NOTEBOOK

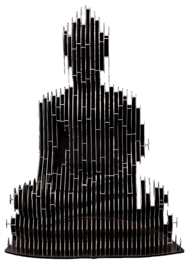
I QUADERNI DI EJTP

2

Logo: Julian Voss–Andreae, *Black Quantum Buddha* in black–oxidized stainless (27" or 69 cm tall).

NOTEBOOK

I QUADERNI DI EJTP



> La più bella e profonda emozione che possiamo provare è il senso del mistero. Sta qui il seme di ogni arte, di ogni vera scienza.
>
> Albert EINSTEIN

Ogni giornale scientifico durante la sua storia ha avuto occasione di ricevere articoli: talvolta particolarmente lunghi per essere considerati tali, talvolta troppo brevi rispetto all'approfondimento necessario che la trattazione di uno specifico argomento avrebbe richiesto.

Oltre la pratica scientifica quotidiana, composta da teorie, commenti e calcoli, alcuni contributi propongono una visione diversa di taluni argomenti, oppure richiedono un approfondimento. A volte i contributi di un autore hanno bisogno di essere raccolti in una sintesi uniforme e complessa per mostrare l'efficacia della proposta.

Nasce così, come una costola della rivista « Electronic Journal of Theoretical Physics », "Notebook. I Quaderni di EJTP", una collana di monografie, dedicate a temi fondazionali della fisica, idealmente legata alla rivista, ma sostanzialmente indipendente. La collana accoglie opere di carattere internazionale, che trattano temi legati a tutti i campi della fisica, con particolare riguardo alla fisica teorica e alla filosofia della fisica.

Vai al contenuto multimediale

Daniel Wohlfarth

On the concept of fundamental time asymmetrie in Physics

Aracne editrice

www.aracneeditrice.it
info@aracneeditrice.it

www.gioacchinoonoratieditore.it
info@gioacchinoonoratieditore.it

via Vittorio Veneto, 20
00020 Canterano (RM)
(06) 45551463

ISBN 978-88-255-0432-3

I edition: July 2017

Contents

Chapter I

Introduction and motivation

1.1. Introduction and motivation

The question of how to understand the difference between the "past" and the "future" (if there is any) has always been a philosophically relevant question. The experience that time appears to flow (bringing the world from a state in the past to a state in the future by passing an ever–changing present) seems to be one of the most basic observations in human life. Thus, attempts have been made to formulate a philosophy of time that suggests that this directed time asymmetry (the flow) is a primitive property of time itself. However, this picture is imbedded in a field with many different issues and unsolved problems, some philosophical and others arising in the physical sciences.

According to the natural sciences, it appears to be a well–motivated view that the most fundamental models of nature are those provided by particular fields of physics. Of course, from a philosophical perspective, this could be rejected, but it need not be. Moreover, if we assume that fundamental physical models describe, even approximately, some properties of nature, these properties can be understood as the most fundamental properties described in scientific theories today. Note that this does not imply that the models of other sciences or other fields in physics are reducible to these fundamental models. My point is only that the view which says that physics describes some of the fundamental properties of nature is well motivated and attractive. The motivation for this investigation is based on this view. However, even if this investigation is motivated by the assumption that the most fundamental properties of nature, which are described in scientific theories, are described in physical theories, this does not mean that the investigation's outcome depends on this assumption. The main claim of the investigation is that some time asymmetric structures should be understood as a "fundamental" property of the physical models currently used to describe nature. Success in proving this claim does not mean that the asymmetries are assumed to be a fundamental property of nature; neither does it mean that the asymmetries of time, if they exist, are assumed to be correctly captured by physical theories. The only point is that the asymmetries of time can be seen as a fundamental property of crucial, well–established physical theories and models. This claim is unaffected by any discussion regarding the question: « do physical models describe, even approximately, the properties of nature, and are those properties fundamental properties of nature itself? ».

