Chapter 13
Time in Modern Philosophy of Physics—A Survey

Holger Lyre

Abstract The *topos* of time ranges among the most puzzling and intriguing topics in our philosophical tradition—a seemingly endless source of deep and unsolved questions: What is time? What is temporal becoming? And how are we to spell out all this without using temporal notions in the first place? These questions are puzzling also in the sense that in our everyday life we seem to be quite familiar with the phenomenon of time. In a famous quote from the *Confessions*, Saint Augustine points out this discrepancy in the following way: "*What is time? If nobody asks me, I know; but if I were desirous to explain it to one that should ask me, plainly I know not.*" Nevertheless, 20th century physics has seen much progress not in finally answering these questions, but in providing us with some new perspectives and perhaps also some deeper insights into the nature of time from a scientific point of view. This article is accordingly devoted to give an overview on the several aspects of the notion of time—and in particular the directedness of time—in modern physics. (A similar version has been published online as: Time in philosophy of physics: the central issues. *Phys. Phil.*, ISSN: 1863-7388, 2008, ID: 012, http://physphil.tu-dortmund.de.)

Keywords Time · Temporality · Endurantism · Perdurantism · Zeno's paradox · Arrows of time · Conventionality of simultaneity · Hole argument · Parmenides · Heraclit · McTaggart · H-theorem · Second law · Maxwell's demon · Entropy · Information · Measurement problem · Ignorance interpretation · Theory underdetermination · Bohmian mechanicstransactional interpretation

1 Philosophical Preliminaries

1.1 Time and Temporality—Being and Becoming

The notion of time has many faces. One of the most important distinctions in debates about time is the distinction between time in the sense of *being* on the one

---

H. Lyre (✉)
Philosophy Department, University of Magdeburg, Magdeburg, Germany
e-mail: lyre@ovgu.de

S. Albeverio, P. Blanchard (eds.), *Direction of Time*,
DOI 10.1007/978-3-319-02798-2_13,

hand and *temporal becoming*—tensed time–on the other. In this connection we find in Carnap's autobiographical notes the following well-known passage about his discussions with Einstein:

> Once Einstein said that the problem of the Now worried him seriously. He explained that the experience of the Now means something special for man, something essentially different from the past and the future, but that this important difference does not and cannot occur within physics. That this experience cannot be grasped by science seemed to him a matter of painful but inevitable resignation. I remarked that all that occurs objectively can be described in science; on the one hand the temporal sequence of events is described in physics; and, on the other hand, the peculiarities of man's experiences with respect to time, including his different attitude towards past, present, and future, can be described and (in principle) explained in psychology. But Einstein thought that these scientific descriptions cannot possibly satisfy our human needs; that there is something essential about the Now which is just outside the realm of science. We both agreed that this was not a question of a defect for which science could be blamed, as Bergson thought. I did not wish to press the point, because I wanted primarily to understand his personal attitude to the problem rather than to clarify the theoretical situation. But I definitely had the impression that Einstein's thinking on this point involved a lack of distinction between experience and knowledge. Since science in principle can say all that can be said, there is no unanswerable question left. But though there is no theoretical question left, there is still the common human emotional experience, which is sometimes disturbing for special psychological reasons. [11, pp. 37–38]

Quite obviously Carnap does not fully understand what Einstein really worries about. Carnap presupposes an understanding of time which coincides with the common usage of an earlier-later relation—mathematically described by a real-valued 1-dimensional parameter. Following John McTaggart [38] this one-parameter time is known as "B-series." It reflects, or at least comes very close to, the way time is treated in physical theories, especially space-time theories: time as being, positions in time as earlier-later relations.

By way of contrast, there is the strong, subjective, human experience of time in terms of the *temporal modes*, the *tenses of time*: whereas the future is open and potential, the past is actual and fixed. Possible events of the future come into being at the present, the Now, and immediately slip into the irreversible past. This represents, in McTaggart's terms, the "A-series" of time. Scientific reductionism, in its usual stance, comprises the idea of reducing the A-series to the B-series. And this was precisely what worried Einstein, since he found that the Now has no place in physics, which indeed is troublesome, if the modes of time are objective parts of the reality rather than mere subjective experiences.

1.2 The Metaphysics of Time

McTaggart's main concern was to present an argument which—purportedly—proves the unreality of time. For the sake of his argument, which we shall not pursue here, he pointed out that there is an element of permanence in the B-series, namely that once an event is earlier than another event, it is earlier at all times. In contrast to this the A-series is manifestly dynamical due to the ever-shifting of events from future to present and past. One may call this aspect of temporal becoming the "Heraclitean view" as opposed to a "Parmenidean view". According to Heraclite everything flows, nothing abides, and the present is primary. Parmenides, instead, banishes temporal changes as being illusory. Only the static "Is" exists.

The Heraclitean view asserts a diachronous existence (or *persistence*) of things in time. Any 3-dimensional spatial object is wholly present at any one time. Proponents of this view are therefore called *3-dimensionalists* or *endurantists*, and one may presumably consider it the common view of the man on the street. In contrast to this the Parmenidean view asserts the eternal existence of tenseless objects which have temporal parts as well as they have spatial parts. Proponents of this view are called *4-dimensionalists* or *perdurantists*.

Corresponding to these two different views about the existence of objects in time there are the views about the existence of time itself—the subject matter of the metaphysics or ontology of time. Here, endurantism corresponds to *presentism*, the view that only the present exists, whereas perdurantism corresponds to *eternalism*, the view that all temporal parts exist. Both ontological views about time are symmetric, which means that they do not respect the distinction between past and future. There is, moreover, *possibilism* as an intermediate view between presentism and eternalism. The possibilist asserts that the present and the actual past are real and, thus, subscribes to the asymmetry of time as attested by our experience. Accordingly, possibilism is in agreement with endurantism, but not with perdurantism.

As we will see in the sections about relativity theory there are obstacles for the views of presentism and possibilism in special as well as in general relativity theory. Another distinction related to the ontology of time, but also to the ontology of space and, hence, space-time, is expressed in the debate between *relationalism* and *substantivalism*. Whereas substantivalists consider space-time as an entity *per se*, relationalists merely think of it as a set of relations of objects. This will also be addressed in the general relativity section.

