THE FRONTIERS COLLECTION

THE FRONTIERS COLLECTION

Series Editors:
A.C. Elitzur M.P. Silverman J. Tuszynski R. Vaas H.D. Zeh

The books in this collection are devoted to challenging and open problems at the forefront of modern science, including related philosophical debates. In contrast to typical research monographs, however, they strive to present their topics in a manner accessible also to scientifically literate non-specialists wishing to gain insight into the deeper implications and fascinating questions involved. Taken as a whole, the series reflects the need for a fundamental and interdisciplinary approach to modern science. Furthermore, it is intended to encourage active scientists in all areas to ponder over important and perhaps controversial issues beyond their own speciality. Extending from quantum physics and relativity to entropy, consciousness and complex systems – the Frontiers Collection will inspire readers to push back the frontiers of their own knowledge.

Information and Its Role in Nature
By J. G. Roederer

Relativity and the Nature of Spacetime
By V. Petkov

Quo Vadis Quantum Mechanics?
Edited by A. C. Elitzur, S. Dolev,
N. Kolenda

Life – As a Matter of Fat
The Emerging Science of Lipidomics
By O. G. Mouritsen

Quantum–Classical Analogies
By D. Dragoman and M. Dragoman

Knowledge and the World
Challenges Beyond the Science Wars
Edited by M. Carrier, J. Roggenhofer,
G. Küppers, P. Blanchard

Quantum–Classical Correspondence
By A. O. Bolivar

Mind, Matter and Quantum Mechanics
By H. Stapp

Quantum Mechanics and Gravity
By M. Sachs

Extreme Events in Nature and Society
Edited by S. Albeverio, V. Jentsch,
H. Kantz

The Thermodynamic Machinery of Life
By M. Kurzynski

The Emerging Physics of Consciousness
Edited by J. A. Tuszynski

Weak Links
Stabilizers of Complex Systems
from Proteins to Social Networks
By P. Csermely

Mind, Matter and the Implicate Order
By P.T.I. Pylkkänen

Quantum Mechanics at the Crossroads
New Perspectives from History,
Philosophy and Physics
By J. Evans, A.S. Thomdike

Particle Metaphysics
A Critical Account of Subatomic Reality
By B. Falkenburg

The Physical Basis of the Direction of Time
By H.D. Zeh

Asymmetry: The Foundation of Information
By S.J. Muller

H. Dieter Zeh

THE PHYSICAL BASIS OF THE DIRECTION OF TIME

5th edition

With 35 Figures

Springer

Professor Dr. H. Dieter Zeh
University of Heidelberg,
Institute of Theoretical Physics,
Philosophenweg 19,
69120 Heidelberg, Germany
email: zeh@uni-heidelberg.de

Series Editors:

Avshalom C. Elitzur
Bar-Ilan University,
Unit of Interdisciplinary Studies,
52900 Ramat-Gan, Israel
email: avshalom.elitzur@weizmann.ac.il

Mark P. Silverman
Department of Physics, Trinity College,
Hartford, CT 06106, USA
email: mark.silverman@trincoll.edu

Jack Tuszynski
University of Alberta,
Department of Physics, Edmonton, AB,
T6G 2J1, Canada
email: jtus@phys.ualberta.ca

Rüdiger Vaas
University of Gießen,
Center for Philosophy and Foundations of Science
35394 Gießen, Germany
email: Ruediger.Vaas@t-online.de

H. Dieter Zeh
University of Heidelberg,
Institute of Theoretical Physics,
Philosophenweg 19,
69120 Heidelberg, Germany
email: zeh@uni-heidelberg.de

Cover figure: Image courtesy of the Scientific Computing and Imaging Institute,
University of Utah (www.sci.utah.edu).