Thus, the interesting discussions of this question in the philosophy of science are considered only in some small parts of this investigation. Nevertheless, crucial questions regarding time directions arise mostly in light of the view that at least some fields in physics describe some crucial parts of nature correctly. If this view could be rejected in the first place, it would be attractive, given that the direction of time is a well–observed fact in everyday life, to assume that the direction of time is simply a primitive fact. The experience of the direction of time appears puzzling only if we assume that some crucial and fundamental structures of nature are captured, at least partly, by physics. The nature of the puzzle is revealed by the following observation: a closer look at the laws of fundamental physics shows that they are time–reversal invariant (or CPT–invariant)[1]. That is, in the fundamental theories, at least in their standard formulations and interpretations, we find no *fundamental* physical difference between past and future according to the fundamental *laws* of physical theories. This, of course, draws an unsatisfactory picture. The basic issue is that the laws of fundamental physics seem to admit no substantial difference between the past and the future, but the future and the past seem different in everyday experience. Why should that be so?

We find different lines of thought regarding this crucial question. One is based on the fact that it is always possible to argue that fundamental physics captures the fundamental properties of nature incorrectly. If this were so, it would be possible that:

1. But, the consideration of charge (C) and parity (P) seems unable to solve the problem. I will come back to this point later.

a) the "true" laws of nature (if they exist) are not time reversal invariant;
b) a non–time reversal invariant formulation or interpretation of known physical laws captures the properties of nature more correctly. Alternatively;
c) fundamental physics cannot capture the real structures of nature, which *may be* time asymmetric.

I now provide a brief motivation for my view that none of these options seems attractive. First consider option c, for which there seems to be two crucial explications:

a) fundamental physics cannot capture the real structures of nature, which *may be* time asymmetric. Therefore it is impossible to say whether the time asymmetry of our everyday experience is based on a fundamental property of nature or only on the structure of the human mind or brain;
b) fundamental physics cannot capture the real structures of nature, which *may be* time asymmetric. But, the time asymmetry of our everyday life is a basic observation, and we should assume that such basic observations arise from real properties of nature; if fundamental physics cannot explain the origin of this property, it just shows that some crucial properties of nature are not captured by physical theories. Nevertheless, the directedness of time should be assumed to be a fundamental property of nature itself.

Both explications of option c seem disentangled from the aim of this investigation for the following reasons.

Obviously, c1 is a possibility. However, if there is a way to understand the occurring of fundamental time asymmetries on the basis of the theories and models of physics, this understanding, in agreement with modern physics, would be attractive even if this does not guarantee that the fundamental and crucial structures of nature are correctly captured in the physical theories. In fact, this situation is identical regarding almost all properties described in physical theories. Hence, I do not think that this uncertainty is a sufficient reason to deny the fruitfulness of physical explanations for crucial observations in nature. The same, I think, should be assumed (at least prima facie) for the observation of the directedness of time. Hence, the search for an understanding of time asymmetries based on fundamental physics should not be abandoned, even if c1 is taken seriously.

According to c2, everyday life experience is assumed to capture the properties of nature more precisely than fundamental physics does. Although this could be the case, I think it is highly problematic. The problems arise not only because this implies that generations of physicists have spent their lives building sophisticated models of nature without success. More importantly, this view, I think, fails to explain that physics provides new predictions (not only in laboratory experiments but also in observations of the physical environment) and that technologies based on fundamental physical theories turn out to be realizable, at least approximately. From a philosophical point of view, therefore, option c2 seems unattractive. In this context, one motivation for this investigation is to show that an understanding of the crucial time asymmetries based on the fundamental theories of physics is possible.

Option *b*) also seems problematic. There are time asymmetric formulations or interpretations of some fundamental physical theories, but they do not seem to be motivated independently from the issue. In fact, they seem motivated by the issue at hand, which means that they were constructed to achieve the goal of formulating a time–asymmetric formalism in fundamental physics. In this situation, it is not clear which formulation (the time symmetric one or time asymmetric one) captures the properties of nature (more) correctly (if any). But, I shall argue that even without time asymmetric non–standard formulations or interpretations, an understanding of time asymmetries, based on fundamental physical theories, is possible. Hence, the issues that arise from taking the view b, so I will show in this investigation, can be avoided.