1.3 Zeno's Paradoxes

Taken at face value, the Parmenidean view seems to be absurdly wrong. Everyday experience obviously tells us that there simply is true and undeniable change in the world! Nevertheless, the Parmenidean topic of the illusory nature of change lies at the roots of western philosophy's tradition. Among the early supporters of Parmenides and his Eleatic school, Zeno of Elea was perhaps the most influential—also given the fact that both Plato and Aristotle took his arguments quite seriously.[1] He presented a host of paradoxes by using a "dialectic" method, which, following Aristotle, was his genuine methodological invention and which, apart from the arguments themselves, certainly impressed both Plato and Aristotle. The idea of the

---

[1] However, almost everything we know about Zeno and much of what we know about Parmenides is due to Plato's and Aristotle's writings.

dialectic method is to argue against a certain view by showing that it entails unacceptable or even absurd consequences. For the particular case at hand, Zeno had argued that the denial of the Parmenidean view—the indivisibility of motion, for instance—leads to absurd consequences—namely that motion is impossible. Note that this is absurd from a non-Parmenidean point of view. What Zeno of course wanted to highlight was the cognitive inconsistency in the non-Parmenidean concept of motion—and, hence, the Parmenidean or Eleatic view of the illusory nature of change and multiplicity as the only viable alternative. Reality must be a single indivisible One.

Among the variety of ways Zeno presented his argument, the paradox of the race between Achilles and the tortoise is certainly the most famous one. The idea is the following: a tortoise (T) has been given a lead for her race with Achilles (A), the fastest of all the Greeks. Once A has got to the place from which T has started, T has already advanced a little farther. We may iterate this idea and come to the paradoxical conclusion that however fast A runs, he can never catch up with T! (And hence Zeno's conclusion: since this is not what we observe, our concept of motion is inconsistent and wrong.)

Another paradox, which has basically the same structure, is even simpler to grasp: Consider a runner who needs to run a finite race distance (which for simplicity's sake we shall normalize to 1). He first has to run the first half $x_1 = \frac{1}{2}$, next the first half of the remaining second half to reach $x_2 = \frac{3}{4}$. Then he has to got to $x_3 = \frac{7}{8}$ and so on. Again, the upshot is that the runner can never reach the end of the race track.

It is now often said that Zeno's paradoxes can easily be resolved within the modern, Cantorian view of transfinites in mathematics. We simply note that the infinite sum $\sum_{n=1}^{\infty} \frac{1}{2^n} = 1$ indeed converges. This is also the predominant view among philosophers of science (cf. [27, 30, 50]), but with the important addendum that there is of course no *a priori* guarantee to assume that space-time has the structure of a continuum. This has to be confirmed empirically, since Zeno's problem is after all physical, not mathematical in nature.

Most certainly, however, a 'modern Aristotle' would not be very much impressed by the Cantorian resolution of the paradoxes. Aristotle's very point was to introduce and to insist on the distinction between actual and potential infinities—and he was fond of the latter (cf. Aristotle's Physics Γ, Δ, Z in Ross [47]). For him, spatial distance must be considered a whole, being only potentially divisible. A runner covering a certain race distance does therefore not actually divide this continuous whole ("synholon") into pieces. Conversely, any actual division of space unavoidably takes time: Achilles indeed does not catch the tortoise, if he performs a halt after each step of iteration! But only this amounts to dividing space into pieces (or, in more operational terms, to measure a certain spatial distance). It seems much likely that Aristotle would rather be gratified to hear about intuitionistic mathematics as a much more appropriate tool to describe nature.

Two further remarks concerning the connection between Zeno's paradoxes and quantum mechanics should be made. The first remark is that there is an interesting analogy between Aristotle's view of the continuum and the way we describe position and motion in quantum mechanics. Suppose we have a moving particle with constant velocity, i.e. definite momentum, then due to the uncertainty relations position is indefinite! Conversely, if the particle has a definite position, its state of motion, i.e. momentum, is totally uncertain. This fits indeed quite nicely with Aristotle's views.

The second remark concerns the *quantum Zeno effect* (cf. [39]). This is not really a quantum version of any of Zeno's paradoxes, but rather a formal result with broad similarities to the original. The general idea is that in quantum theory a system "freezes up" under continuous observations or measurements. Consider, for instance, a system of radioactive, decaying atoms. The decay probability will be $p(t) \sim e^{-t}$, which for short times is proportional to t^2. Thus, after a time t_o the probability of decay is $p(t_o) \sim t_o^2$. But now we make an observation at $\frac{t_o}{2}$, where we get $p(\frac{t_o}{2}) \sim (\frac{t_o}{2})^2$. After the observation we must reset our clock and consider the same decay rate for the second sub-period. So, effectively we get the sum $p(t_o) \sim (\frac{t_o}{2})^2 + (\frac{t_o}{2})^2 = \frac{t_o^2}{2}$. Accordingly for n observations we have $p(t_o) \sim \frac{t_o^2}{n}$, which, in the limit $n \to \infty$ of infinitely many observations leads to probability zero. Thus, for a continuous measurement the system does not change at all!

A first attempt of an experimental realization of this paradoxical prediction was made by Itano et al. [31]. The authors used trapped ions and observed certain state transitions in dependency on disturbing radiation pulses, which they considered as 'measurements.' And, indeed, the results were of the Zeno fashion in the sense that the transition rate was decreasing with increasing radiation pulse number. Surely, this particular experimental set-up raises questions about what counts as a measurement and also, more generally, whether the idea of a continuous measurement has an operational meaning (after all, any real detector has a finite responding time). The lurking discussion of the measurement process shall be postponed to Sect. 5.1.

2 Physical Preliminaries

Our considerations have already reached a technical level, but some preliminary remarks concerning the notions of time, time reversal and the arrows of time should be made before addressing the particular problems in physical theories.

2.1 Newtonian Space-Time and Time Reversal (Reversal of Motion)

Newtonian space-time is generally considered the epitome of a fixed background space-time reflecting the spatio-temporal symmetries of classical mechanics. Due to its mathematical structure $\mathbb{R}^3 \times \mathbb{T}$, Newtonian space-time allows for a unique 3-space foliation and, hence, a global cosmic time. Its 3-dimensional spatial slices can be understood as planes of absolute simultaneity, meaning that the notion and measurement of time in Newtonian space-time is independent of any reference frame. In his famous *scholium* Newton described time as an absolute entity: "*Absolute, true and mathematical time, of itself and from its own nature, flows equably without relation to anything external.*"

As well-known, Newtonian physics shows invariance under $\widehat{T}: t \rightarrow -t$ with

$$q(t) \rightarrow q(-t) \quad \text{and} \quad \dot{q}(t) \rightarrow -\dot{q}(-t), \tag{1}$$

such that the Hamiltonian transforms as $H(q, p) \rightarrow H(q, -p)$. The operation $\widehat{T}$ is usually called "time reversal." However, this should be taken with a grain of salt, since what $\widehat{T}$ really does is rather a *reversal of motion*, as should be clear from (1). Hence, physicists define temporal reversibility as reversal of motion—a reversal in the sense of the B-series.

