physics imagine several simultaneous times. All of them, except time as we know it, would be wound or rolled up on themselves, ie, they would be cyclical.⁵ These new ideas suggest that polychrony might also concern physics.

A third issue is the question of causality, as defined in philosophy and physics: if the principle is to be respected, there is no possibility of any beginning, either with linear nor with cyclical time.

When one turns toward dictionaries, with their usual charming circularity, one reads that time is a duration,

that it is a succession, or that it is represented in its essence.

In the first meaning, time is a duration; it can then be indeterminate and continuous; it can also be a fragment of a given duration, itself limited by the activity of a person, or by the nature of a biological process. In many cases, duration can be objectively measured, as finite phenomena within complex ensembles. For example, part of a step in dancing, a beat in music, time-sharing in data processing, etc.

In the second meaning, time is a succession: it is a moment in a series of states, of single events; one speaks of the time of ancient culture, of a person's period in life, etc.

The third meaning, time considered in its essence, refers to several definitions. Time is associated, depending on historical period and literary genre, with precariousness, with the fleeting nature of life, with the end of all human achievements. Through personification, time is described as the allegory of an old man holding a scythe. In religion, for example Christianity, the coming of Jesus inserts human time into the eternity of God. In philosophy, time is a recurrent theme.

It is a daily observation that there is an opposition between the time of physics and the psychological time, between *Chronos* and *Tempus*.

Philosophical distinctions are defined in *Box 1*.

Box 1

Guide to philosophical concepts cited in this review

Materialism: matter constructs reality; all things are composed of material and all phenomena (including consciousness) are the result of material interactions; opposed to any kind of **transcendence** (superstition, mythology, supernatural, spiritualism, theology, religion, deism, idealism). Authors: Democritus, Lucretius, Nietzsche, Bertrand Russell. "Matter is the substratum of mind (soul, spirit...)."

Empiricism: knowledge comes only or primarily from sensory experience; Authors: Aristotle, Okham, Bacon, Hobbes, Locke, Hume, Einstein. Opposed to **innatism** (innate ideas) or knowledge a priori. Authors: Plato, Descartes, Leibniz.

Idealism: the nature of reality rests on the mind, on abstract forms or mental representations. Authors: For idealism: Plato, Plotinus, Descartes, Leibniz, Kant, Poincaré. "Mind (soul, spirit...) is the substratum of matter." Opposed to **realism**, which asserts that the external world has an independent existence of human consciousness or human knowledge; it may consist in refusing all reality to phenomena, it may assert that thought is the only certain reality, it may derive reality from a spiritual principle. Authors: Aristotle, Thomas Aquinas.

Chronos, from empirism to idealism

Chronos, time according to physics, is objective (does not depend on us), is uniform (shows no acceleration), is linear, and we know how to measure it. As of October 13, 1967, a second is the duration of about 9 billion periods of the electromagnetic wave emitted by a Cesium 133 atom, when it changes from one level of energy to another. Astronomic clocks were the first to be used by man. Before clepsydra and hourglasses (egg timers), we counted the days, taking advantage of the colossal clock that is the sun.

There have been methodological difficulties in calculating the mean solar day, because one has to assume that the sun moves at a constant speed, or to calculate the mean sidereal day, because one has to assume that stars keep the same relative position with respect to each other.

In precision clocks, the regularity of movement comes from a pendulum that oscillates under the influence of gravity: the duration of a half-cycle depends on two elements, the length of the pendulum and the intensity of gravity (which is not uniform at different earth locations). The unit of time is thus defined using a measure of length.

According to Aristotle (384–322 BC), time is just this—a degree of motion with respect to “before” and “after.”⁶ And “hence time is not movement, but only movement in so far as it admits of enumeration.”⁷ Moreover, time is continuous⁸ and is the same everywhere and simultaneously.⁹ What Aristotle includes in the term *movement* concerns the place (moving, shifting) as well as the quality (change in shape or state), the quantity (increment, decrement), and the essence (appearance/disappearance, birth/death). There are ties between time and movement, but time is not movement: movement varies, and is polymorphous, while time does not change.

But time, which is a number, does not exist without the soul (nowadays we would say the mind), outside of the soul.¹⁰ “The instant, the “now,” that separates between “before” and “after,” is an abstraction that exists only in the mind. It is a boundary conceived to delimitate, not a part of time.”¹¹

The measure of time determines what separates the beginning and the end of a movement. Plotinus (205–270), a neo-platonician philosopher, raised the issue of self-reference in a definition of time based on time, and said that this was a confusion between what is numbered

(measured) and what numbers (measures). In contrast to Aristotle, he argued that time existed before number was applied to it.¹²

One should remember that, at the time of Plotinus, Christianity strongly influenced philosophy and science: Adam had committed a sin, and since then the soul of man was separated from God and thrown out of eternity into temporality.

