

What is Time? – Thoughts of a Physicist

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1 Introduction

The notion of time plays a fundamental role in human experience, thinking, and feeling. Our image of the world is inconceivable without the concept of time. So, what is time?

With this question, the sixth chapter of Thomas Mann’s “The Magic Mountain” begins: “What is time? A mystery – insubstantial and almighty. A prerequisite of the world of appearances, a motion, coupled and mingled with the being of bodies in space and their movement. But would there be no time, if there were no motion? No motion if no time? Just ask! Is time a function of space? Or the other way around? Or are both identical? Go ahead, ask!” [1]

For a physicist, time is a concept of prime importance. So, let us ask about the nature of time. This, however, is more a question for philosophers. Not being a philosopher, allow me to skate on thin ice for a moment. In the literature, you find quite different answers. According to Wittgenstein [2], “What is time?” is not a meaningful question but a misleading one. “Time” is not the name of an object. On the other hand, Kant gives an answer in his transcendental philosophy: according to him, time is a pure form of sensible intuition (*reine Form der Anschauung*). “Time is a necessary representation that grounds all intuitions. In regard to appearances in general one cannot remove time, though one can very well take the appearances away from time. Time is therefore given *a priori*. In it alone is all actuality of appearances possible.” [3]

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Natural scientists often express themselves in a more casual way. The physicist John A. Wheeler, the Ph. D. adviser of Richard Feynman, liked to characterise time in the way he found it in a graffito in the men’s room of the Pecan Street Cafe in Austin, Texas, in 1976: “Time is nature’s way to keep everything from happening all at once.” [4]

The phenomenon of time leads to a number of interesting questions: Does time have a beginning or an end? Is “time travel” possible? Can time cyclically close in a circle? How does the difference between past and future come about? Which of these questions can be answered by physics?

A distinction concerning the concept of time, which is often discussed in the philosophical literature about time, has been made by the Cambridge philosopher J. M. E. McTaggart (1866–1925) [6]. He introduced the notions of A-series and B-series for the temporal ordering of events. In the A-series, events are divided into those belonging to the past, to the present, and to the future. The classification continuously changes: events are first in the future, then in the present, and finally remain in the past. Time is of course ordered in the A-series: for each pair of unequal times, t_1 and t_2 , either t_1 is earlier than t_2 or vice versa. The A-series allows tensed propositions, like “we had a reception yesterday evening”. In the B-series, temporal positions are just linearly ordered with the earlier/later relation. It does not make use of the notions of past, present, and future. Only tenseless propositions, like “we had a reception in the evening of April 8th”, are possible in the B-series. The most significant difference between the two series is the fact that in the A-series, there is a “now”, whereas this concept is missing in the B-series. In the philosophy of time, those who consider the A-series or the B-series to be more fundamental are called A-theorists or B-theorists, respectively. Philosophers discuss whether future and past are real or whether they exist, and they debate about the status of the present (see e. g. [7]). We shall, however, not delve into these metaphysical questions here.

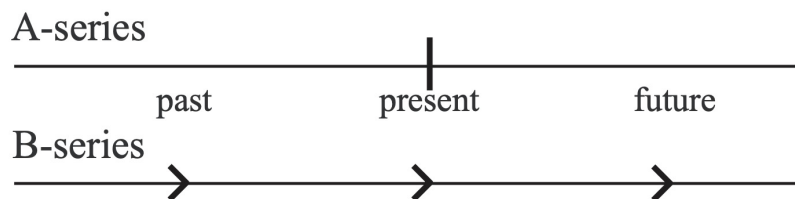


Figure 1: McTaggart’s A-series and B-series.

Time, the experience of time, and the measurement of time have philosophical, biological, physiological, psychological, sociological, and physical aspects, which are viewed differently in the different disciplines. For example, in physiology, the subjectively experienced “moment” (the critical time interval T_c) covers a period of about 30 msec, and the

“subjective presence” (the mental presence time T_p) has a duration of several seconds [8], while in physics, the presence is understood as the sharp boundary between past and future.

