1

The Physical Concept of Time

The concept of time has been discussed since the earliest records of philosophy, when science had not yet become a separate subject. It is rooted in the subjective experience of the 'passing' present or moment of awareness, which appears to 'flow' through time and thereby to dynamically separate the past from the future. This has led to the formal representation of time by the real numbers, and to the picture of a present as a point that 'moves' in the direction defined by their sign.

The *mechanistic concept of time* is also based on this representation of time by the real numbers, but it avoids any subjective foundation: it is defined in terms of objective motion (in particular that of the celestial bodies). This concept is often attributed to Aristotle, although he seems to have regarded such a definition as insufficient.[1] A concept of time *defined* (not merely measured) by motion may indeed appear as a circular construction, since motion

---

[1] "Time is neither identical with movement nor capable of being separated from it" (Physics, Book IV). This may sound like an argument for some absoluteness of time. However, the traditional philosophical debate about time is usually linked to (and often confused with) the psychological and epistemological problem of the *awareness* of time 'in the soul', and hence related to the problem of consciousness. This is understandable, since ancient philosophers could not have anticipated the role of physico-chemical processes (that is, *motions*) in the brain as 'controlling the mind', and they were not in possession of reasonable clocks to give time a precise operational meaning for fast phenomena. According to Flasch (1993), Albertus Magnus (ca. 1200–1280) was the first philosopher who supported a rigorously 'physical' concept of time, since he insisted that time exists in Nature, while the soul merely perceives it: "Ergo esse temporis non dependet ab anima, sed temporis perceptio."

Another confusing issue of time in early philosophy, reflected by some of Zeno's paradoxes, was the mathematical problem of the real numbers, required to characterize the continuum. Before the discovery of calculus, mathematical concepts ('instruments of the mind') were often thought to be restricted to the natural numbers, while reality would correspond to the conceptually inaccessible continuum. Therefore, periodic motion was essential for *counting* time in order to grasp is defined as change with (that is, dependence on) time, thus rendering the metaphor of the *flow of time* a tautology (see, e.g., Williams 1951). However, it forms a convenient *tool for comparing* different motions, provided an appropriate concept of simultaneous events is available. In pre-relativistic physics, this could be operationally defined by their simultaneous observation – later corrected for the time required for the propagation of light in a presumed 'ether'. (In German, an instant is called an *Augenblick*.) The possibility of comparing different motions, including clocks, indeed provides a sufficient basis for all meaningful temporal statements. All 'properties of time' must then be abstractions from *relative* motions and their empirical laws.

Physicists concerned with the concept of time have usually been quite careful in avoiding any hidden regress to the powerful prejudice of *absolute time*. Newton postulated it as a means to formulate his empirically founded laws, which then in turn justified this concept. More recent conceptions of time in physics may instead be understood as a *complete elimination* of absolute time, and hence of absolute motion. This approach is equivalent to the construction of 'timeless orbits', such as $r(\phi)$ for motion in a plane, which may be derived by eliminating t from the time-dependent solutions $r(t)$ and $\phi(t)$ of Newton's equations. In a similar way, all motions $q_i(t)$ in the Universe can be replaced by 'timeless' trajectories $q_i(q_0)$ in a global configuration space, where the hand of an appropriate 'clock' may be used as q_0.

These timeless trajectories may also be described by means of a *physically meaningless* parameter λ in the form $q_i(\lambda)$ for all i, where equal values of λ characterize the simultaneity of different q_i's. Such a parametric form was used by Jacobi to formulate his variational principle of mechanics (see Sect. 5.4), since astronomers without precise terrestrial clocks had to define time operationally as *ephemeris time* in terms of celestial motions obtained from their combined efforts (perturbation theory). If Jacobi's principle is applied to Newton's theory, absolute time can be recovered as a specific parameter λ that *simplifies* the equations of motion (Poincaré 1902). The existence of such a preferred time parameter, and its uniqueness up to linear transformations, is thus a non-trivial empirical property of Newtonian dynamics. It may then also be used to define equal time intervals at *different* times (as done by means of all conventional clocks, which *measure* this preferred time).

According to the most radical position about 'relational time', even its topology (ordering) has to be regarded as no more than the *consequence of this choice of an appropriate time parameter*. The 'timeless history' of the whole Universe would then be equivalent to an unordered 'heap of states' (or a stack of shuffled movie frames) that *can* be uniquely ordered and given a

---

it, not only to provide a measure. *Uniform* circular motion then appears as a natural assumption.

Since Newton, and even more so since Einstein, the concept of *time in Nature* has almost exclusively been elaborated by physicists. The adjective 'physical' in the title of this chapter is thus not meant as a restriction.

measure of distance only by the relations between their *intrinsic* structures (Barbour 1986, 1994a, 1999). This view will lead to entirely novel aspects in quantum gravity (see Sect. 6.2). If certain states from the stack (called 'time capsules' by Barbour) contain intrinsically consistent correlations representing memories, they may give rise to the impression of a flow of time to intrinsic observers, since the latter would remember properties of those global states which they interpret as forming their subjective past.