Moreover, we find that some time asymmetric formalisms (for example, the rigged Hilbert space approach) in fundamental physics are usually constructed by the following considerations:

a) in the considered standard formalisms of fundamental physics, time evolutions in both time directions are describable and allowed (symmetrically). So it becomes possible to "cut out via hand" the possible evolution in the past direction;

b) then the task is "only" to find a coherent mathematical formulation of the remaining possible temporal evolution;
c) the result is a time asymmetric formalism in fundamental physics.

However, such formalisms seem ad hoc and unmotivated by independent reasons. Thus, in cases like the rigged Hilbert space approach, option b appears unattractive, at least from a philosophical perspective. Nevertheless, I shall argue in Chapt. VI that some time asymmetric formulations can be motivated independently by the analysis presented later. Specifically, in the rigged Hilbert space approach the time asymmetric formulation can be seen as motivated by a physical analysis if the right conceptual framework is used. Here, however, I will simply conclude that option b seems unattractive, as long as (as this investigation claims) there is a way of understanding time asymmetries as fundamental properties of the standard formulation and interpretation of physical theories. Option a is always a possibility. However, it shifts the question only to a not–yet–formulated (or never formulated) physical theory. Therefore, this option should not be taken if other options are available to solve the issue, especially in the context of currently formulated theories of physics.

But, one different and prominent suggestion is that time asymmetries are surely *not* a fundamental property of the physical theories (see, for example, Price 1996). In this view, physics is taken seriously, and the experience of time in everyday life is assumed to capture only some other properties, which could be provided by the biological structure of the human brain. This option, I think, looks more attractive than the three views discussed above. Note that this option is slightly distinguished from option c1. The distinction arises from the fact that, according to c1 it is impossible to say if time asymmetries are understandable as a natural property or not, whereas e.g. Price (Price 1996) argues that there are good physical arguments to assume that the experience of time directions in everyday life is provided from other structures and in particular *not* from physics.

Nevertheless, by recognizing how deeply imbedded the notion of "past" and "future" (and also the notion of a fundamental difference between past and further) is in our everyday experience, it would be a more satisfying option to base the time directions on fundamental properties of the physical theories used to describe nature. This investigation claims to support this view even if the standard formulation and interpretation of fundamental physics is assumed and even if, in this formulation and interpretation, all fundamental physical laws are time reversal invariant (or CPT invariant). In Chapt. II, I propose a possible understanding of "fundamentality" of time asymmetries, which is based not on time–reversal variance of fundamental physical laws but on the structure of their solution sets. However, before I come to this proposal in Chapt. II, I discuss some other aspects of the investigation.

In different physical models, we deal with different time parameters. In general and special relativity, we deal with proper time, which is the fundamental time coordinate in relativistic physics. In the Newtonian limit, those proper time coordinates become approximately the Newtonian background time from non–relativistic physics, which seems to describe most experiences in everyday life. According to cosmology, however, there is also cosmic time, which is an important time coordinate. In cosmological models, the cosmic time parameter, if it is definable in a particular spacetime (which seems to be the case in our actual universe), plays a similar (although not identical) role to Newtonian time, and it is connected to the fundamental proper times of different world lines (and not only by a non–relativistic approximation). Thus, according to physics, we find at least two interesting time parameters, which could be directed or not. It is also noteworthy that, according to physics, in a non–time orientable spacetime, which is allowed according to the Einstein equation, the proper times, even of parallel world lines, can have opposite directions. Thus, regarding proper times, we find that every world line, and thus every elementary physical system, can have its own time direction, which would be valid only in a local environment of a given spacetime point on one particular world line. This notion of a "fundamental" time asymmetry (fundamental, because this notion is based on proper times) surely cannot capture some intuitive requirements for a "fundamental" time asymmetry. One of these requirements, which I think is reasonable, is that a fundamental time asymmetry should be valid for at least a spacetime region that captures most parts of our environment in our particular universe without switching the alignment. I shall argue, following Castagnino, Lara and Lombardi (Castagnino, Lara, Lombardi 2003) and Castagnino and Lombardi (Castagnino, Lombardi 2009), that the asymmetries of cosmic time are *fundamentally* imbedded in the models of cosmology (Chapt. III and V). Also, I will argue that asymmetries of proper times arise in many physical contexts and can be seen as consequences of a time asymmetric energy flux in spacetimes similar to ours. But, in contrast to Castagnino and Lombardi (Castagnino, Lombardi 2009), I shall argue that the crucial question as to whether the proper time asymmetries can be seen as fundamental too, will remain unsolved in this investigation. However it will be shown that the time asymmetries of proper times, understood as consequences from a time asymmetric energy flux, produce an understanding of many properties of many prominent time arrows, even if the crucial question of fundamentality will not be solved but only revealed and formulated in this investigation.