Library of Congress Control Number: 2007922924

ISSN 1612-3018
ISBN 978-3-540-68000-0 Springer Berlin Heidelberg New York
ISBN 978-3-540-42081-1 4th ed. Springer Berlin Heidelberg New York

This work is subject to copyright. All rights are reserved, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilm or in any other way, and storage in data banks. Duplication of this publication or parts thereof is permitted only under the provisions of the German Copyright Law of September 9, 1965, in its current version, and permission for use must always be obtained from Springer. Violations are liable for prosecution under the German Copyright Law.

Springer is a part of Springer Science+Business Media

springer.com

© Springer-Verlag Berlin Heidelberg 1989, 1992, 1999, 2001, 2007

The use of general descriptive names, registered names, trademarks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

Typesetting: Data supplied by the author
Production: LE-TEX Jelonek, Schmidt & Vöckler GbR, Leipzig
Cover design: KünkelLopka, Werbeagentur GmbH, Heidelberg

Printed on acid-free paper SPIN 11908548 57/3100/YL - 5 4 3 2 1 0

Preface

Four previous editions of this book were published in 1989, 1992, 1999, and 2001. They were preceded by a German version (Zeh 1984) that was based on lectures I had given at the University of Heidelberg.

My interest in this subject arose originally from the endeavor to better understand all aspects of irreversibility that might be relevant for the statistical nature and interpretation of quantum theory. The quantum measurement process is often claimed to represent an 'amplification' of microscopic properties to the macroscopic scale in close analogy to the origin of classical fluctuations, which may lead to the local onset of a phase transition, for example. This claim can hardly be upheld under the assumption of universal unitary dynamics, as is well known from the example of Schrödinger's cat. However, the classical theory of statistical mechanics offers many problems and misinterpretations of its own, which are in turn related to the oft-debated retardation of radiation, irreversible black holes with their thermodynamical aspects, and – last but not least – the expansion of the Universe. So the subject offered a great and exciting 'interdisciplinary' challenge. My interest was also stimulated by Paul Davies' (1977) book that I used successfully for my early lectures. Quantum gravity, that for consistency has to be taken into account in cosmology, even requires a complete revision of the concept of time, which leads to entirely novel and fundamental questions of interpretation (Sect. 6.2).

Many of these interesting fields and applications have seen considerable progress since the last edition came out. So, while all chapters have again been thoroughly revised for this fifth edition in order to take these developments into account, changes concentrate on Sects. 2.3 (Radiation Damping), 4.3 (Decoherence), 4.6 (Interpretations of Quantum Theory), 5.3 (Expansion of the Universe) and Chap. 6 (Quantum Cosmology). There are new Sects. 3.5 (on Cosmic Probabilities and History) and 4.3.3 (on Quantum Computers), while Sect. 5.3 has been subdivided and extended. In general, I have tried to remove 'vague' statements, or to make them more precise – although this was not always possible because of the complexity or even speculative nature of some fields. As in previous editions, the focus of the book is on questions of interpretation and relations between different fields – not on technical formalisms and empirically unfounded or predominantly mathematical ideas and concepts.

Many friends and colleagues helped me with their advice on various subjects during the preparation of all previous editions. I cannot here repeat all their names (I hope they are all duly mentioned in the corresponding previous prefaces), but I wish to thank here my former collaborators Erich Joos and Claus Kiefer for their enduring support to all editions. Special thanks this time go to Angela Lahee for her encouragement to prepare a fifth edition (the first one for the Springer Frontiers Collection), and to Stephen Lyle for editing it (although he is not responsible for any errors I may have introduced with numerous last-minute corrections).

I intend to post corrections or revisions to some sections of the book at my website www.time-direction.de whenever it should turn out to be appropriate.

Heidelberg, *H.D. Zeh*
April 2007

Contents

Introduction

The asymmetry of Nature under a 'reversal of time' (that is, a reversal of motion and change) appears only too obvious, as it deeply affects our own form of existence. If physics is to justify the hypothesis that its laws control everything that happens in Nature, it should be able to explain (or consistently describe) this fundamental asymmetry which defines what may be called a *direction in time* or even – as will have to be discussed – a direction *of* time. Surprisingly, the very laws of Nature are in pronounced contrast to this fundamental asymmetry: they are essentially symmetric under time reversal. It is this discrepancy that defines the enigma of the direction of time, while there is no lack of asymmetric dynamical formalisms or pictures that go beyond the fundamental empirical laws.