The idea of $\widehat{T}$ is to expresses the *isotropy* of time. But of course, since $\widehat{T}$ is a *discrete* symmetry, Noether's theorem does not apply and there is no conserved quantity connected with $\widehat{T}$. Instead of isotropy, the *homogeneity* of time *is* expressed via a conserved quantity—total energy—in terms of the first law. In fact, both laws of thermodynamics can be seen as laws about the nature of time: while the first law expresses the homogeneity, the second law stresses the anisotropy of time—in contrast to the alleged isotropy of the $\widehat{T}$-symmetry. Section 4 takes up this issue.

2.2 Arrows of Time

In his 1979 paper on "Singularities and time-asymmetry," [43] Roger Penrose presented a list of seven possible arrows of time, which might be helpful to structure the following sections.[2]

1. *Weak interaction arrow*: The "decay of the K^0-meson" is a clear experimental result and as such an 'almost' direct indication that Nature at least in one manifest case distinguishes past and future. However, this is only 'almost' an indication since, first, this literally *weak* interaction effect is, as Penrose puts it, "utterly minute" (smaller than 10^{-9}) and it seems therefore highly implausible to try to establish the more apparent arrows of time on this tiny effect. Second, the K^0-decay can only be observed indirectly via *CP*-violation and under the assumption that *CPT* is conserved.
2. *Quantum mechanical arrow*: "Quantum mechanical observations," whether in terms of 'collapses of the wave function' or stated otherwise, are time-asymmetric phenomena which give rise to quantum indeterminism. The quantum measurement process is discussed in Sect. 5.1.
3. *Thermodynamical arrow*: The "general entropy increase" of isolated systems on the macro-level according to the second law clashes with $\widehat{T}$-symmetry on the micro-level. Consequences will be laid out in Sect. 4.

---

[2] The expressions in quotes are Penrose's formulations.

4. *Electrodynamical arrow*: Classical electrodynamics is time-symmetric—there are future-directed, retarded waves as well as past-directed, advanced waves possible—, but still we only observe the "retardation of radiation," as for instance the spherical emission of (point) sources into the future time direction. We touch upon this issue in Sect. 5.2.
5. *Psychological arrow*: There is our indisputable feeling that the past is fixed, whereas the future is open and mutable, and also that causation acts towards the future only. Penrose calls it the "psychological time." Here, in our subjective time perception, we clearly distinguish between A- and B-time series.
6. *Cosmological arrow*: The "expansion of the universe" favors the future direction. This arrow is often connected to the thermodynamical as well as the electrodynamical arrow. It will be mentioned in Sect. 4.
7. *Gravitational arrow*: This arrow is due to the fact that gravitational collapses result in black hole singularities, whereas white holes have not been observed so far. While Penrose is particularly concerned with it, it plays no role in this article (readers may refer to Penrose's and similar literature).

3 Relativity Theory

3.1 Special Relativity

Special relativity (SR) mainly differs from pre-relativistic, classical mechanics by the assumption of a universal and finite limiting velocity, empirically identified with the vacuum velocity of light c (we already presuppose the relativity principle for inertial reference frames, which may be reconciled with classical mechanics either). The finite c equips space-time with a causal lightcone structure and, thus, replaces Newtonian space-time by Minkowskian space-time, a united combination of space and time in the sense that, in general, Lorentz transformations mix temporal and spatial parameters. It must have been this feature of the transformations which led Minkowski in his famous 1908 Cologne lecture on "space and time" to the statement: "*Henceforth space by itself, and time by itself, are doomed to fade away into mere shadows, and only a kind of union of the two will preserve an independent reality…*" (cf. [42, p. 152]). But here we have almost obviously, from the quite contradictory nature of his quote by using "henceforth" (or, even more obviously "von Stund an"—"from this hour"—in the German original), the entire problem in a nutshell, whether time in its independency with respect to *all* its features must really be given up. Does not it seem that Minkowski did at best dispense with the independency of B-series time, while being still committed to A-series time?

Nevertheless SR's resulting *relativity of simultaneity*, that is, the frame-dependency of simultaneity and hence the denial of absolute time, poses problems for endurantism and, correspondingly, presentism or possibilism as views about the reality of temporal objects and the ontology of time. The relativity of simultaneity means that the temporal distance between two space-like separated events is not defined.

This is usually illustrated for observers with different relative velocities, which are high compared to c. But we may as well consider low velocities and far remote events instead, as Roger Penrose shows in a drastic example by considering two persons who differ in their views about the launching of a space fleet on Andromeda to invade planet Earth [44, p. 303]: "*Two people pass each other on the street; and according to one of the two people, an Andromedean space fleet has already set off on its journey, while to the other, the decision as to whether or not the journey will actually take place has not yet been made.*" This is obviously an odd situation, since the existence of events itself seems to become frame-dependent. Many authors in this debate[3] are convinced that the relativity of simultaneity cannot be reconciled with presentism (or possibilism) and that we have to be eternalists instead. Parmenides strikes back!

The problem gets even worse, if we consider the further thesis of the *conventionality of simultaneity*: the view that the simultaneity relation of two inertial clocks must be chosen by convention (cf. [46, § 19] and [26]). Consider two clocks A and B in an arbitrary inertial frame of reference. To synchronize these clocks we may send a light signal at A-clock's time t_1 from A to B, where it is instantaneously reflected back to A, arriving at t_2. The standard simultaneity is then the definition that the event at $t' = t_1 + \varepsilon(t_2 - t_1)$ with $\varepsilon = 1/2$ is simultaneous with the signal's reflection at B. However, as Einstein himself has put it in his famous popular book on relativity theory: "*That light requires the same time to traverse …* [both paths] *is in reality neither a* supposition nor a hypothesis *about the physical nature of light, but a* stipulation *which I can make of my own freewill in order to arrive at a definition of simultaneity*" [21, § 8]. Thus, the choice $\varepsilon = 1/2$ is a mere convention—and this, then, could be exploited to the claim that the existence of events is not only frame- but convention-dependent!

However, David Malament [36] has shown that—under some "minimal, seemingly innocuous conditions"—standard simultaneity is the only non-trivial equivalence relation in accordance with causal connectability (this assumption might be considered a version of the causal theory of time). Nevertheless, commentators have even attacked these minimal assumptions. Sarkar and Stachel [51] raised particular doubts about the fact that in Malament's proof the simultaneity relation has to be symmetric under temporal reflections $\widehat{T}$. Thus, the conventionality issue is still not settled.

