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Five surprises about the physics of time

The question of time has been debated and revisited countless times, leading me to doubt whether I have anything new to contribute to the discourse. The abundance of literature on the subject often feels like a discouraging indication that we are no closer to grasping anything that transcends common sense. Purely philosophical explorations of the concept rely on painstaking introspection, accompanied by linguistic analysis and insightful quotes from thinkers like Plato and Augustine. As a high school student, I found these extensive discussions unsatisfying, yielding little tangible outcome. However, as I embarked on my academic journey and delved into research, I gradually realized that there was more to be said about time, provided I was willing to engage with the mathematics of modern physics.

The concept of "time" is special as it exists both in everyday language and scientific theories. Unlike "electron," which had no existence in common language, or "fire," which has vanished from scientific discourse, "time" has transitioned into a scientific concept with the aid of a technological invention – the clock. The advent of the pendulum clock by Huygens in 1657 marked the initial significant step in the *phenomenotechnical* invention of time. Later steps were achieved by technical tools, either technological, mathematical or conceptual.

Understanding time means overcoming the epistemological obstacles that obstruct the path from common language to scientific theories. A meaningful philosophy of time should focus on the gradual transformations that have reshaped what physicists refer to as time. Drawing from my personal experiences, I have identified five crucial insights that struck me during my journey of learning, representing genuine progress in understanding the nature of time. Each of these surprises will constitute a section of this article:

1. Time means different things in different contexts
2. The present is full of space
3. The arrow of time is the result of a blurred vision
4. Classical mechanics can be expressed without time
5. Quantum time holds future surprises in store

Bachelard Studies / Études Bachelardiennes / Studi Bachelardiani, nn. 1-2, 2024 • Mimesis Edizioni, Milano-Udine Web: mimesisjournals.com/ojs/index.php/bachelardstudies • ISSN (online): 2724-5470 • ISBN: 9791222317328 • DOI: 10.7413/2724-5470102

1. Time means different things in different contexts

There is a common linguistic temptation to take the existence of a noun for the sign of the existence of an underlying tangible reality, thus yielding an inclination to treat time as a concrete entity. However, with a word as encompassing as time, natural languages offer a wide variety of uses, which lack coherence as a whole. Attempting to establish a singular definition of time that encompasses all its linguistic usages carries the risk of disappointment, often resulting in a minimalist and vague definition that offers little utility in understanding its nature.

It is a first useful trick of dialectic games to admit the polysemy of words. A second helpful moment of the scientific analysis is to recognize that a word does not command the existence of a physical reality, and that we must therefore strive to gradually separate the physical invariants from their linguistic gangue. To attain scientific rigor, time must be dissected into various notions, each approached through distinct methods and objectivized by a different apparatus.

Consequently, we encounter different physical theories, each employing time in its unique manner, albeit sharing certain similarities. We can establish a hierarchical structure of theories based on their proximity to our preconceived notion of time:

1. Psychology operates with a complex and subjective time characterized by varying durations dependent on mood.
2. Thermodynamics incorporates a universal and directional time.
3. Classical physics incorporates a universal but non-directional time.
4. Special/general relativity employs a non-directional time lacking a global order.
5. Quantum gravity involves a non-directional time without a global order, potentially devoid of objective duration, possibly discrete, or even fuzzy.

As we descend the hierarchy, time gradually diminishes and becomes elusive. This is why some individuals assert that "time doesn't exist". While this statement may seem provocative, it encapsulates the idea that our intuitive understanding of time emerges as a derived notion, similar to how the concept of a water's surface emerges from a molecular theory where the notion of surface is absent.

The dissection of the problem of time into sub-problems tied directly to specific theories or experiments serves as an initial analytical approach to navigate the intricacies of the subject. There will remain a synthetic task of understanding how these levels can be interconnected and articulated with one another.

2. The present is full of space

In Newtonian physics, spacetime is conceptualized as a 4-dimensional manifold with a global foliation that defines slices of simultaneity. The present is a thin 3-dimensional hyperplane situated between the vast expanses of the future and the past.