It has indeed proven appropriate to divide the formal dynamical description of Nature into *laws* and *initial conditions*. Wigner (1972), in his Nobel Prize lecture, called this conceptual distinction Newton's greatest discovery, since it demonstrates that the laws by themselves are far from determining Nature. The formulation of these two pieces of the dynamical description requires that appropriate *kinematical* concepts (formal *states* or *configurations* z, say), which allow the unique mapping (or 'representation') of all possible states of physical systems, have already been defined on empirical grounds.

For example consider the mechanics of N *mass points*. Each state z is then equivalent to N points in three-dimensional space, which may be represented in turn by their $3N$ coordinates with respect to a certain frame of reference. States of physical *fields* are instead described by certain functions on three-dimensional space. If the laws of Nature contain kinematical elements (constraints on kinematical concepts that would otherwise be too general, such as $\mathrm{div}\boldsymbol{B} = 0$ in electrodynamics), one should distinguish them from the dynamical laws proper. This is only in *formal* contrast to relativistic spacetime symmetry (see Sect. 5.4).

The laws of Nature, thus refined to their purely dynamical content, describe the time dependence of physical states, $z(t)$, in a general form – usually by means of differential equations. They are called *deterministic* if they uniquely determine the state at time t from that (and possibly its time derivative) at any earlier or later time, that is, from an appropriate initial or final condition. This symmetric dynamical determinism is much more rigorous than the traditional concept of *causality*, which requires that every event in Nature must possess a specific *cause* (in its past), while not necessarily a specific *effect* (in its future). The *Principle of Sufficient Reason* (or at least its 'causal root'[1]) can be understood in this asymmetric causal sense that would define an absolute direction of time.

However, only since Newton has uniform motion been interpreted as 'eventless' (thus not needing a cause), while acceleration requires a *force* as the modern form of *causa movens* (usually assumed to act in a retarded, but hardly ever in an advanced manner). From the ancient point of view, terrestrial bodies were usually regarded as eventless or 'natural' only when at rest, and celestial ones when moving in circular orbits (later also including epicycles), or when at rest on the celestial ('crystal') spheres. These motions thus did not require any dynamical causes according to this picture, similar to uniform motion today. None of the traditional causes (neither physical nor others) ever questioned the fundamental asymmetry in (or of) time, since there were no conflicting symmetric dynamical laws yet.

Newton's concept of a force determining acceleration (the *second* time derivative of the 'state') forms the basis of the formal Hamiltonian concept of states in *phase space* (with corresponding dynamical equations of *first* order in time). First order time derivatives of states in configuration space, required to define momenta, can then be freely chosen as part of the initial conditions. In its Hamiltonian form, this part of the kinematics is intermingled with dynamics, as the definition of canonical momentum depends in general on a dynamical concept (the Lagrangean).

Newton recognized friction as a source of time asymmetry. While different motions which may start from one and the same unstable position of rest would require different initial perturbations as sufficient reasons, friction (if understood as a fundamental force) could deterministically bring different motions to the same rest. States at which the symmetry of determinism may thus come to an end (perhaps asymptotically in time) are called *attractors* in some theories.

The term 'causality' is unfortunately understood in very different ways. In physics, it is often synonymous with dynamical determinism, or it may refer to the relativistic limits for the propagation of causal effects, based on the light cone structure of spacetime. In philosophy, it sometimes means the existence of laws of Nature in general. In mathematical physics, dynamical determinism is often understood asymmetrically as applying only in the 'forward' direc-

---

[1] Its 'logical root' has nothing to do with time, but is often confused with dynamical causality. For example, logical *operations* are performed in time by physical systems, even though they can, in a strict sense, only lead to tautologies, which are true regardless of any physical operations (see also the end of Sect. 3.3).

tion of time (thus allowing attractors – see Sect. 3.4). Time-reversal-symmetric determinism was discovered together with the dynamical laws of mechanics in situations where friction could be neglected (as in celestial mechanics). An asymmetric concept of 'intuitive causality' that is compatible with (though essentially different from) symmetric determinism will be defined and discussed in the introduction to Chap. 2.