3.2 General Relativity

General relativity (GR) poses even severe problems on a Heraclitean view of time than does SR. Let us start with the most prominent, recent argument concerning the

---

[3] For the more recent debate compare the contributed papers to the sections "Special Relativity and Ontology" and "The Prospects for Presentism in Spacetime Theories" (and references therein) in the Proceedings of the 1998 Biennial Meetings of the Philosophy of Science Association, Part II, *Philos. Sci.* **67**(3), Supplement (2000).

ontological status of space-time, the question, whether space-time *substantivalism*, the view that space-time has a substantial or existential status on its own, is possible at all. The question has its traditional forerunner in the famous debate between Newton and Leibniz about the status of space. Whereas Newton hold a substantivalist position, Leibniz advocated the opposing *relationalist* view according to which space is nothing but the set of possible relations of bodies (cf. [14, Chap. 6, and 9 for the following]).

When Einstein—around 1912 during his search for a relativistic gravitational theory—came to realize that the field equations must be generally covariant, i.e. invariant under all coordinate transformations, he was quite confused about the physical meaning of this requirement. He actually invented an argument saying that generally covariant field equations cannot uniquely determine the gravitational field. Part of the argument was to consider an empty region in the energy-matter distribution, and so it was dubbed the "hole argument" ("*Lochbetrachtung*" in German).[4]

In 1987, John Earman and John Norton [18] presented a new version of the hole argument focusing on its ontological implications. They considered diffeomorphic models of GR, which are usually understood to represent the same physical situation (this was Einstein's early confusion). More precisely, let $\phi : \mathcal{M} \rightarrow \mathcal{M}$ be a diffeomorphic mapping defined on the space-time manifold $\mathcal{M}$ and $M = \langle \mathcal{M}, g_{\mu\nu}, T_{\mu\nu} \rangle$ be a model of GR with metric $g_{\mu\nu}$ and stress-energy tensor $T_{\mu\nu}$, then $M' = \langle \mathcal{M}, \phi^* g_{\mu\nu}, \phi^* T_{\mu\nu} \rangle$ is also a model of the theory. The reason for this is that M and M' are empirically indistinguishable. However, under certain ontological premises, in particular under the substantivalist assumption of space-time points as entities *per se*, M and M'—despite their empirical indistinguishability—represent *different* states of reality. Since Einstein's field equations cannot uniquely determine the temporal development of different diffeomorphic models (owing to general covariance), the space-time substantivalist has to accept a radical indeterminism arising in his picture of the world. Earman and Norton chose a 'hole diffeomorphism' h with $h = id$ for $t \leq t_o$ and $h \neq id$ for $t > t_o$ (obeying usual smoothness and differentiability conditions at t_o). We then have $M = M'$ for $t \leq t_o$, but $M \neq M'$ for $t > t_o$—an apparent breakdown of determinism from the substantivalist's point of view.

The new hole argument has caused a host of debates and comments—including intriguing objections and new options for substantivalists—but the majority of philosophers of science today is convinced that such an *ad hoc* indeterminism is far too high a price to pay for space-time substantivalism. Earman has shed new light on the debate by focusing on the, as he calls it, "*ideological*" rather than ontological implications of the hole argument [16]. These implications mainly arise from the non-trivial aspect of general covariance in GR. Take, for instance, Kretschmann's famous 1917 objection against Einstein's alleged 'principle of general covariance'

---

[4] We cannot follow the original argument due to lack of space. Historians of science have wondered about the trivial nature of Einstein's hole argument (besides the fact that he could not make use of modern differential geometry), but I am inclined to follow Stachel's [57] position that it was not a trivial argument. The reader may also consult Norton [41] for a comprehensive overview on the debates about general covariance.

in GR. Indeed, general covariance as the mere requirement of covariance under coordinate transformations is physically vacuous, it should quite generally be applicable in any sensible physical theory. But in GR the situation is far more complex: we must carefully distinguish between two applications of the concept of diffeomorphisms, for they might either correspond to mere coordinate transformations, but also to transformations of reference frames in the sense of physically instantiated transformations of observers provided with measuring rods and clocks. GR is thus characterized by the fact that not only the purely mathematical requirement of general coordinate covariance holds, but also the principle of general relativity, according to which any possible reference frames are seen as physically equivalent (for non-inertial frames one has of course to take compensating gravitational fields into account).

It is possible, in fact, to reconstrue GR as a gauge theory of the diffeomorphism group. This causes, already on the level of classical GR, the infamous problem of time: motion is pure gauge, all the genuine observables (i.e. gauge invariant quantities) are constants of the motion. Taken at face value this is a dramatic result! Parmenides indeed strikes back twice as hard, since this not only means a block universe stripped of A-series change (and accordingly the problems with presentism already in SR), but no B-series change, a "*truly frozen universe*" as a sort of "*neo-Parmenideanism*" or "*McTaggartism,*" as Earman [17] puts it.

Physicists usually begin to pay attention to these problems on the level of quantizing gravity, since here the problem of time becomes apparent because of the timeless Wheeler–DeWitt equation. However, this equation is nothing but the quantum variant of the Hamiltonian constraint and so, strictly speaking, the problem of no B-series change already exists on the classical level. Indeed, many of the leading figures in quantum gravity, relationalists in the majority, are aware of this fact (cf. [49]). We shall not say more about quantum gravity here, but brief mention should be made about two further aspects of the concept of time as they must presumably be expected from a truly quantized space-time theory: the possibility of instants of time (e.g. "chronons," [23]), and time as a quantum operator. Another source of questions about time connected with GR is cosmology. Since the cosmological arrow also relates to the thermodynamical arrow, cosmological aspects will be touched upon in the following section.

4 Thermodynamics

Most of the arguments about time presented so far have been arguments about the ontology rather than arguments about the directedness of time. In thermodynamics, however, the general entropy increase of isolated systems according to the second law reflects an asymmetry of time: the thermodynamical arrow.[5]

---

[5] Compared to the importance of this issue the presentation in the following is far too brief. Some more elaborate references are: Ben-Menahem and Pitowsky [3], Guttmann [28], Sklar [56] and Uffink [59, 60].