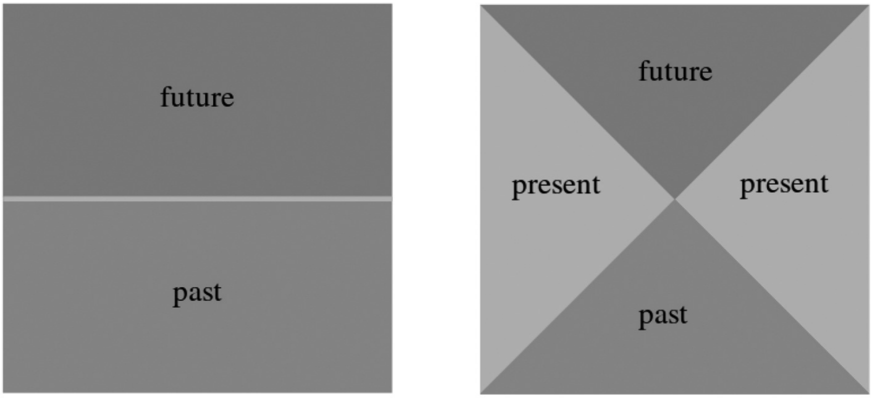

Figure 1. Newtonian spacetime (left). Minkowski spacetime (right).

However, Einstein's work demonstrates that there are events that cannot be consistently ordered in time, leading to the realization that there is no global time foliation of spacetime. In Minkowski spacetime, the structure of spacetime is characterized by a 4-dimensional manifold with a light cone at each point, serving as the boundary of past and future events. In the region between, events exist at a *space-like* distance, not belonging to either the past or the future.

The conventional presentation in textbooks provides technical clarity, yet it leaves one pondering the significance of this unexpected region of space-like separated events, which emerges as a true novelty brought by special relativity. In his popular book *La realtà non è come ci appare* (2014), Carlo Rovelli daringly refers to this region as the *present*. The term is more usually kept to refer to a slice of simultaneity that is relative to the velocity of the reference frame, which makes the only non-relative present be at the origin of the reference frame. In contrast, Rovelli suggests calling the present the collection of events that are neither in the future nor in the past.

The choice of terminology is not crucial to scientific research but holds significance in aligning our intuition as closely as possible with the picture of reality depicted by physics. Einstein compels us to question what we define as the present: is it the class of simultaneous events or the class of events that are neither past nor future? The former approach links the present to the notion of simultaneity, leading to the present being relative to both the position and the velocity of the observer, while the past and the future are only relative to its position. This hierarchy of concepts that poses simultaneity as primary and present as secondary is not a natural choice. Additionally, if the present is defined conventionally as a slice of simultaneity, what term would one use to describe the non-empty set of events that are not future, past, or present? The latter approach, on the other hand, aligns with a philosophical tradition that considers the present solely through the negation of its belonging to the future or the past. Adopting this perspective allows us to retain the concept of the present within the framework of special relativity, which, in my opinion, is a better choice for the pedagogical aim of minimally modifying our everyday language.

Thus far, I have not encountered any detrimental consequences of this choice. On the contrary, I find satisfaction in this conservative adjustment as it adheres to the principle of simplicity, refining our language without inflating it. Compared to the Newtonian model, the present now exists in four dimensions, similar to the past and the future. Except for the origin, it remains inaccessible to any traveler moving at speeds below that of light.

3. The arrow of time is the result of a blurred vision

In special relativity, the labels of past and future are purely conventional, meaning they could be interchanged without anyone noticing. Indeed, the theory itself does not prescribe a direction of time. At the kinematical level, the convention typically defines the future as the direction of increasing time t. However, at the dynamical level, if x(t) is a solution to the equations of motion, then x(-t) is also a valid solution. Hence, apart from the arbitrary labeling of clocks with an increasing series of numbers, nothing distinguishes the past from the future. Special relativity does not have an arrow of time. The same holds true for electrodynamics and general relativity, as Einstein's equations and Maxwell's equations are time-reversal symmetric.

Understanding the origin of the experienced arrow of time has been a central question in thermodynamics. Our initial impression of time is profoundly asymmetrical: we remember the past but not the future. The first answer provided by thermodynamics may seem tautological, as it introduces a new concept, entropy, and declares that "*the future is the direction of increasing entropy*":

$$dS > 0.$$

This equation introduces time-orientation in physics. It is a thermodynamic equation and, therefore, not fundamental. Physicists have been wondering how to derive it from statistical physics, which relies on the symmetrical equations of dynamics.

Although not all physicists would agree, I find that the most satisfactory explanation has been given by Jaynes and can be summarized as "the arrow of time is the result of a blurred vision"[1]. Adopting the perspective of Laplace's demon, who can observe all microscopic degrees of freedom, it becomes impossible to determine whether an evolution is forward or backward; both directions describe equally plausible dynamical evolutions. The situation is different if the demon has only access to a limited set of degrees of freedom. A macroscopic state is a set of va-

[1] E.T., Jaynes, *Gibbs vs Boltzmann Entropies*, American Journal of Physics, 33, 391, (1965), doi: 10.1119/1.971557.

lues for an incomplete selection of macroscopic quantities. Physicists postulate the existence of an underlying microscopic state, which can only be inferred from the values of the macroscopic variables. This inference is described by a probability distribution W over the phase space, where the microscopic state is guessed with certain probabilities. The "best guess", using all the available information without making extra-assumptions, corresponds to maximizing the Gibbs entropy

$$S = -\int W \log W$$

while maintaining fixed the macroscopic values.