Saint Augustine (354–430) says that there is no time outside of the soul. Here is the quotation that follows the epigraph:

But, then, how is it that there are the two times, past and future, when even the past is now no longer and the future is now not yet? But if the present were always present, and did not pass into past time, it obviously would not be time but eternity. If, then, time present—if it be time—comes into existence only because it passes into time past, how can we say that even this is, since the cause of its being is that it will cease to be?

Thus, can we not truly say that time is only as it tends toward nonbeing?¹³

This quotation follows the idealistic philosophy that, from Parmenides (~520–~455 BC) to Plato (~428–~348 BC), stands in opposition to the empiricism of Aristotle. As another illustration, Plato wrote that time is a moving image of eternity.¹⁴

If time only exists by and for the soul, then what does one measure when speaking of time? Saint Augustine gives a clear answer: “I measure something in my memory which remains fixed.”¹⁵ He was the first to relate time to memory; much later, Dali did the same when he entitled his 1931 painting of soft watches, mentioned above, *The Persistence of Memory*; currently, the role of memory functions in relation to time is the theme of much research in neuroscience.

The opposition between the phenomenological description of time using memory by Saint Augustine and the mechanistic explanation of Aristotle of time being the *number of movement* has never fully been solved in Western philosophy.

The beginning of modern physics

The materialist tradition also favors eternity in relation to time: atoms and the emptiness of the universe are infinite, uncreated, and imperishable. Time represents an illusion due to the appearance in consciousness of events that, in themselves, are accidental, according to Lucretius

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(~98~55 BC).¹⁶ Until the 17th century, one did not make the distinctions between three versions of time: time as an abstract number, time as it is measured in physics, and duration (a version of time as felt in our consciousness).

Galileo (1564–1642), the founder of modern physics, considered the universe to be written in the language of mathematics—an idealistic idea opposite to Aristotle’s empirism—and saw the world as expressing an eternal order of things, that we can conceive, although we cannot feel them. Galileo’s idea of an eternal and undifferentiated time replaced the concept of a time consecutive to movement. From Galileo to Einstein, separating rest from uniform movement became a matter of frame of reference, or, put differently, a matter of position of the observer. A popular example of the role of the observer’s position is when we are seated in an immobile train, and the departure of another train gives us the impression that our train is moving.

Galileo also invented thought experiments: if one makes the hypothesis that a theory is true and one demonstrates that reasoning based on this hypothesis leads to dead ends, then the theory is false. Performing such a thought experiment, he concluded that the speed of fall of an object is proportional to the duration of the fall and independent of the mass of the object. This was the first historical occurrence of a physical law being expressed using the parameter of time.

Later on, Newton (1643–1727) asserted the reality of an absolute space and of an absolute time: “Absolute, true, and mathematical time, of itself, and from its own nature, flows equably without relation to anything external, and by another name is called duration.”¹⁷ He defined time as a succession of mathematical instants (an entity with no length). Thus, with respect to his own definition, using the name of duration is inadequate. Time according to Newton is a mathematical variable having one dimension, continuous. Only two topological objects have this characteristic, a line and a circle. It thus follows that time is either infinite or cyclic.

Leibniz (1646–1716) was as idealistic as Plato, when he stated: “I hold space to be something merely relative, as time is, taking space to be an order of coexistences, as time is an order of successions.”¹⁸

Conversely, wrote Kant (1724–1804), one can neglect all information coming from our senses (sensitive data), but never can one leave out time and space, which are indispensable for any representation.

The representation of space cannot, therefore, be empirically obtained from the relations of outer appearance. On the contrary, this outer experience is itself possible at all only through that representation.¹⁹

Time is, therefore, given a priori. In it alone is actuality of appearances possible at all. Appearances may, one and all, vanish; but time (as the universal condition of their possibility) cannot itself be removed.²⁰

The principle of causality

Physicists chose the linear version of time on the basis of the principle of causality, which was first introduced by Leibniz. There are several descriptions of this principle,²¹ ie, the relationships between causes and effects. First, a cause necessarily precedes its effects (this precludes a cyclical time). Second, the same causes induce the same effects (and the repetition of a cause leads to the repetition of the effects, sometimes leading to cycles. I emphasize that cyclical time is not synonymous with repetition of cycles). Third, there is a mandatory chronology between the effect and the cause, and the effect of a cause cannot act retrospectively on the cause. In cyclical time, a cause A leads to an effect B, and in the future of B one could come back to the past of A: while growing older, one could enter one’s parents’ past and prevent them from meeting one another! Cyclical time is not time, since there are then no distinctions between past and future. And fourth, the past cannot be modified (it will always be that what occurred in the past did occur).