The concept of absolute motion thus shares the fate of the flow of time. 'Time reversal' is meaningful only as a *relative* reversal of motion (for example, relative to those physiological processes which control the subjective awareness of time and memory). Anyone who regards this mechanistic concept of time as insufficient should be able to explain what a reversal of *all* motion would *mean*. Ancient versions of a concept of time based on motion may have been understood as a 'causal control' of all motion on earth by the motions of (or on) the celestial spheres – an idea of which astrology is still a relic.

According to *Mach's principle* (see Barbour and Pfister 1995), the concept of absolute time is not only *kinematically* redundant – it should not even play any dynamical role as a preferred parameter, as it does in Newton's theory.[2] Similarly 'relativistic' ideas (although retaining an absolute concept of simultaneity) had already been entertained by Leibniz, Huygens, and Berkeley. They may even have prevented Leibniz from co-discovering Newton's mechanics, but led him to a definition of time in terms of *all* motions in the Universe. In this sense, an exactly periodic universe would describe the recurrence of the *same time*. This concept is far more rigorous than its ancient predecessor in not ascribing any preferred role to the motion of the celestial bodies.

Newton's mechanistic time, as used in his dynamical laws, specifies neither a direction in time nor a specific present. One may define a phenomenological direction by taking into account thermodynamical effects (including friction), thus arriving at the concept of a *thermodynamico-mechanistic time*. This concept is then based on the evidence that the thermodynamical arrow of time always and everywhere points in the same direction. Explaining this fact (or possibly its range of validity) must be part of the *physics of time asymmetry*. As will be explained, it can be understood within physics and cosmology, whereas physics does not even offer any conceptual means for deriving the concept of a present that would objectively separate the past from the future (see also the Epilog).

The concept of a present thus seems to have as little to do with the concept of time itself as color has to do with light (or with the nature of objects

[2] Mach himself was not very clear about whether he intended to postulate what is now often called his principle, or whether he intended to prove such a principle meaningless (see Norton 1995). A related confusion between the trivial invariance of a theory under a mere rewriting of the laws in terms of new spacetime coordinates ('Kretzschmann invariance') and the nontrivial *invariance of the laws* under such coordinate transformations led to some dispute in early general relativity (Norton 1989).

reflecting it). Both the present and color characterize our subjective *perception* of time and light, respectively. Just as most information that is contained in the frequency spectrum of light being observed is lost in the eye or visual cortex before it may cause any brain activities associated with consciousness, all information about observed events which are separated in time by perhaps as much as two or three seconds seems to be combined to form certain neuronal 'states of being conscious' (see Pöppel, Schill, and von Steinbüchel 1990). The *moments of awareness* might thus even be discrete rather than reflecting the time continuum in terms of which the corresponding physical brain activities are successfully described. The time continuum remains a heuristic fiction – just like *all* concepts describing 'reality'. Similarly, the topology of colors (forming a closed circle), or the perception of different frequency mixtures of light as representing one and the same color, may readily be understood by means of physiological structures (see Goldsmith 2006, for example). However, neither the subjective appearance of colors (such as 'blue') nor that of the present can be derived from physical and physiological concepts. This non-trivial relationship between reality and the observed phenomena seems to assume an even more important and quite novel role in quantum descriptions – see Sects. 4.3 and 6.2.2. In contrast, the *direction* of the apparent 'passage' of time seems to be a consequence of the objective (thermodynamical) arrow that must also control neurobiological processes, and thus allows memories *of the past* to affect those 'states of being conscious'.

In Einstein's *special* theory of relativity, the mechanistic or thermodynamico-mechanistic concept of time may still be applied locally, that is, along time-like world lines. These *proper times*, although anholonomous (that is, path-dependent – as exemplified by the twin paradox), possess the hypothetical absoluteness of Newton's time, since they are assumed to be defined (or to 'exist') even in the absence of anything that may represent a clock. The claim of proper time as controlling all motion is formulated in the *principle of relativity*. While any *simultaneity* of spatially separate events represents no more than a choice of spacetime coordinates, local geometric and physical objects and properties can be defined 'absolutely'. An example is the *abstract* spacetime metric (to be distinguished from its basis-dependent representation by a matrix $g_{\mu\nu}$), which defines all proper times and the light cone structure. Hence, one may define a spacetime future and past *relative* to every spacetime point P (see Fig. 1.1), and unambiguously compare their orientations at different spacetime points by means of the path-independent parallel transport in this flat spacetime. So one may distinguish globally between past and future directions, and thus once again introduce a thermodynamico-mechanistic concept of time.[3]

[3] While superluminal objects ('tachyons') may be compatible with the relativistic light cone structure, they would pose severe problems to thermodynamics or the formulation of a physically reasonable boundary value problem (see Sect. 2.1).