Thus, this investigation may propose a counterintuitive picture, as follows: the fundamental time asymmetry appears in cosmic time. In contrast, the time asymmetry of the fundamental time coordinates appears as non–fundamental and only understood as consequences of fundamental time asymmetries if some crucial questions regarding the connections between the cosmic and proper time asymmetries could be solved, as we will see. I will show this in greater detail in Chapt. III, IV and VI.

1.1.1. *Arrows of time in physical models*

In discussions regarding the formulation of time arrows in physical models, some prominent examples are often discussed in physics and in the philosophy of physics and time. These examples are the time arrow in cosmology, the arrow of radiation, the arrow of time in thermodynamics and the arrow of time in quantum mechanics. In Chapt. III, IV, V and VI, I develop an alternative understanding of those time arrows motivated by the suggestion in Chapt. II (the suggestion of a new understanding of the term "fundamentality" in the context of time asymmetries). The alternative understanding of these time arrows is distinguished from the traditional understanding in many ways. From the philosophical point of view, this differentiation occurs most importantly by:

a) the possibility that the time asymmetries (arrows) regarding cosmic time (in classical cosmology, quantum cosmology and thermodynamics) can be seen as fundamental properties or products of fundamental properties of the physical theories used to describe nature;

b) the possibility to understand the origin of proper time asymmetries by considering a time asymmetric energy flux in spacetimes similar to ours. The question as to whether those asymmetries can be understood in a fundamental way, like the asymmetries with respect to cosmic time, will depend on an unsolved question regarding the connections between the alignments of proper and cosmic time asymmetries.

In this Chapter, I shall only give a short overview of the different aspects and issues regarding these prominent time arrows. Because this will be discussed in greater detail in the following Chapters, here I only sketch the traditional understanding of these arrows. Moreover, I will add some brief thoughts which motivate the claim that a new understanding of the different arrows is required in order to understand the *origin* of time asymmetries on the basis of fundamental physics (if the asymmetry is one of cosmic time) or a time asymmetric energy flux in spacetimes similar to ours (for proper time asymmetries).

1.1.1.1. The arrow of time in cosmology

Traditionally, the cosmological time arrow is defined in terms of the evolution and expansion of the three–dimensional universe and it is defined for cosmic time coordinates. The past, in this definition, is identified as the cosmic time direction in which the three–dimensional universe has a lower three–volume, and the cosmic future is defined as that in which the three–dimensional universe has a larger three–volume. In modern cosmological models, the universe expands. Thus, as long as this expansion holds, the time arrow will not change direction.

Regarding this traditional definition of the cosmological time arrow, many objections can be made to demonstrate that this cannot provide a fundamental understanding of cosmological time asymmetries. I deal with some of them in Chapt. III; at this point I only sketch one crucial objection, which shows that the cosmological time arrow, in this simple traditional notion, cannot describe a fundamental time asymmetry. This is because our universe can be described as a particular solution of the Einstein equation. Also, the Einstein equation shows that, even if the definability of cosmic time is assumed, there is no reason to rule out a closed spacetime in general. Even the discovery that our particular universe shows an accelerated expansion does not mean that closed spacetimes are ruled out as possible spacetimes (see also Chapt. III). Thus, even if our particular universe is an ever expanding universe, the cosmological time arrow defined by this expansion is not necessarily a fundamental property of physics because closed spacetimes are also possible according to the fundamental physical laws. Therefore, I think the cosmological time asymmetry in this traditional understanding cannot be seen as fundamental. I shall focus on some prominent and more sophisticated accounts of the cosmological time arrow in Chapt. III. Nevertheless, I will argue (Chapt. III) that they give rise to essentially the same problems as the traditional notion outlined here. Thus, in my suggestions in Chapt. III and V, I shall propose an understanding of cosmological time asymmetries, which can be seen as explications of a fundamental time asymmetry in the solution set of the fundamental dynamical equations of cosmology.