In the following, we shall deal with a few aspects of time in the context of physics.

2 Time in physics

Einstein is said to have answered the question asked at the beginning of this paper with: “Time is what the clock shows.” What at first glance seems like a flippant answer is, in fact, an expression of his years of struggle over the fundamentals of space and time. The operational approach to time, reflected in the quote, was the key to setting up the theory of relativity. The associated success and progress in understanding time is based on a retreat, a simplification, in that within the framework of physics, the subjective elements are disregarded, and we content ourselves with the measurable. This notion of time, measured by clocks, is called “physical time” or “objective time”.

On the other hand, there is “phenomenological time” or “subjective time”, which is the time that we see passing in our individual experience. Depending on our particular state of being, phenomenological time might appear to run faster or slower than physical time. Also, our experience of events and processes includes the modal structure of time, corresponding to the A-series, with its past, present, and future.

In contrast to that, physics does not know the “now”. Why is this so? In general, physics is not interested in single events or processes. It is not interested in the fall of Newton’s apple or of my teacup. Instead, it is interested in regularities, which it tries to describe in terms of laws, e. g. Galileo’s law of falling bodies. Such a law is supposed to be valid (within its scope of application and within a certain precision) universally and at all times. Therefore, references to singular points in time, and in particular to the “now”, are not admitted in physical laws. It should be mentioned that in exceptional cases reference to particular dates is made in physics, like in astrophysics, where, for example, the detection of gravitational waves on 14th September 2015 and Tycho Brahe’s supernova of 11th November 1572 are considered. Nevertheless, these dates are referred to in a tenseless way. So, in general, physical statements about temporal instances are made according to the B-series.

Are physical time and phenomenological time in contradiction to each other? Are the A-series and B-series incompatible? I do not think so. Every account of temporal processes or events has its origin in human perception. Expressing experiences in terms of phenomenological time or physical time, using the A-series or the B-series, means to employ different representations of the same reality. Objective time is obtained by an abstraction of subjective time, based on an intersubjective agreement about the meaning of clocks.

3 Measurement of time

Time, more precisely time intervals, is measured with clocks. What is a clock? Clocks are characterised by periodic processes that are used to define periods of time. In the course of history, time measurement developed from the rotation of the earth to water clocks and wheel clocks to more modern technical constructs. A milestone was the chronograph by John Harrison from 1759. The development continued to today's quartz clocks and atomic clocks. The precision of the currently available atomic clocks has given rise to the valid definition of the fundamental unit of time by means of atomic processes: One second corresponds to 9,192,632,770 periods of the radiation emitted by the transition between the two hyperfine levels of the ground state of atoms of caesium 133.

Is not a vicious circle lurking here? Is not the definition of time units via periodic processes, whose uniformity is assumed, circular? Would not the old definitions of the hour and the second via the rotation of the earth be just as viable as the one using modern atomic clocks? In this spirit, Percy W. Bridgman (1882–1961), winner of the 1946 Nobel Prize in physics, proposed to define physical concepts and units in an operational way [9]. The meaning of a scientific term would then be given by a specific measurement method. Consequently, there would be different seconds: an “earth second”, a “quartz clock second”, a “caesium clock second” etc. When I was young, I read in a newspaper about the – at that time – most accurate atomic clock. Its precision was also specified, and I wondered how it could have been determined if no more accurate clock existed for comparison. Indeed, in the operational framework, it would not make sense to ask for the precision of an atomic clock if time units are defined by means of this clock.