A subtle but important point here is that the time reversal symmetry of the *concept of determinism* does not necessarily require symmetric dynamical laws. For example, the Lorentz force $e\boldsymbol{v} \times \boldsymbol{B}$, acting on a charged particle and resulting from a *given* external magnetic field, changes sign under time reversal (defined by replacing t by $-t$).[2] Nonetheless, determinism applies equally in both directions of time. This is possible, since the time reversal asymmetry of this equation of motion may be compensated for by a simultaneous reversal of the magnetic field.

Other (more or less physical) *compensating symmetry operations* are known (see Atkinson 2006). For example, the time reversal symmetry of the Schrödinger equation is restored by complex conjugation of the wave function. This can be described by means of Wigner's anti-unitary operation T which leaves the configuration basis unchanged, $Tc|q\rangle = c^*|q\rangle$ for complex numbers c. T may be chosen to contain further self-inverse operations, such as multiplication with the matrix β for the Dirac equation. A trivial example is the time reversal of *states in classical phase space*, $q, p \rightarrow q, -p$. This transformation restores invariance of the Hamiltonian equations, which would be violated under a *formal* time reversal $p(t), q(t) \rightarrow p(-t), q(-t)$. In quantum theory it corresponds to the transformation $T|p\rangle = |-p\rangle$, which is now a *consequence* of anti-unitarity when T is applied to the state $|p\rangle = (2\pi)^{-1/2} \int \mathrm{d}q\, \mathrm{e}^{\mathrm{i}pq}|q\rangle$.

For trajectories of states, $z(t)$, one usually includes the transformation $t \rightarrow -t$ in the action of T rather than applying the latter only to the state z: $Tz(t) := z_T(-t)$, where $z_T := Tz$ is the 'time-reversed state' defined above. In the Schrödinger picture of quantum theory this is again automatically taken care of by the anti-unitarity of T when commuted with the time translation $\mathrm{e}^{-\mathrm{i}Ht}$ for a time reversal invariant Hamiltonian H. In this sense, 'T invariance' does indeed mean time reversal invariance. When discussing time reversal, one usually also presumes invariance under *translations* in time in order not to specify an arbitrary origin for the time reversal transformation $t \rightarrow -t$.

The time reversal asymmetry characterizing weak forces, which is responsible for K-meson decay, may similarly be compensated for by an additional CP transformation, where C and P are charge conjugation and spatial reflection, respectively. The latter do *not* just reflect a time reversal elsewhere

---

[2] Any distinction between reversal of time and reversal of motion (or any other kind of change) would require some concept of absolute or extraphysical time (see Chap. 1). For example, an asymmetry of the fundamental dynamical laws would *define* (or presume) an absolute direction of time – just as Newton's equations define absolute time up to linear transformations (which thus do allow a reversal of sign).

(such as the inversion of a magnetic field that is caused by the reversal of external currents). Only if the compensating symmetry transformation represents an observable, such as CP, and is not the consequence of a time reversal elsewhere, does one speak of a *violation* of time reversal invariance of the dynamics.

The possibility of compensating for a dynamical time reversal by another symmetry transformation (observable or not) reflects the prevailing *symmetry of determinism.* Such ‘symmetric’ violations of time reversal invariance have therefore nothing to do with irreversibility, which forms the subject of this book. All known *fundamental* laws of Nature are symmetric under time reversal after compensation by an appropriate symmetry transformation, thus defining a combined symmetry, say $\hat{T}$. For example, $\hat{T} = CPT$ in particle physics, while $\hat{T}\{\boldsymbol{E}(\boldsymbol{r}), \boldsymbol{B}(\boldsymbol{r})\} = \{\boldsymbol{E}(\boldsymbol{r}), -\boldsymbol{B}(\boldsymbol{r})\}$ in classical electrodynamics. This means that for every solution $z(t)$ of the dynamical laws there is precisely one time-reversed solution, $z_{\hat{T}}(-t)$, where $z_{\hat{T}} = \hat{T}z$. This fact is essential for all statistical arguments regarding irreversibility.