4.1 The Second Theorem—A Law?

In his kinetic theory of gases, Boltzmann considered a transport equation for the distribution function $f(q, p, t)$ in phase space and was able to describe entropy as

$$S = -H\big(f(q, p, t)\big) = -\int d^3q d^3p f(q, p, t) \log f(q, p, t). \tag{2}$$

His aim was to arrive at a proper microscopic underpinning of macroscopic thermodynamics—and in particular to obtain a microscopic version of the second law. For this purpose he introduced the famous "Stoßzahlansatz" (a.k.a. the assumption of molecular chaos), where the two-particle distribution function is written as a simple product of one-particle functions, which amounts to the assumption of uncorrelated particles before collision. From this ansatz he was able to derive the infamous H-theorem

$$\frac{dH(f(q, p, t))}{dt} \leq 0, \tag{3}$$

which describes the tendency of a gas to evolve to the Maxwell equilibrium distribution. However, the well-known and quite general problem with this account (as expressed in the early and famous objections of Loschmidt, Poincaré and Zermelo) is the obvious contradiction between the alleged macroscopic irreversibility as opposed to the undoubtedly existing reversibility on the mirco-level of classical particle mechanics. Indeed, how should it be possible at all to infer logically from a perfectly reversible mirco-mechanics to an irreversible macro-world?

The usual stance is to consider the increase of entropy only statistically and, thus, granting the H-theorem merely the character of a statistical law. But this does not solve the problem entirely, since the main worry with Boltzmann type accounts is to understand where the incredibly low *initial* entropy state comes from. Boltzmann himself (cf. [6]) was fully aware of this problem and tried to circumvent it—in various ways. One of his ideas is known as the *fluctuation hypothesis*: our known world is a real fluctuation phenomenon in a universe of much greater spatial and temporal extension. A this point the connection between the thermodynamical arrow and the cosmological arrow comes into play.

However, there is an underlying and sometimes overlooked time-symmetry of the whole Boltzmannian approach, which becomes visible in the fluctuation hypothesis. The point is that due to (3) and starting from an initial, low entropy state at $t = t_o$ we get increasing entropy in either time direction! In other words, the H-theorem indeed establishes increasing entropy for the future direction $t > t_o$, but—from the same logic—also for the past direction $t < t_o$. One must therefore come to the conclusion that the H-theorem does not single out the future direction and, hence, is *not* equivalent to the second law (seen as a law which truly distinguishes between past and future).

An account to secure the second law and, hence, irreversibility, based on a pure epistemological consideration was proposed by Carl Friedrich von Weizsäcker. By using a transcendental argument, i.e. referring to our methodological *preconditions of experience*, Weizsäcker claims that the distinction between past and future is already a fundamental precondition of experience—as can be seen from the analysis of our usual way of defining experience:

> A possible definition of experience may be that it means to learn from the past for the future. Any experience I now possess is certainly past experience; any use I now can still hope to make of my experience is certainly a future use. In a more refined way one may say that science sets up laws which seem to agree with past experience, and which are tested by predicting future events and by comparing the prediction with the event when the event is no longer a possible future event but a present one. In this sense time is a presupposition of experience; whoever accepts experience understands the meaning of words like present, past, and future. [61]

Thus, the central argument here is that in our empirical sciences we necessarily presuppose an understanding of the tenses of time, otherwise we were not able to explain what we mean by "empirical." As a presupposition, however, we cannot expect the distinction between past and future dropping off from physics as an empirical result, since this would be circular. We rather have to make explicit the distinction as a precondition of experience, which then might help to bridge the decisive gap between the H-theorem and the second law.

4.2 Maxwell's Demon, Entropy and Information

Besides the difficulties of a microscopic underpinning of the second law, microscopic attacks on its validity, conversely, also seem to fail. The probably most famous example of this type is *Maxwell's demon*. James Clerk Maxwell's idea was the following:

> ... the second law of thermodynamics ... is undoubtedly true as long as we can deal with bodies only in mass, and have no power of perceiving or handling the separate molecules of which they are made up. But if we conceive a being whose faculties are so sharpened that he can follow every molecule in its course, such a being, whose attributes are still as essentially finite as our own, would be able to do what is at present impossible to us. For we have seen that the molecules in a vessel full of air at uniform temperature are moving with velocities by no means uniform, though the mean velocity of any great number of them, arbitrarily selected, is almost exactly uniform. Now let us suppose that such a vessel is divided into two portions, A and B, by a division in which there is a small hole, and that a being, who can see the individual molecules, opens and doses this hole, so as to allow only the swifter molecules to pass from A to B, and only the slower ones to pass from B to A. He will thus, without expenditure of work, raise the temperature of B and lower that of A, in contradiction to the second law of thermodynamics. [37]

This thought experiment of Maxwell provoked a debate which has not stopped until today[6] and from which only the most important highlights shall be mentioned: The early discussions focused on the aspect of the physical realizability of the demon and brought to light that pure technical solutions fail and that the demon must in addition be 'intelligent.' This was most clearly worked out by Leo Szilard [58],

---

[6] For a most comprehensive collection of important papers in the more than a century long debate about Maxwell's demon see Leff and Rex [35], and also Earman and Norton [19, 20].

who showed that, quite generally, any measurement produces an increase of entropy. These considerations, carried on by Brillouin, Gabor and von Neumann, led to the idea of a *thermodynamic equivalent of a bit* $\Delta E = k_B T \ln 2$, understood as the minimum energy to produce or storage 1 bit of information. The final clue, however, came with the work of Rolf Landauer [34] and Charles Bennett [4]. Landauer discovered that memory erasure in computers results in an entropy increase in the environment, and Bennett therefore argued that the demon, who has to storage and to remember the data he obtains about the molecule velocities, saves the second law by the very act of resetting his memory (which is unavoidable for any realistic demon with a finite memory).

Landauer's and Bennett's work points out the deep connection between the concepts of entropy and information, as already suggested in the thermodynamic equivalent of a bit. Indeed, their information theoretic exorcism of Maxwell's demon hints at a renewed and fundamental interpretation of entropy in pure information theoretic terms. From a mathematical point of view, the close analogy between Boltzmann's formula $S = -k_B \sum_i p_i \ln p_i$ (in different notation than (2); p_i is the probability of a system to be in a certain microstate and k_B the Boltzmann constant) and the well-known Shannon [54] *information entropy* $H = -\sum_i p_i ldp_i$ giving the expectation value of the information content of a source (where $I = -ldp$ is the information content of a sign with probability p) is already striking. A certain confusion, however, arose about the sign of both quantities. Entropy may indeed be interpreted as a specific kind of non-information—the ignorance of the particular microstate in a given macrostate. Brillouin [7], therefore, envisaged a *negentropy principle of information*. Perhaps here we have a rather verbal problem which might just be resolved by distinguishing *potential* from *actual information*, as Weizsäcker [61] has proposed. In this terminology, entropy is potential information, the possible amount of information of a given macrostate, if all the microstates were known.