The actual meaning of time and definition of time units in physics is, however, different. The concept of time is theory-laden. It does not have its meaning by virtue of any particular periodic process, which is defined to be uniform, but within an entire system of description of nature, which should be consistent in itself and simple. The laws of physics contain time as a parameter, often denoted t . For example, in Newtonian mechanics, the motion of a free particle is described by the equation of motion $\ddot{x} = 0$ and its solution $x(t) = vt$, where v is the velocity. The time parameter t is involved in the laws of electrodynamics, relativity, quantum theory, etc. It is a theoretical term that finds its meaning within the framework of a theoretical description of a domain of phenomena. It is specified in such a way that the laws of physics take a simple form. Imagine, for example, that by contrast, t would be defined in terms of the rotation of the earth. This would be logically possible, but in this case, the motion of a free particle would not be uniform, and the various laws of physics would take rather complicated and impractical forms, since the rotation of the earth is not uniform with respect to these other phenomena. Instead, time is an idealised concept, which is tied to the phenomena and experiments by means of models, idealisations, and bridge principles. Time intervals and units are then

best represented by clocks that currently run most uniform according to their physical description.

4 Time's arrow

The term “arrow of time” means the fact that time has an inherent direction that distinguishes the past from the future. It becomes apparent in our experience in everyday life and in the sciences. The directionality of time has been put into words very nicely by Schiller [10]:

Threefold is the march of time:
While the future slow advances,
Like a dart the present glances,
Silent stands the past sublime.

Friedrich Schiller, Proverbs of Confucius

C. F. von Weizsäcker [11] has summed up this fact in the succinct statement “the past is factual, the future is possible.” This structure of time appears to be inextricably linked to the concept of time. Why is that? Kant again had a deep insight into this. In our lives, we constantly have experiences. Gaining experience, however, means learning from the past for the future. So this structure of time, the difference between past and future, is a necessary condition for the possibility of experience.

Physics is an empirical science; it is based on experience. The arrow of time is thus a prerequisite for physics. Therefore, at first glance, it appears reasonable to assume that physics cannot justify the arrow of time. Is that really the case? I do not think so. The circle that arises when physics searches for a physical reason for the arrow of time does not have to be vicious. It is a matter of semantic consistency [11] whether the physical justification for the arrow of time, expressed in the language of physics, and the arrow of time as a prerequisite for physics fit together. So let us turn to the issue of an eventual physical justification for time's arrow. There is a lot of literature about this, but I will only mention the books [5, 12, 13].

The fundamental laws of physics that describe particles and their interactions are time-reversible.¹ Each process may also run backwards in time. But the processes taking place in nature are obviously not time-reversible: a cup that falls to the ground shatters into many pieces; the reverse process has never been observed. How does that come about? Where does this arrow of time come from, which does not originate from the fundamental laws of nature?

On closer inspection, one can distinguish several arrows of time:

¹There is an exception to this in the microphysical laws for the weak interactions of elementary particles (CP violation), which, however, does not matter for the present discussion.

1. psychological: our memory is directed towards the past and not towards the future,
2. thermodynamic: according to the 2nd law of thermodynamics, entropy always increases (I leave out the details and necessary prerequisites for this law here),
3. electrodynamic: radiation propagates outwards from the source as time progresses and does not flow in concentrically,
4. quantum theoretical: the changes of state in the measurement process of a quantum system are irreversible,
5. cosmological: the universe is expanding.

Detailed inspection shows that the time's arrows 1 to 4 are connected to each other. The irreversible processes associated with them take place on the basis of probability laws, which describe a progression from ordered to more disordered states. Thereby, the overall disorder of the systems under consideration increases. Counterintuitive as it might appear, this also applies to our memories. To remember some event means that it has left traces in our memory, which are realised by certain neuronal structures. Traces in general represent remnants of irreversible processes, which are accompanied by an increase of the total disorder (entropy).

In physics, entropy is a measure of the disorder of a system. The time arrow can then be traced back to the fact that an ordered initial state (with low entropy) has been present. While the laws are time-reversible, the initial conditions lead to irreversibility of processes. The question of time's arrow therefore leads to the question of the origin of the ordered initial state. There is still no generally accepted answer to this, but there is a plausible hypothesis that the origin is based in cosmology, and the expansion of the universe acts as a kind of "master arrow of time".