‘Initial’ conditions are usually understood as conditions which fix the integration constants, that is, which select *particular* (individual) solutions of the equations of motion. They could just as well be formulated as final conditions, even though this would not represent the usual *operational* (hence asymmetric) application of the theory. These initial conditions may select the solutions which are ‘actually’ found in Nature. An individual (contingent) trajectory $z(t)$ is generically *not* symmetric under time reversal, that is, not *identical* with $z_{\hat{T}}(-t)$. If $z(t)$ is sufficiently complex, the time-reversed process is not even likely to occur anywhere else in Nature within reasonable approximation.

However, most phenomena observed in Nature violate time reversal symmetry in a less trivial way if considered as whole *classes of phenomena*. The members of some class may be abundant, while the time-reversed class is not realized at all. Such symmetry violations will be referred to as ‘fact-like’ – in contrast to the mentioned CP symmetry violations, which are ‘law-like’. In modern versions of quantum field theory, even the boundary between laws of Nature and initial conditions gets blurred. Certain parameters which are usually regarded as part of the laws (such as those characterizing the mentioned CP violation) may have arisen by *spontaneous symmetry breaking* (an indeterministic irreversible process of disputed nature in quantum theory – see Sects. 4.6 and 6.1).

In contrast to what is often claimed in textbooks, this asymmetric appearance of Nature cannot be explained by statistical arguments. If the laws are invariant under time reversal when compensated by another symmetry transformation, there must be precisely as many solutions in the time-reversed class as in the original one (see Chap. 3).

Since Eddington, classes of phenomena characterizing a direction in time have been called *arrows of time*. The most important ones are:

1. **Radiation.** In most situations, fields interacting with local sources are appropriately described by means of retarded (outgoing or defocusing) solutions (see Chap. 2). A spherical outgoing wave is observed *after* a point-like event that represents a source. This may lead to *damping* of the source. One may easily observe 'spontaneous' emission (when incoming radiation is absent – see Item 5), while absorption requires retarded consequences. Even an ideal absorber leads to *retarded* shadows (destructive interference with a retarded field).
2. **Thermodynamics.** The Second Law $\mathrm{d}S/\mathrm{d}t \geq 0$ is often regarded as a *law* of Nature. In microscopic description it has instead to be interpreted as *fact-like* (Chap. 3). This arrow is certainly the most general and important one. Because of its applicability to human memory and other physiological processes, it may also be responsible for the *impression* that time itself has a direction (corresponding to an *apparent flow of time* – see Chap. 1).
3. **Evolution.** Dynamical 'self-organization' of matter, for example observed in biological and social evolution, may appear to contradict the Second Law. However, *global* entropy always keeps growing if the environment is properly taken into account (Sect. 3.4).
4. **Quantum Mechanical Measurement.** The probability interpretation of quantum mechanics is usually understood as describing a fundamental indeterminism of the future, although its interpretation and compatibility with the deterministic Schrödinger equation constitutes a long-standing open problem. Stochastic quantum 'events' are often dynamically described by a collapse of the wave function – not only in measurements. The Schrödinger equation itself may describe growing entanglement as an arrow of time that is analogous to (but different from) statistical mechanics – see Chap. 4.
5. **Exponential Decay.** Many unstable physical systems *decay* exponentially in time (see Sect. 4.5). Exponential growth is only observed under specific circumstances in self-organizing systems (Item 3 above).
6. **Gravity** seems to 'force' massive objects to move towards each other with increasing time. Stars or star clusters contract. However, this is another prejudice about the *causal* (time-directed) action of forces. Gravity describes attraction in *both* directions of time, since Newton's laws are of *second* order. The asymmetry occurs since we often *prepare* objects in an initial state of rest, while the observed contraction of stars against their internal pressure is controlled by thermodynamic and radiation phenomena. On the other hand, gravitating objects are characterized by a negative heat capacity, and classically even by the capacity to contract without limit in accordance with the Second Law if appropriately prepared (see Chap. 5). In general relativity this leads to time asymmetric *future horizons* in spacetime (characterizing black holes), through which objects can only *dis*appear. *Expansion* against gravity is observed for the Universe as a whole – thus indicating an unconventional *cosmic* initial condition. Since cosmic expansion does not define a *class* of phenomena, it has often been