Conceptual links between entropy and (potential) information have been advocated by important thinkers in the foundations of thermodynamics (cf. [32, 33, 48] and [61]). But of course, the main worry with the information theoretic view is the seemingly subjective nature of the concept of information as opposed to the alleged objective nature of entropy as a system state quantity—or, in other words, the rather epistemic nature of information as a property of the observer as opposed to the ontic nature of entropy as a property of physical systems. This is why, for instance, Earman and Norton [20] dismiss the information theoretic exorcism of Maxwell's demon altogether. On the other hand, it seems that physics in many of its modern developments uncovers the importance of the notion of information.

5 Quantum Mechanics

5.1 The Measurement Problem

As Penrose has pointed out (see Sect. 2.2), quantum mechanics gives rise to an arrow of time because of the measurement problem. To begin with, we should review the measurement problem in brief. We consider a system $\mathcal{S}$ and a measuring apparatus $\mathcal{A}$, and split the measurement process into different steps: As a first step, $\mathcal{S}$ and $\mathcal{A}$ must couple, such that formally one has to enlarge the Hilbert space of $\mathcal{S}$ to the Hilbert space of the compound system $\mathcal{S} \otimes \mathcal{A}$, while, secondly, a measurement interaction $\widehat{H}_{\text{int}}$ takes place. Next, the compound system, being still in a pure state, will be separated into subsystems $\mathcal{S}$ and $\mathcal{A}$ again. The states of the subsystems are now formally given by the reduced density operators $\hat{\rho}_{\mathcal{S}}$ and $\hat{\rho}_{\mathcal{A}}$. At the end of the measuring chain we may read off the measuring result—a definite pointer state of $\mathcal{A}$ (if all went well).

The measurement problem arises now from the fact that the operators $\hat{\rho}_{\mathcal{S}}$ and $\hat{\rho}_{\mathcal{A}}$, which we obtain after the formal separation of $\mathcal{S}$ and $\mathcal{A}$, are so-called *improper mixtures*, which means that the *ignorance interpretation* is not applicable. This amounts to saying that it is not possible to attribute a definite state to $\mathcal{S}$ (or $\mathcal{A}$, respectively)—neither of the subsystems does allow for an objectification (the assumption of a definite, i.e. observer-independent state of $\hat{\rho}_{\mathcal{S}}$ leads to formal contradictions; cf. [40]). Since we do, however, expect measuring results to be definite and objective, the replacement of *improper* by *proper mixtures*, known as the reduction of the wave function, has to be put in by hand ("Heisenberg cut"). According to this *minimal instrumentalist interpretation*, as one could have it, the reduction of the wave function, which cannot be described by some unitary process, must be seen as an indeterministic element over and above the deterministic quantum dynamics.

It should particularly be emphasized that the failure of the ignorance interpretation really is the hard problem of the measurement process. This remark is in order in view of the successful and persuasive application of the various *decoherence* approaches on the market, whose importance could undoubtedly be established within the last decades: in realistic cases, the coupling of $\mathcal{S}$ to the environment will unavoidably destroy the typical quantum correlations (cf. [25]). However, following John Bell's classic phrasing, the vanishing of correlations FAPP ("for all practical purposes," [2]), should not be confused with the vanishing of the non-applicability of the ignorance interpretation. For even if, in a suitable pointer basis, we are left with, say, probabilities $\frac{1}{2}$ each and negligible superposition probabilities for the two outcomes of a simple binary quantum alternative (a quantum coin tossing, for instance), the failure of the ignorance interpretation implies that it is still not the case that the quantum coin does possess some definite state with corresponding probabilities as merely expressing the observer's ignorance about this very state.

This, indeed, causes a severe problem for determinism in quantum mechanics. In contrast to the classical statistical mechanics case (see Sect. 4), non-objectifiable quantum probabilities do not allow for a merely statistical indeterminism (and, hence, a hidden determinism). It has therefore become quite fashionable among 'decoherentists' to subscribe to a many worlds interpretation in order to establish an 'ontologically adequate' approach to the occurrence of quantum probabilities by asserting one real world for each measuring outcome. Those, who do not wish to enlarge reality in such a drastic manner, have to accept a radical quantum indeterminism on the bottom level—since otherwise the question, why apparently only one of the two dynamically independent components of a quantum alternative is experienced, remains entirely unexplained.

5.2 Interpretations of QM

Quantum theory—unlike other physical theories—is loaded with deep interpretational problems. The above sketched minimal instrumentalist interpretation is ‘minimal’ in the sense that it suffices to use the theory as a highly successful tool for applied physics. And to be sure, in this sense quantum theory is the most precise and successful physical theory mankind has ever discovered. To many and from a more concerned ontological point of view, however, the instrumentalism of the working physicist seems to be unsatisfactory. This is why we see a garden variety of competing interpretations of quantum theory—some who either deny the measurement problem or the indeterminism claim or both. In the following, we shall concentrate on two such interpretations—the Bohmian and transactional interpretation—which take different views on time-(a)symmetry and (in)determinism in quantum physics, but which are nevertheless empirically equivalent. We are therefore facing remarkable cases of *theory underdetermination by empirical evidence*.

Bohm’s [5] original 1952 account of quantum mechanics is indeed basically a clever re-formulation of ordinary quantum mechanics in the sense that one extracts a term from the Schrödinger equation which formally looks like a potential—a non-local quantum potential, however—and which is then used in a Newton-type equation of motion. This additional equation, which does not exist in the minimalist formulation, re-introduces an ontological picture of particle trajectories into Bohmian mechanics. Bohmians consider their view as ‘realistic’—without neglecting the genuine quantum non-locality (which makes the particle trajectories quite ‘surrealistic’; cf. [22]).