As of the 19th century, the definition of what is a cause became more complex as the science of thermodynamics developed: mathematical distribution functions were used to describe gas molecules in terms of probabilities, a rather new concept. More recently, at the beginning of the 20th century, a form of causality principle without cause arose from quantum physics: with certain types of phenomena, which are causally related, a chronology is mandatory, but one cannot establish that the first phenomenon causes the second. Despite these new ideas about the nature of causes, physicists kept the principle of causality as a valid axiom for their work.

In conclusion, in the terms of physics, the principle of causality makes it such that time cannot be cyclical (repeating itself indefinitely), but that cycles in time can exist (phenomena can repeat themselves).

Tempus

The other time, Tempus, is time as we experience it subjectively. It does not flow uniformly, it depends on our emotional status, in the broad sense of activation, vigilance, and mood: time is *elastic*, and the phenomenology of this characteristic has been the theme of many studies. Tempus, the subjective or psychological time can not be measured with Chronos, but nevertheless can be compared with it. Tempus rarely flows as we would wish it to: a minute being bored or an hour of passion cannot be measured using the tools of physics. This is why we carry watches, so that we do not lose track of time.

Aristotle had already observed the subjective nature of time: “but neither does time exist without change; for when the state of our own minds does not change at all, or we have not noticed its changing, we do not realize that time has elapsed.”²²

In myths, time is considered as what will occur, the future. Many myths speak of a world before time, a world in which time had yet to come into existence. Amusingly, astrophysicists have a similar argument when they describe the origin of the universe. Recall that in the Bible, after Adam ate the apple, God said: “behold, the man has become like one of us, knowing good and evil; and now, lest he put forth his hand and take also of the tree of life, and eat, and live for ever.”²³ Adam was punished for wanting to achieve eternity and he was thrown into temporality.

Etienne Klein (1958-)²⁴ reinterpreted a Greek myth about the birth of time as follows: At the beginning of all things, Gaia arose from Chaos and gave birth to her son Ouranos while she was sleeping—out of time. Gaia was in the center, Ouranos all around, and there was no space between them. Gaia became pregnant and the Titans, children of Ouranos, could not be born because of the lack of space. One of the Titans, Kronos, made it possible to chase away Ouranos, and this enabled space to be created. Gaia was able to give birth to the Titans. They later procreated, and this succession of births created time, Chronos.

According to Klein, a confusion we make between time and future dates back to that myth. A major contribution from this author is the notion that time has never been thought of as what produces duration.²⁴

Time and biology

Biological clocks such as the suprachiasmatic nucleus deal with the generation of circadian rhythms.²⁵ Many

other temporal physiological functions are distributed in other brain areas, independent of the suprachiasmatic nucleus. They are the temporal coordination of spatially distributed neuronal networks, as well as brain structures that relate to Tempus, ie, the prediction and evaluation of durations.

Many observations and experiments have confirmed that living species are able to measure durations. The measurement of short durations, of less than a second, are probably less dependent on attention or emotion, although these can modulate even the measurement of short durations. The evaluation of longer durations, from seconds to hours or weeks, involves cognitive functions such as attention, emotion, and memory. More than 100 years ago, the Swiss psychiatrist Auguste Forel (1848–1931), known for his work in psychiatry, neurohistology and for his extensive studies on ants, noticed that bees came to his breakfast table regularly at the same time, even when no breakfast was being served.²⁶ He coined the term *Zeitgedächtniss*, or memory of time. Indeed, bees can be conditioned to go at a given moment of the day to a given location where food was previously provided.

A theoretical model on how biological systems could measure duration, ie, how a brain system might generate a continuous metric, was proposed by Treisman in 1963.^{27,28} The model proposed by Treisman provides the organism with a centralized system of time measurement. This has been criticized on the following basis: it could be that each biological function has an inbuilt duration measuring system, for example, a different one for motor action, for vision or for audition. Moreover, there might even be independent duration measuring systems for subfunctions in each motor or perceptive system. David M. Eagleman summarized issues raised by the handling of time by the brain:

A challenge for the brain is that afferent signals from the different sensory modalities are processed at different speeds. When receiving signals from several modalities, how does the brain determine the timing correspondence? The answer seems to be that the brain dynamically recalibrates its expectations.²⁹

The requirements of such coordination leave room for illusions to occur. For example, with short durations, when the event occurs in the immediate proximity or during an eye saccade, there is compression of time.³⁰

An experiment by Stetson³¹ illustrates this recalibration of duration, in the case of the visual modality. When a

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delay of 100 ms is artificially introduced between the moment of pressing a button and the occurrence of a flash of light, the subject rapidly adapts to this delay, which seems progressively shorter. When the presence of this delay is abruptly interrupted, the subject can have the impression that the flash occurred before he or she pressed the button. These adaptations of duration judgments are independent of one another, in the sense that if duration compression or dilation occurs in one perceptive aspect or system, eg, vision, it generally does not occur in other modalities, eg, audition. These observations speak in favor of more than one neuronal networks that judges duration, since the temporal outputs of these networks can become desynchronized.