A remark is in order here. On Earth, we often observe the emergence of ordered structures in apparent contradiction to the increase in disorder (entropy). This contradiction is illusory: in open systems, complexity can grow locally at the expense of disorder in the outside world [14]. Evolution does not conflict with thermodynamics.

5 Theory of relativity

It is not possible for a physicist to talk about time without taking the theory of relativity into account. It was established in one of the five famous works from Einstein's "annus mirabilis", 1905, entitled „Zur Elektrodynamik bewegter Körper“ (“On the Electrodynamics of Moving Bodies”). The title sounds inconspicuous and rather technical. But this work is about the very nature of space and time. In it, Einstein overthrows concepts of space and time that had been thousands of years old.

Difficulties in electrodynamics and optics led Einstein to investigate the fundamentals of the concepts of space and time. From 1902 to 1909, he worked in the patent office in Bern. He wrote to his friend Conrad Habicht [15]: “After eight working hours there are still eight hours for miscellaneous, and a whole Sunday.” The result of this was the theory of relativity, which brought with it a radical new way of thinking about space and time. Consequences of the theory are:

1. Relativity of simultaneity,
2. Relativity of time,
3. Relativity of lengths.

Let me make a few remarks about the relativity of time. What is meant with that? The passage of time, more precisely the running of clocks, depends on how the observer and the clock move relative to each other. A clock moving at a certain speed relative to us runs slower than a clock at rest. So does running keep you young? Well, the effect is extremely small for ordinary speeds. The factor by which the moving clock of a cyclist slows down is 1.00000000000000017, which is equivalent to 1 second in 200 million years. Only at speeds comparable to the speed of light of 299,792.458 km/sec does the effect become significant. At 90% of the speed of light, the factor is 2.3, and at 99% of the speed of light, it is already 7.1.

It is important that not only artificial clocks are affected, but all processes, including biological ones. It is time itself, the passing of which is relative. The relativity of time is often illustrated by the so-called twin paradox: a twin leaves earth in a spaceship, which travels into space at high speed and returns several years later. While the twin who remained on Earth has aged to an old man, his much-less-aged sister climbs out of the spaceship. Although the realisation of this story is far beyond today’s possibilities, the effect has been confirmed experimentally with the help of atomic clocks in airplanes.

The effects resulting from the theory of relativity are by no means esoteric fantasies of scientists but play a role in many areas of today’s physics and technology. An example is the GPS (Global Positioning System). Without taking into account the theory of relativity, an error of 10 km would add up in the GPS devices every day, and some of you would have missed today’s venue by a long way!

6 Simultaneity

The relativity of simultaneity is a consequence of the theory of relativity, which is of crucial significance for our understanding of time. Surprisingly, it has received rather little attention among philosophers. Exceptions are, for example, H. Putnam [16] and works cited in [17].

In physics before Einstein, the idea of an absolute time prevailed, which is equally universally valid and measurable for every observer. In his “*Philosophiae Naturalis Principia Mathematica*” from 1687, Newton writes: “Absolute, true, and mathematical time, of itself, and from its own nature, flows equably without relation to anything external.” Absolute time implies that a concept of global simultaneity is possible. If, in Newtonian space-time, an event A takes place at a certain location x_A and time t_A , then an event B, happening at any other location at the same time t_A , is simultaneous with A. The existence of an absolute notion of simultaneity allows to define the concepts of future, present, and past unambiguously; see Fig. 2. What is now for me here is now for everybody elsewhere.