It is an indeed remarkable fact that in Bohmian mechanics the measurement problem may be said to disappear. Given the quite general analysis in terms of the non-applicability of the ignorance interpretation in the preceding section, one might wonder how this is possible at all. So here’s a first motivation: The non-applicability of the ignorance interpretation amounts to saying that an observer cannot distinguish between improper and proper mixture states of $\mathcal{S}$ or, in other words, that he has no means to decide whether the measuring apparatus $\mathcal{A}$ is still correlated to $\mathcal{S}$ or not. To decide this he would have to apply a suitable meta-observable on the compound system $\mathcal{S}' = \mathcal{S} \otimes \mathcal{A}$, but this can obviously only be done by a meta-observer with apparatus $\mathcal{A}'$. We may extend this consideration to the universe as the largest physical system possible. As inner observers we cannot distinguish between proper and improper mixtures of subsystems of the universe, such that it is logically possible to assume the initial conditions of any particle positions, as Bohmians would have it, as non-local hidden variables with determinate values fixed by a deterministic velocity equation. Hence, our usual quantum mechanical probability calculus must be interpreted as arising due to our subjective ignorance of the objective state of the universe much like the usage of probabilities in classical statistical mechanics (where we do apply an ignorance interpretation). This is why Bohmians are indeed able to circumvent the problem of the ignorance interpretation in the measurement process. We may hence conclude that *per constructionem* Bohmian mechanics is purely deterministic and time-symmetric in analogy to classical mechanics.

Let us now turn to a somewhat lesser well-known approach of quantum mechanics: Cramer's [12] *transactional interpretation*. It is mainly inspired from the Wheeler–Feynman approach [62] of electrodynamics (which has only recently attracted new interest from philosophers of physics; cf. [24, 45]). The main idea is that Wheeler and Feynman allowed for the full time-symmetric set of solutions of the Maxwell wave equations, in particular the existence of advanced solutions. Usually, these backwards-in-time radiating waves are dismissed on the basis of suitable boundary conditions as for instance the *Sommerfeldsche Ausstrahlungsbedingung*, according to which the universe must be seen a sink of radiation. Thus, the electrodynamical arrow is based in one way or the other either on the cosmological or the thermodynamical arrow.

In the same line of thinking Cramer considers both retarded and advanced wave functions. The Wheeler–Feynman absorber condition—a suitable canceling of retarded and advanced solutions—turns in Cramer's account into a *transaction* ("hand-shaking") between retarded "offer" waves from the emitter and advanced "confirmation" waves from the absorber. As an exchange between waves from the past and waves from the future the transaction as such is *atemporal*. Over and above that the approach is time-symmetric (despite, Cramer's remarks in his 1986, Sect. III.J). The situation is analogous to the underlying time-symmetry of Boltzmann's H-theorem (Sect. 4): Cramer's account cannot single out the future lightcone.

Cramer believes that his interpretation gives better explanations of non-local effects such as EPR-Bell correlations and delayed choice measurements than the standard formulation, but simultaneously emphasizes that both lead to the same experimental predictions. We are thus left with three apparent cases of theory underdetermination—the minimal interpretation, Bohmian mechanics, and transactional interpretation—which are empirically equivalent but drastically differ in ontology.[7] Thus, on the basis of pure interpretational manoeuvres one may choose between indeterminism, determinism, and partial atemporalism!

6 Conclusion

We have reached the end of our *tour de force* through questions about time and its direction in modern philosophy of physics. It goes without saying that we could only touch upon a few of a whole universe of aspects of this extensive topic. For instance, no mention was made of phenomena involving 'backwards causation,' such as time-travel (cf. [15]). Indeed, the whole issue about causation was omitted, just as counterfactuals have not been addressed (cf. [29]). Finally, some further literature shall be indicated to the interested reader: Very good physics references, for instance, are Schulman [53] and Zeh [63]. Among the philosophy of physics literature

---

[7] Some Bohmians do assert possible empirical differences to the standard approach by introducing "effective wave functions," which are completely decoupled from their environment (cf. [13]; I like to thank David Albert and Roderich Tumulka for indicating this to me).

mention should be made of Albert [1], Butterfield [8], Butterfield and Earman [9], Callender [10], Horwich [29], Savitt [52], Sklar [55], and Price [45]. Again, this little list of references is of course far from being complete, but rather provides useful entries for more elaborate studies of the fascinating issue of time and its direction in physics and philosophy.

References

1. Albert, D.: Time and Chance. Harvard University Press, Cambridge (2000)
2. Bell, J.S.: Against 'measurement'. Phys. World **8**, 33–40 (1990)
3. Ben-Menahem, Y., Pitowsky, I. (eds.): Special issue: the conceptual foundations of statistical physics. Stud. Hist. Philos. Mod. Phys. **32**(4) (2001)
4. Bennett, C.H.: The thermodynamics of computation—a review. Int. J. Theor. Phys. **21**, 905–940 (1982)
5. Bohm, D.: A suggested interpretation of the quantum theory in terms of "hidden" variables. Phys. Rev. **85**, 166–179, 180 (1952)
6. Boltzmann, L.: Vorlesungen über Gastheorie. Barth, Leipzig (1896)
7. Brillouin, L.: Science and Information Theory. Academic Press, London (1962)
8. Butterfield, J. (ed.): The Arguments of Time. Oxford University Press, Oxford (1999)
9. Butterfield, J., Earman, J. (eds.): Handbook for the Philosophy of Physics. Elsevier, Amsterdam (2006)
10. Callender, C. (ed.): Time, Reality, and Experience. Cambridge University Press, Cambridge (2002)
11. Carnap, R.: Intellectual autobiography. In: Schilpp, P.A. (ed.) The Philosophy of Rudolf Carnap, Library of Living Philosophers, vol. X. Open Court, La Salle (1963)
12. Cramer, J.G.: The transactional interpretation of quantum mechanics. Rev. Mod. Phys. **58**, 647–688 (1986)
13. Dürr, D., Goldstein, S., Zanghi, N.: Quantum equilibrium and the origin of absolute uncertainty. J. Stat. Phys. **67**, 843–907 (1992)
14. Earman, J.: World Enough and Space-Time. MIT Press, Cambridge (1989)
15. Earman, J.: Bangs, Crunches, Whimpers, and Shrieks. Oxford University Press, New York (1995)
16. Earman, J.: Gauge matters. PSA 2000 conference lecture, to appear in Philos. Sci. (2000)
17. Earman, J.: Thoroughly modern McTaggart: or what McTaggart would have said if he had learned the general theory of relativity. Philos. Impr. **2**(3) (2002). http://www.philosophersimprint.org/002003
18. Earman, J., Norton, J.: What price spacetime substantivalism? The hole story. Br. J. Philos. Sci. **83**, 515–525 (1987)
19. Earman, J., Norton, J.: Exorcist XIV: The wrath of Maxwell's demon. Part I. From Maxwell to Szilard. Stud. Hist. Philos. Mod. Phys. **29**, 435–471 (1998)
20. Earman, J., Norton, J.: Exorcist XIV: The wrath of Maxwell's Demon. Part II. From Szilard to Landauer and Beyond. Stud. Hist. Philos. Mod. Phys. **30**, 1–40 (1999)
21. Einstein, A.: Relativity: The Special and General Theory. Holt, New York (1920)
22. Englert, B.-G., Scully, M.O., Süssmann, G., Walther, H.: Surrealistic Bohm trajectories. Z. Naturforsch. **47a**, 1175–1186 (1992). Comment: Dürr et al.: Z. Naturforsch. **48a**, 1261 (1993); Reply to Comment: Englert et al.: Z. Naturforsch. **48a**, 1263 (1993)
23. Finkelstein, D.: Quantum Relativity: A Synthesis of the Ideas of Einstein and Heisenberg. Springer, New York (1996)
24. Frisch, M.: (Dis-)solving the puzzle of the arrow of radiation. Br. J. Philos. Sci. **51**, 381–410 (2000)