suggested to represent the 'master arrow' from which all others may be derived (see Sects. 5.3 and 6.2).

In spite of their fact-like nature, these arrows of time, in particular the thermodynamical one, have been regarded by some of the most eminent physicists as even more fundamental than the dynamical laws themselves. For example, Eddington (1928) wrote:

> The law that entropy always increases holds, I think, the supreme position among the laws of Nature. If someone points out to you that your pet theory of the Universe is in disagreement with Maxwell's equations – then so much the worse for Maxwell's equations. ... but if your theory is found to be against the second law of thermodynamics, I can give you no hope; there is nothing for it but to collapse in deepest humiliation.

And Einstein (1949) remarked:

> It [thermodynamics] is the only physical theory of universal content concerning which I am convinced that, within the framework of the applicability of its basic concepts, it will never be overthrown.

These remarks were hardly meant to express doubts over the *derivability* of the thermodynamical arrow of time by statistical means when using those 'less credible theories' (see Chap. 3). Rather, they are intended to express their authors' conviction in the *invariance* of the derived thermodynamical concepts and laws under modifications and generalizations of these theories. However, this statistical derivation will be shown to require important assumptions about the initial state of the Universe. *If* the Second Law is fact-like in this sense, its violation or reversal must at least be conceivable, and thus cannot be excluded *a priori*.

The arrows of time listed above characterize an asymmetric *history* of the Universe. This history can be conceived of as a whole, comparable to a movie film sitting on the desk, or an ordered stack of picture frames ('states'), without any selection of a present (that is, of a specific 'actual' frame) or an external distinction between beginning and end. This is called the 'block universe view' (see Price 1996). It may be contrasted with the view of an *evolving* history, observed by an *external* movie viewer as a definer of 'absolute' time for the running movie.

It appears questionable whether these different *views* might possess different power in explaining an asymmetry of the (hi)story described by the movie, but they are regarded as basically different in this respect by many philosophers, including also some physicists (Prigogine 1980, von Weizsäcker 1982). The second view is related to the idea that the past is 'fixed', while the future is 'open' and 'does not yet exist'. The asymmetric history is then regarded as the 'outcome' (or the consequence) of this time-directed 'process of coming-into-being'. (The abundance of quotation marks indicates how our language is loaded with prejudice about the flow of time.) The fact that there are documents, such as fossils, only about the past, and that we cannot remember the future,[3] appears as evidence for this so-called 'structure of time' or the 'historical nature' (*Geschichtlichkeit*) of the world.

However, an asymmetry in the stack of movie frames on the desk is defined regardless of any presentation or production of the movie in external time. *Correlations* between an individual movie frame and certain others, which may represent 'documents' about the latter, are properties of the set of frames on the desk. If consistent asymmetric memory relations existed throughout the whole story, an intrinsic observer, who was part of the story, could know its content only at the (intrinsically defined) 'end'. He could nonetheless conceive of a 'potential' complete story even within the story, in particular if he discovered dynamical laws. Existing 'actually' only in a specific frame, he could neither deny nor prove the existence of other frames, although he might 'remember' those frames which represent his intrinsic past (even if the movie were presented backwards). The time he is aware of has to be read from clocks showing up on the picture frames – not from the watch of an external movie viewer or from any frame numbers (see also Chap. 1 and Sect. 5.4). The concept of 'existence' is here evidently used with various meanings, and the debate may easily become one about words. Similarly, within our 'world movie', concepts like *fixed* and *open*, or *actual* versus *potential*, can only be meaningful either as statements about *practical abilities* of predicting and retrodicting, or as statements about dynamical *models*.