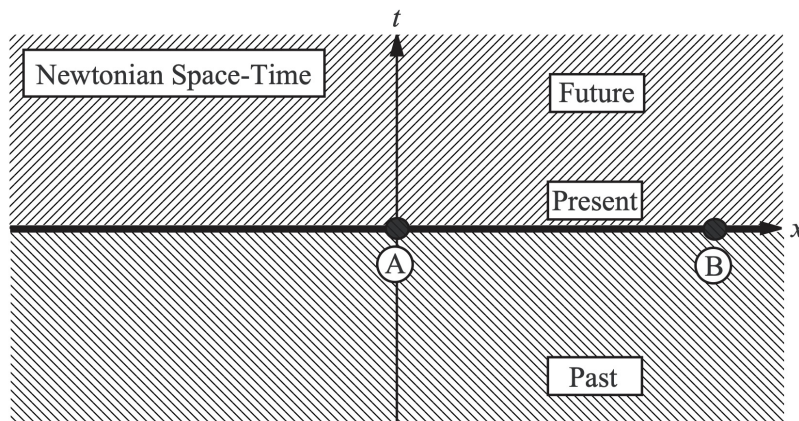


Figure 2: Newtonian space-time. Shown are the time axis and one spatial axis. The global present is indicated by a thick horizontal line.

The relativistic situation is substantially different from the Newtonian one. The geometry of space-time is represented by the so-called Minkowski space; see Fig. 3.

The global past and future of an event A in Newtonian space-time are now replaced by two regions called “causal past” and “causal future”, depending on A. (Choosing $x_A = 0$ and $t_A = 0$ for simplicity, they are specified by the conditions $t \leq -|x|/c$ and $t \geq +|x|/c$, respectively, where c is the speed of light.) The Newtonian present of A has become a whole region of space-time between past and future, the points in it being called space-like relative to A.

Which points in Minkowski space are simultaneous with A? Consider the following situation in Fig. 3. Physicist Bob works in a distant laboratory. At a certain time, he is looking for the result of a quantum physical experiment. This event is denoted B. Let us assume that the result of the experiment is not predetermined. For Bob, its outcome is open before B and factual afterwards. At point A, philosopher Alice wonders how the experiment of physicist Bob went. For her, the question is whether event B has already taken place or not. That amounts to the question of simultaneity of A and B.

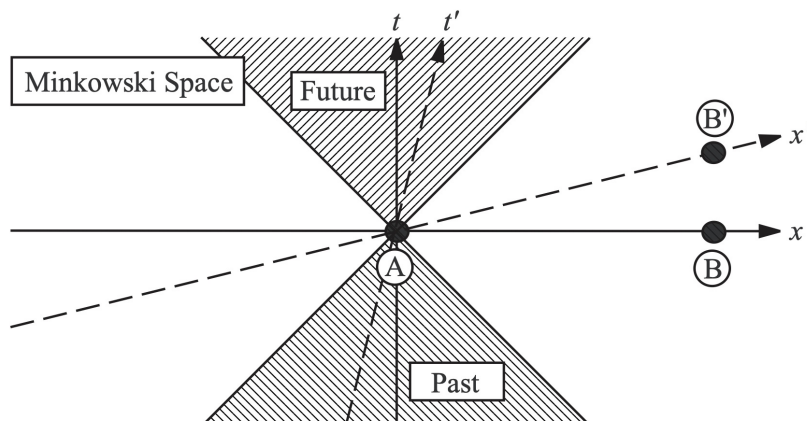


Figure 3: Minkowski space. Shown are the time axis and one spatial axis. Note that for better visibility of relativistic effects, units are chosen such that propagation of light takes place on diagonal lines. So if 1 cm on the t -axis corresponds to 1 sec, then 1 cm on the x -axis corresponds to 300.000 km. Causal past and causal future are abbreviated as past and future. Depending on the velocity of an observer at A, events B or B' are Einstein-simultaneous with A.