Conclusion

When thinking and speaking about time, we confuse a series of terms. Imprecision, ambivalence, and contradiction are often how we speak of time, and this influences how we think about it. A major imprecision is that we do not set apart time and temporal phenomena: without noticing it, we attribute to time properties that are those of the temporal phenomena that we observe. For example, succession of days and nights, or the repetitive obligation to fill out tax declarations, will lead us to say that time repeats itself, and thus that is cyclical. Defining time is a challenge. Indeed, defining a concept is feasible when the concept is referred to something more fundamental. And nothing has been found that could be considered to be more fundamental than time. Thus, definitions of time are circular; they are tautological, as found by Aristotle, who saw time as the amount of movement with respect to before and after.

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When thinking about time, we remain under the influence of old analogies and metaphors. We hesitate between two pillars of Greek philosophy, Parmenides and the concept of immobility, and Heraclitus and the concept of a future. Heraclitus has shaped our discourse about time for the last two millennia, and still today, we cannot consider other metaphors than that of time analogous to a river and the flow of water.

Space remains, while time passes: could this be a manner to differentiate them? But if we define time as a machine that produces instants, then we have to conclude that it is not time that passes, but that all these instants are fabricated by time. We should learn not to confuse time with duration, time with future, or time with temporal phenomena.

A stimulating but radical view about time was proposed by Wittgenstein (1889–1951): “...there is no such thing”³² and it is just a form of objects.³³ The solution of the riddle of life in space and time lies outside space and time.³⁴ We stand inexorably in time and space, and our challenge is to live with time as an object that we remain unable to define.

And I confess to thee, O Lord, that I am still ignorant as to what time is. And again I confess to thee, O Lord, that I know that I am speaking all these things in time, and that I have already spoken of time a long time, and that “very long” is not long except when measured by the duration of time. How, then, do I know this, when I do not know what time is? Or, is it possible that I do not know how I can express what I do know? Alas for me! I do not even know the extent of my own ignorance.

Saint Augustine³⁵ □

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Las múltiples definiciones del tiempo

¿Qué es el tiempo ?

*Si nadie me lo pregunta, lo sé,
Si alguien me lo pregunta y que yo quiera explicarlo, ya no lo sé.
San Agustín*

Nosotros no somos capaces de experimentar el tiempo utilizando nuestros cinco sentidos, ni de definirlo empleando nuestra inteligencia, ya que inevitablemente estamos dentro del tiempo. Logramos una representación del tiempo a través de los cambios en nosotros y en el ambiente. Esto resulta posible por las funciones de la memoria. ¿Qué ocurriría si el tiempo sólo existiera como un constructo de nuestra mente, o si la ausencia de este constructo nos resultara incómoda a nuestra forma de pensar? Si nuestras dos principales herramientas para construir el mundo -el sentimiento y la razón- fueran de poca ayuda, entonces el estudio del tiempo, es decir la cronología, podría existir como un listado de hipótesis científicas y permanecería en alguna medida como una pregunta filosófica (un enigma que ha sido abordado por los pensadores por más de dos milenios). En esta revisión se discuten varios campos del conocimiento en relación con el tiempo, desde la filosofía y la física hasta la psicología y la biología. Se revisan las diferencias entre Chronos y Tempus, que corresponden respectivamente al tiempo de los físicos y de los psicólogos.

Les diverses définitions du temps

Qu'est-ce donc que le temps ?

*Si personne ne me pose la question, je sais ;
Si quelqu'un pose la question et que je veuille l'expliquer, je ne sais plus.
Saint Augustin*

Nous avons conscience du temps comme changement, grâce à la mémoire essentiellement, mais nous ne pouvons ni sentir (par nos cinq sens), ni définir (par notre intelligence), le temps : nous sommes inexorablement dedans. Le concept de temps est riche de sens et d'histoire. Et si le temps n'existait que pour et dans notre esprit ? Si la perception comme la raison sont tenues en échec, il s'ensuit que la chronologie (science du temps) ne peut exister que comme une liste d'hypothèses scientifiques et reste ainsi en quelque sorte une question de philosophie, une énigme que des penseurs ont tenté d'approcher pendant plus de deux mille ans. Dans cet article, plusieurs champs du savoir en relation avec le temps sont abordés, de la philosophie et de la physique à la psychologie et à la biologie : en particulier, quelles sont les différences entre Chronos et Tempus, le temps des physiciens et celui des psychologues, respectivement.

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