The argument that the historical nature of the world be a prerequisite (in the Kantian sense) for the fact that we *can* make experience does not exclude the possibility (or necessity) of explaining it in terms of those laws and concepts that have been distilled from this experience. They may then be hypothetically extrapolated to form a 'world model', whereby the historical nature may even turn out *not* to apply to other spacetime regions (see Sect. 5.3.3).

In classical physics, the Second Law is usually regarded as the physical basis of the historical nature of the world. Its statistical interpretation would then mean that this 'structure of time' (that is, its apparent direction) is merely the consequence of contingent facts which characterize our specific world. For example, one may explain thermodynamically why there are observations, but no 'un-observations' in which initially present information (memory about the future) would disappear by means of a controlled interaction between the observing and observed systems. This un-observation has to be distinguished from the usual process of forgetting, which represents an information loss in the memory device in accordance with an increase of entropy (see Sect. 3.3).

The concept of 'retarded' information would thus arise as a *consequence* of thermodynamics (and not the other way round, as is sometimes claimed). The

---

[3] "It's a bad memory that only works backwards" says the White Queen to Alice.

inconsistency of presuming either an extra-physical concept of information or extra-physical operations has often been discussed by means of *Maxwell's demon*. In particular, the 'free will' of an experimenter should not be misused to *explain* the specific (low entropy) initial conditions that he prepares in his laboratory. If the experimenter (or demon) were not required to obey the thermodynamical laws himself, his actions could readily *create* the thermodynamical arrow of time observed in his experiments. Nonetheless, the possibility that conscious beings require new fundamental laws cannot *a priori* be excluded.

The indeterminism of quantum measurements and other 'quantum events' has often been interpreted as evidence for such an extra-physical concept of (human?) information. This is documented by many statements by important physicists. For example, Heisenberg argued in the spirit of idealism that "a particle trajectory is created only by its observation,"[4] while von Weizsäcker claimed that only "what has been observed exists with certainty."[5] One can similarly understand Bohr's statement: "Only an observed quantum phenomenon is a phenomenon." He insisted that a quantum measurement cannot be analyzed as an objective dynamical process ("there is no quantum world"). A similar view can be found in Pauli's letter to Born (Einstein, Born and Born 1984): "The appearance of a definite position x_0 during an observation ... is then regarded as a creation existing outside the laws of Nature."[6] Born often expressed his satisfaction with quantum mechanics, as he felt that his probability interpretation saved free will from the determinism of classical laws.

The extra-physical time arrow appears in all *operational* formulations of quantum theory, such as those describing probabilistic relations connecting preparations and subsequent measurements – thus restricting quantum theory to laboratory physics performed by humans. Most of these formulations rely on a given (absolute) direction of time. This should then be reflected by the dynamical description of quantum measurements and 'measurement-like processes' even in the block universe picture. The impact of such phenomena (provided they do indeed occur) on the formal physical description should therefore be precisely located.

Much of the *philosophical* debate about time is concerned with language problems, some of them simply arising from the pre-occupied usage of the tenses, particularly for the verb 'to be' (see Smart 1967, or Price 1996). Aristotle's famous (pseudo-)problem regarding the potential truth value of the claim that there will be a sea battle tomorrow survives not only in *Sein und Zeit*, but even in quantum theory in the form of an occasional confusion of logic with dynamics ('logic of time') – see footnote 1. A careful distinction

---

[4] "*Die Bahn entsteht erst dadurch, daß wir sie beobachten.*"

[5] "*Was beobachtet worden ist, existiert gewiß.*"

[6] "*Das Erscheinen eines bestimmten Ortes x_0 bei der Beobachtung ... wird dann als außerhalb der Naturgesetze stehende Schöpfung aufgefaßt.*"

between temporal and logical aspects of actual and ‘counterfactual’ measurements can be found in Mermin (1998).