Looking at Fig. 3, it seems as if A and B are simultaneous. But Einstein's revolutionary insight was that there is no unambiguous concept of simultaneity. As he showed, one can indeed define a kind of simultaneity, called "Einstein-simultaneity", which, however, depends on the velocity of the observer A and is thus a relative notion. I refer to Einstein's beautiful book *Relativity: The Special and the General Theory* [18], where he explains these issues in a generally understandable way by means of moving trains. If the x - and t -axes in Fig. 3 correspond to the rest frame of Alice, then the points on the x -axis, including B, are Einstein-simultaneous to A. As mentioned, this notion depends on the motion of Alice. If she walks through her office, her rest frame is represented by the x' - and t' -axes, obtained from the previous coordinates by a Lorentz transformation. (For better visibility, the angles are exaggerated in the figure.) The event in Bob's laboratory, which is Einstein-simultaneous to A, is now indicated by B'. In everyday situations, the difference will be extremely small. But for the sake of principle, consider Bob's laboratory to be located in the Andromeda galaxy. If Alice moves with 3 km/s towards him, the event B' is later than B by a considerable amount of 9 days.

A remark is in order. Fig. 3 might suggest that the x - t -frame is privileged because of the 90° angle between its axes. But this is an optical illusion. This orthogonality does not have a meaning in Minkowski geometry. The same situation can be displayed in an equivalent manner as in Fig. 4.

We have to see that for events at Bob's place, being simultaneous with event A does not have an inherent meaning. So we have to realise that there is no unambiguous way

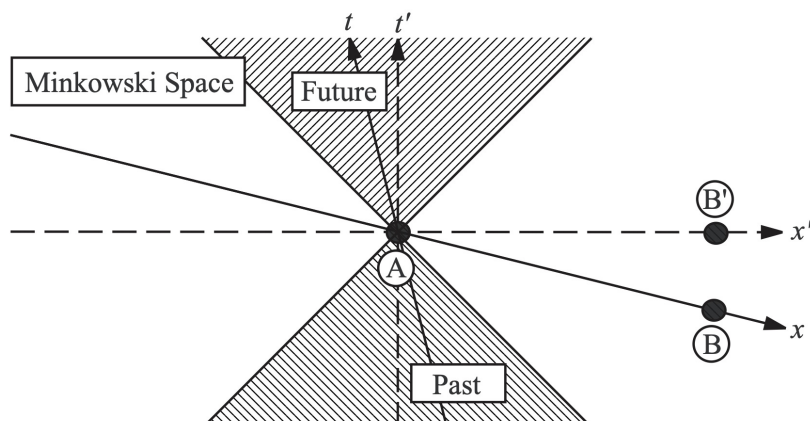


Figure 4: Minkowski space. The same situation as in Fig. 3 is drawn differently, but equivalently.

for Alice to consider one of Bob's times as "now" simultaneous with her "now".

The inevitable conclusion of this consideration is that for Alice, now thinking about Bob's experiment, there is no way to give a meaning to statements about its status of being completed or being still open. This is a severe challenge for our understanding of reality and for A-theorists in particular. I consider this to be the most serious problem in the philosophy of time.

Einstein appears to have been aware of the consequences of the relativity of simultaneity. He probably arrived at a deterministic worldview, in which there is no room for an open future. Shortly before his death in 1955, in a letter to the family of his deceased friend Michele Besso [19], he wrote "For us believing physicists, the distinction between past, present and future only has the meaning of an illusion, though a stubborn one."

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Thomas Mann, *Der Zauberberg*, S. Fischer Verlag, Frankfurt am Main, 2002;
English translation by me.
- [2] L. Wittgenstein, *Das blaue Buch*, 1970.
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- ob man zwar ganz wohl die Erscheinungen aus der Zeit wegnehmen kann. Die Zeit ist also a priori gegeben. In ihr allein ist alle Wirklichkeit der Erscheinungen möglich.“
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Zögernd kommt die Zukunft hergezogen,
Pfeilschnell ist das Jetzt entflohen,
Ewig still steht die Vergangenheit.“
Friedrich Schiller, *Sprüche des Konfuzius*;
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