The maximum Gibbs entropy for a given macroscopic state is referred to as the thermodynamic entropy. The system is in equilibrium when the values of the macroscopic variables do not change over time. When the system is out of equilibrium, its time evolution leads to different macroscopic states at different times, each corresponding to different values of thermodynamic entropy. Starting from a given macroscopic state, the Hamiltonian evolution of the distribution W (aka Liouville flow) preserves the value of the Gibbs entropy. However, the values of the macroscopic variables change, so that the thermodynamic entropy changes as well, in way which, by definition, can only increase further the value of S.

Crucially, the arrow of time depends on the choice of macroscopic variables that imposes a blurred vision of reality. This implies that a different selection of filters could potentially yield a different arrow of time, which is reminiscent of the mixing paradox. Therefore, the orientation of time is not fundamental but rather dependent on a particular point of view, a blurred vision of reality. This is a striking example of a property of time, *irreversibility*, which physics has successfully traced back to its origin.

4. Classical mechanics can be expressed without time

The modern formulation of mechanics employs symplectic geometry, which is explained in various textbooks as follows:

1. The phase space is described by a symplectic manifold.
2. The action is the integral of a local area, called the symplectic form.
3. The Hamiltonian is a function over the phase space, and its differentiation yields a vector field that defines the flow of time.

Unfortunately, this description is not compatible with Galileo's principle of relativity. In other words, the Galilean group does not act as a symplectomorphism on the phase space, meaning that it does not preserve the symplectic form. In simpler terms, the phase space described above represents a space of initial data, and the dynamical evolution is described within a fixed reference frame, disregarding the possibility of changing the reference frame throughout the time evolution.

In his book *Structure des systèmes dynamiques* (1970) Jean-Marie Souriau clearly highlighted this issue and proposed an elegant solution to overcome the difficulty and achieve a covariant description. The key is to view the phase space as a space of possible motions, i.e. solutions of the equations of motion, rather than a space of initial data. Both spaces are isomorphic, as there exists a one-to-one correspondence between initial data and motions. However, the latter approach avoids imposing an arbitrary time frame for describing the motion.

The space of solutions for a given physical equation e.g., Einstein, Newton may be a complicated space but is at least a symplectic space. A point in this space represents a complete trajectory of motion. Consequently, time evolution is not described by a Hamiltonian but is incorporated in the new symplectic form of the covariant phase space. As a result, the symplectic form remains invariant under the action of the Galilean group, thereby restoring covariance.

Therefore, there exists a concise method to describe classical physics without an explicit time flow. This description proves powerful to perform a paradigm shift from Newton to Einstein: instead of imposing invariance under the Galilean group, the phase space of special relativity must be invariant under the Poincaré group. Additionally, this formulation sheds light on the "problem of time" in quantum gravity, which physicists have raised due to the observation that the Hamiltonian of general relativity vanishes. This actually holds true for any generally covariant theory but should not deter physicists seeking to describe an evolution. In fact, different variables can be used to depict the evolution along a trajectory. Time is not inherently special but rather a gauche choice for describing motion. For example, the motion of a pendulum can be described by its position relative to the time displayed on a watch, which could simply be the position of another pendulum.

Hence, despite the apparent emphasis on time in the conventional formulations of classical mechanics, a complete assimilation of the principle of relativity suggests placing all variables on a more equal footing, and classical physics can function effectively within a covariant phase space.

5. Quantum time holds future surprises in store

Quantum physics has introduced a range of sophisticated techniques that hold the potential to revolutionize our understanding of time. However, this transformation has yet to occur, as quantum physics has mainly been applied within a regime where time behaves similarly to classical physics. Exploring the profound impact of quantum physics on the concept of time remains one of the key objectives of quantum gravity.

Quantum gravity should incorporate the lessons on time learned from previous theories, which have gradually stripped away some of its fundamental attributes such as universality and direction. Certain properties of time, such as its continuity, still remain open to investigation and potential revision. Currently, researchers are actively exploring this uncharted territory, and in the following sections, I will present three modern hypotheses that challenge conventional notions about time.

A. Causal order may be superposed

In 2011, Oreshkov, Costa, and Brukner have found that quantum mechanics allows for the description of processes without assuming a fixed global causal order in which they are embedded. They introduced a formalism known as process matrices, which allows for the superposition of causal orders, where process A occurs before process B *and* B occurs before A. Astonishingly, certain process matrices cannot be described by superpositions of causal order and are termed causally nonseparable.