25. Giulini, D., Joos, E., Kiefer, C., Kupsch, J., Stamatescu, I.-O., Zeh, H.D.: Decoherence and the Appearance of a Classical World in Quantum Theory. Springer, Berlin (1996)
26. Grünbaum, A.: Philosophical Problems of Space and Time. Knopf, New York (1963). Second, enlarged edition, Reidel, Dordrecht (1973)
27. Grünbaum, A.: Modern Science and Zeno's Paradoxes. Wesleyan University Press, Middletown (1967)
28. Guttmann, Y.M.: The Concept of Probability in Statistical Physics. Cambridge University Press, Cambridge (1999)
29. Horwich, P.: Asymmetries in Time. MIT Press, Cambridge (1987)
30. Huggett, N. (ed.): Space from Zeno to Einstein: Classic Readings with a Contemporary Commentary. MIT Press, Cambridge (1999)
31. Itano, W.M., Heinzen, D.J., Bollinger, J.J., Wineland, D.J.: Quantum Zeno effect. Phys. Rev. A **41**(5), 2295–2300 (1990)
32. Jaynes, E.T.: Information theory and statistical mechanics. Phys. Rev. **106**, 620 (1957)
33. Jaynes, E.T.: Information theory and statistical mechanics II. Phys. Rev. **108**, 171 (1957)
34. Landauer, R.: Irreversibility and heat generation in the computing process. IBM J. Res. Dev. **5**, 183–191 (1961)
35. Leff, H.S., Rex, A.F. (eds.): Maxwell's Demon: Entropy, Information, Computing. Princeton University Press, Princeton (1990)
36. Malament, D.: Causal theories of time and the conventionality of simultaneity. Noûs **11**, 293–300 (1977)
37. Maxwell, J.C.: Theory of Heat. Longmans, London (1871)
38. McTaggart, J.M.E.: The unreality of time. Mind **17**(68), 457–474 (1908)
39. Misra, B., Sudarshan, E.C.G.: Zeno's paradox in quantum theory. J. Math. Phys. **18**, 756 (1977)
40. Mittelstaedt, P.: The Interpretation of Quantum Mechanics and the Measurement Process. Cambridge University Press, Cambridge (1998)
41. Norton, J.D.: General covariance and the foundations of general relativity: eight decades of dispute. Rep. Prog. Phys. **56**, 791–858 (1993)
42. Pais, A.: 'Subtle is the Lord...': The Science and the Life of Albert Einstein. Oxford University Press, Oxford (1982)
43. Penrose, R.: Singularities and time-asymmetry. In: Hawking, S.W., Israel, W. (eds.) General Relativity: An Einstein Centenary Survey. Cambridge University Press, Cambridge (1979)
44. Penrose, R.: The Emperor's New Mind. Oxford University Press, New York (1989)
45. Price, H.: Time's Arrow and Archimedes' Point. Oxford University Press, New York (1996)
46. Reichenbach, H.: Philosophie der Raum-Zeit-Lehre. de Gruyter, Berlin (1927). Engl. transl.: Philosophy of Space and Time. Dover, New York (1957)
47. Ross, W.D.: Aristotle's Physics. Clarendon Press, Oxford (1936)
48. Rothstein, J.: Informational generalization of entropy in physics. In: Bastin, T. (ed.): Quantum Theory and Beyond. Cambridge University Press, Cambridge (1971)
49. Rovelli, C.: The century of the incomplete revolution: Searching for general relativistic quantum field theory. J. Math. Phys. **41**(6), 3776–3800 (2000)
50. Salmon, W.C. (ed.): Zeno's Paradoxes. Bobbs-Merrill, Indianapolis (1970). Repr., Hackett, Indianapolis (2001)
51. Sarkar, S., Stachel, J.: Did Malament prove the non-conventionality of simultaneity in the special theory of relativity? Philos. Sci. **66**, 208–220 (1999)
52. Savitt, S.F.: Time's Arrows Today. Cambridge University Press, Cambridge (1995)
53. Schulman, L.S.: Time's Arrows and Quantum Measurement. Cambridge University Press, Cambridge (1997)
54. Shannon, C.E.: A mathematical theory of communication. Bell Syst. Tech. J. **27**(3), 379–656 (1948)
55. Sklar, L.: Space, Time, and Spacetime. University of California Press, Berkeley (1974)
56. Sklar, L.: Physics and Chance. Cambridge University Press, Cambridge (1993)

57. Stachel, J.: Einstein's search for general covariance, 1912–1915. In: Howard, D., Stachel, J. (eds.) Einstein and the History of General Relativity. Einstein Studies, vol. 1. Birkhäuser, Boston (1989)
58. Szilard, L.: Über die Entropieverminderung in einem thermodynamischen System bei Eingriffen intelligenter Wesen. Z. Phys. **53**, 840–856 (1929)
59. Uffink, J.: Bluff your way through the second law of thermodynamics. Stud. Hist. Philos. Mod. Phys. **32**(3), 305–394 (2001)
60. Uffink, J.: Issues in the foundations of classical statistical physics. In: Butterfield, J., Earman, J. (eds.): Handbook for the Philosophy of Physics. Elsevier, Amsterdam (2006)
61. Weizsäcker, C.F.v: Die Einheit der Natur. Hanser, München (1971). Engl. transl.: The Unity of Nature. Farrar, Straus and Giroux, New York (1980)
62. Wheeler, J.A., Feynman, R.P.: Interaction with the absorber as the mechanism of radiation. Rev. Mod. Phys. **17**, 157–181 (1945)
63. Zeh, H.-D.: The Physical Basis of the Direction of Time. Springer, Heidelberg (1989). Fourth edition (2001)