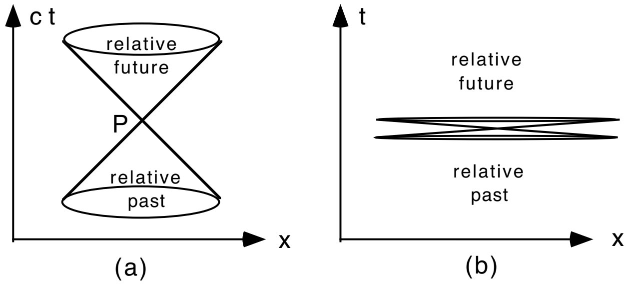

Fig. 1.1. (**a**) Local spacetime structure according to the theory of relativity. Spacetime future and past are defined *relative* to every event P, and independent of any choice of reference frame. (**b**) In conventional units (large numerical value of the speed of light) the light cone opens widely, so its exterior seems to degenerate into a space-like hypersurface of 'absolute' simultaneity. What we *observe* as an apparently global present is in fact the backward light cone with respect to the subjective *here-and-now* P. Since only non-relativistic speeds are relevant in our macroscopic neighborhood, this apparent simultaneity then seems also to coincide with the forward light cone, that is, the spacetime border to the 'open' future that we (now) may affect by our 'free will' (things we can 'kick')

These consequences remain valid in *general* relativity if one excludes non-orientable manifolds, which would permit the continuous transport of forward light cones into backward ones. On the other hand, world lines may begin or end on spacetime singularities at finite values of their proper times. This prevents the applicability of Zermelo's recurrence objection that was raised against a statistical interpretation of thermodynamics (see Chap. 3). One may also have to avoid solutions of the Einstein equations which contain closed time-like curves (world lines which return into their own past *without* thereby changing their orientation). While compatible with general relativity, and even with flat spacetime if non-trivial topologies were considered, they would be incompatible with the usual assumption that the global past and future of an event exclude one another.

If local states of matter (such as described by fields) are unique functions on spacetime, a closed time-like curve must lead back to the *same* local state (including all memories and clocks). This would be inconsistent with a persisting thermodynamical arrow and/or 'free will' along closed world lines, and thus eliminate the much discussed murderer of his own grandfather when the latter was a child. Spacetime 'travel' is a misconception and a misleading picture that may require an external *second* concept of time – similar to the picture of a flowing time. Nonetheless, scenarios that would allow time travel are apparently quite popular even among professional relativists who do not care about thermodynamics. A 'spacetime traveler' would either have to stay forever on a loop in an exactly periodic manner (hence forming an exactly isolated reversible system), or to meet his older self already at his *first* arrival at their meeting point in spacetime. This would give rise to severe consistency problems if *all* irreversible phenomena (such as the documentation represented by retarded light) were consistently taken into account – in contrast to the usual science fiction stories. It is, therefore, not surprising that spacetime geometries with closed time-like curves seem to be *dynamically unstable* (and thus could never *arise*) in the presence of thermodynamically normal matter (Penrose 1969, Friedman et al. 1990, Hawking 1992, Maeda, Ishibashi, and Narita 1998). Closed time-like curves seem to be excluded by the same initial condition that is responsible for the arrow(s) of time. Other relations between thermodynamics and spacetime structure will be presented in Chap. 5.

If closed time-like curves are in fact excluded, then our spacetime can be time-ordered by means of a monotonic foliation. While there have been speculations about 'time warps' in *quantum gravity* (see Morris, Thorne and Yurtsever 1988, Frolov and Novikov 1990), their consistent description would have to take into account the rigorous revision of the concept of time that is a consequence of this theory (Sect. 6.2). A *quasi-classical* spacetime would have to presume the time arrow of decoherence for its justification (see Sects. 4.3 and 6.2.2). In quantum theory, the dynamically evolving state must be strongly entangled, that is, nonlocal (Sect. 4.2). There is then nothing to evolve locally (along time-like *curves* in spacetime).

The most important *novel* aspect of general relativity for the concept of time is the *dynamical* role played by spacetime geometry. It puts the geometry of space-like hypersurfaces in the position of 'physical objects' that evolve dynamically and interact with matter (see Sect. 5.4). In this way, spatial geometry itself becomes a *physical* clock, and the program of Leibniz and Mach may finally be fully taken into account by completely eliminating any relic of absolute time. While proper times (defined by means of the abstract metric) are traditionally regarded as a prerequisite for the formulation of dynamical laws, they are now *consequences of an evolving object* (the metric). In general relativity with matter, the spatial metric does not remain the *exclusive* definer of time as a controller of motion – although geometry still dominates over matter because of the large value of the Planck mass (see Sect. 6.2.2). This is reminiscent of Leibniz's elimination of the special role played by the celestial bodies, when he defined time in terms of *all* motion in the Universe.

This *physicalization of time* in accordance with Mach's principle (that may formally appear as its *elimination*) allows us even to speak of a direction *of* time instead of a direction *in* time – provided the spacetime of our Universe is clearly asymmetric. The dynamical role of geometry then also permits (and *requires*) the quantization of time (Sect. 6.2). Consequently, even the concept of a history of the Universe as a parametrizable succession of global states has to be abandoned. The conventional concept of time can at best be derived as a quasi-classical approximation.

General Literature: Reichenbach 1956, Mittelstaedt 1976, Whitrow 1980, Denbigh 1981, Barbour 1989, 1999.