In quantum gravity, the superposition of causal order is anticipated as a natural consequence of the superposition of the gravitational field. To date, no experiments have been conducted to directly test this hypothesis. Nonetheless, the field of quantum foundations is actively exploring this concept.

B. Time may be discrete

One notable prediction of loop quantum gravity is the discreteness of space: area and volume are observables with discrete spectra. This implies the existence of a fundamental unit or chunk of space characterized by a minimum nonzero volume.

Considering the lorentzian symmetries between space and time, it becomes tempting to entertain the idea that time itself may also be discrete. However, precisely formulating this notion requires the definition of a time operator that acts on a suitable Hilbert space, which has yet to be accomplished.

Speculating based on this hypothesis, there would exist a minimum duration, likely on the order of the Planck time:

$$t_P = \sqrt{\frac{\hbar G}{c^5}} \approx 10^{-44}\ \mathrm{s}$$

The Planck time is incredibly minuscule, to the extent that it may seem implausible to find a clock precise enough to test this hypothesis. Currently, the most accurate optical clocks employing strontium have a period of approximately 10^{-15} seconds. However, physicists can potentially compensate for imprecision using statistical methods. For instance, they can determine with confidence that the top quark has a lifetime of approximately 10^{-25} seconds. Together with my colleagues, I have proposed an experiment that could theoretically test the possibility of time discreteness[2]. Although this experiment remains a distant endeavor, it highlights the significance of exploring this question and the potential for making testable claims.

[2] M. Christodoulou, A. Di Biagio, P. Martin-Dussaud, *An experiment to test the discreteness of time*, Quantum 6 (2022), doi: 10.22331/q-2022-10-06-826.

C. Light cones may be pathological

Within the framework of spinfoams, spacetime is described by a discrete structure known as a spinfoam. It can be visualized as a two-dimensional graph consisting of vertices, edges, and faces. It represents the time evolution of a spin-network, which depicts quantum state of space in loop quantum gravity. The transition amplitude between two states of the gravitational field can be computed as a summation over spinfoams, employing rules akin to Feynman diagrams.

The vertex of a spinfoam represents a fundamental discrete unit of spacetime. In collaboration with Bianchi[3], I have demonstrated that the local causal information is encoded on ten *wedges*, which are 2-dimensional objects surrounding the vertex. These wedges can be categorized as "time-like" or "space-like." To construct a coherent local light cone, the wedges must align in a specific manner, which is not always guaranteed. Surprisingly, at the quantum level, there can exist configurations of wedges that fail to form a proper light cone. This leads to the existence of a multitude of pathological light cones, for instance with only one cone instead of two, or no cone at all, purely space, purely time, or all mixed together. Of course, these strange configurations are suppressed in the classical limit to yield the well-ordered spacetime we are familiar with.

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In *La formation de l'esprit scientifique* (1934), Gaston Bachelard emphasizes that progress in science is achieved through abstraction and distancing from naive conceptions. This rings particularly true on the topic of time, where the modern developments of our understanding necessitates a language free from concrete representations. However, as physics delves into greater levels of abstraction, the language used by physicists becomes increasingly devoid of common terms. The seemingly naive yet meaningful questions one may initially pose about time gradually dissolve, lacking appropriate words to even formulate the inquiry. The abstraction of the answers goes hand in hand with a transformation of the questions. The process of elevating common questions to expert-level inquiries is a rare occurrence. Achieving this endeavor without distorting the initial question is a challenge for the philosophysicists. The latter are not particularly concerned with whether a peculiarly defined operator possesses a discrete spectrum; rather, their interest lies in knowing whether they can reasonably envision the flow of time as a coarse-grained representation of a rapidly changing sequence of images. The remnant of the everyday notion of time in quantum gravity is so drastically different and minimal that one can argue in favor of the claim that "time does not exist".

The five surprises regarding the physics of time represent significant milestones that have given me a sense of understanding. Nowadays, the question "what is

[3] E. Bianchi, P. Martin-Dussaud, *Causal structure in spin-foams* (2021), arXiv: 2109.00986.

time?" has become tedious to me. Not because I possess the answer, but because I have discovered more specific and refined questions to explore, using precise language and with clear objectives. Questions like, "What could be a time operator in quantum gravity?" or "How could the superposition of causal order be experimentally tested?" or even "How pathological can a light cone be?". These new technical inquiries, constructed with sophisticated concepts, will yield phenomenotechnical answers, further expanding the realm of knowledge and understanding.

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