The prime intention of this book is to discuss the relations between various arrows of time, and to search for a universal *master arrow*. To this end, certain open problems which have often been pragmatically put aside in the traditional theories will have to be clearly worked out. They may indeed become essential in more general theories, or have important cosmological implications (see Chaps. 5 and 6).

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 nontrivial 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).

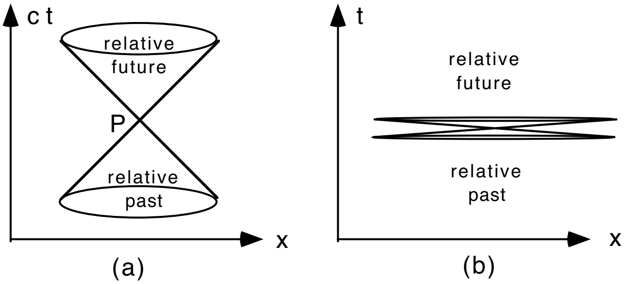

Fig. 1.1. (**a**) Local spacetime structure according to the theory of relativity. Spacetime future and past are defined *relative* to every event P, and independent of any choice of reference frame. (**b**) In conventional units (large numerical value of the speed of light) the light cone opens widely, 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.

2

The Time Arrow of Radiation

After a stone has been dropped into a pond, one observes concentrically diverging ('defocusing') waves. Similarly, *after* an electric current has been switched on, one finds a retarded electromagnetic field that is coherently propagating *away* from its source. Since the fundamental laws of Nature, which describe these phenomena, are invariant under time reversal, they are equally compatible with the reverse phenomena, in which concentrically focusing waves (and whatever may be dynamically related to them – such as heat) would 'conspire' in order to eject a stone out of the water. Deviations of the deterministic laws from time reversal symmetry would modify this argument only in detail (see the Introduction). However, the reversed phenomena are never observed in Nature. In high-dimensional configuration space, the absence of dynamical correlations which would focus to create local effects characterizes the time arrow of thermodynamics (Chap. 3), or, when applied to wave functions, even that of quantum theory (see Sect. 4.3).

Electromagnetic radiation will here be considered to exemplify wave phenomena in general. It may be described in terms of the four-potential A^μ, which in the Lorenz gauge obeys the wave equation

$$-\partial^\nu \partial_\nu A^\mu(\boldsymbol{r}, t) = 4\pi j^\mu(\boldsymbol{r}, t) \ , \quad \text{with} \quad \partial^\nu \partial_\nu = -\partial_t^2 + \Delta \ , \tag{2.1}$$

using units with $c = 1$, the notations $\partial_\mu := \partial/\partial x^\mu$ and $\partial^\mu := g^{\mu\nu}\partial_\nu$, and Einstein's convention of summing over identical upper and lower indices. When an appropriate boundary condition is imposed, one may write A^μ as a functional of the sources j^μ. For two well known boundary conditions one obtains the *retarded* and the *advanced* potentials,

$$A^\mu_{\text{ret}}(\boldsymbol{r}, t) = \int \frac{j^\mu(\boldsymbol{r}, t - |\boldsymbol{r} - \boldsymbol{r}'|)}{|\boldsymbol{r} - \boldsymbol{r}'|} \mathrm{d}^3\boldsymbol{r}' \ , \tag{2.2a}$$

$$A^\mu_{\text{adv}}(\boldsymbol{r}, t) = \int \frac{j^\mu(\boldsymbol{r}, t + |\boldsymbol{r} - \boldsymbol{r}'|)}{|\boldsymbol{r} - \boldsymbol{r}'|} \mathrm{d}^3\boldsymbol{r}' \ . \tag{2.2b}$$