1.1.1.2. The arrow of radiation

It seems hard to determine the *traditional* understanding or characterisation of the arrow of radiation. The most traditional view seems to be the standard characterisation from physics (see, for example, Jackson 1999, Frisch 2000 or Rohrlich 2005). According to this characterisation, the arrow of radiation arises from the empirical fact that fully advanced radiation (of a specific type) is not observable in nature. Both the fully advanced and the fully retarded solutions of Maxwell equations are time–mirrored pictures of each other. Thus, it seems that in nature, one time direction, identified with the fully retarded solution, is favoured.

I think that most attempts to understand this fact are problematic; I shall discuss this in much greater detail in Chapt. IV. Various accounts attempt to explain or describe the origin of the arrow of radiation, but, as I shall argue in Chapt. IV, they are unsuccessful in explaining its origin in physics. Thus, I argue, partly on the basis of philosophical suggestions from Frisch (Frisch 2000), Castagnino and Lombardi

(Castagnino, Lombardi 2009) and the physical analysis of Castagnino, Lara and Lombardi (Castagnino, Lara, Lombardi 2003), that there are crucial structures, at least in spacetimes similar to ours, that forbid the occurrence of fully advanced radiation of a specific but crucial kind. This will provide the retardation condition of Frisch (Frisch 2000) on the basis of physics. Additionally, I shall draw attention to the question of the connection between this time arrow of proper times and the fundamental time asymmetry in spacetimes similar to ours (see Chapt. IV).

1.1.1.3. The arrow of time in thermodynamics

Perhaps the most prominent arrow of time is that in thermodynamics. This arrow is traditionally defined in terms of the behaviour of entropy in closed systems. According to the second law of thermodynamics, apart from fluctuations, the entropy of a closed system will increase with time up to a maximum value. In discussions of this arrow of time in physics as well as in the philosophy of physics and time, crucial objections can be made to show that the thermodynamic time arrow, based on this definition, is not caused by fundamental physical reasons. I shall consider some of them in Chapt. V, but in this Chapt. I will present some more introductory thoughts on the understanding of this prominent time arrow. Statistical mechanics predicts that, as the time coordinate decreases, most entropy values, apart from fluctuations, would also increase, as they do for an increasing time coordinate (as long as no initial conditions are used). Thus, according to the descriptions of statistical physics, thermodynamics does not include an entropic time asymmetry at a more fundamental level as the initial condition. Instead, some crucial initial conditions must be applied to provide the entropic arrow of time in thermodynamics. One crucial condition is that, in the systems "past", the entropy value was low (which, then, defines "past"); the second law of thermodynamics provides a time asymmetry only under this condition. Of course, the set of possible initial conditions also includes other initial conditions (and in fact more likely ones according to statistical physics) that cannot yield a time arrow in thermodynamics. In fact, the special choice of a particular initial condition seems to be motivated not by intrinsic structures of the theory in question (thermodynamics) but by empirical data or anthropic considerations. Both approaches seem prima facie unable to provide an understanding of entropic time asymmetries based on fundamental physics but only based on boundary conditions or anthropic considerations. Thus, I think, the time arrow in thermodynamics, in this traditional understanding and based on crucial initial conditions, cannot constitute an understanding of the time direction based on the fundamental properties of physical theories.

In Chapt. V, I show that, according to specific entropy definitions in quantum thermodynamics and motivated by the physical analysis of Castagnino and Laciana (Castagnino, Laciana 2002), the thermodynamic time arrow can be understood as a necessarily occurring by–product of a more fundamental cosmological time asymmetry if some crucial conditions are fulfilled (which seems to be the case in our particular universe). Thus, I argue that the arrow of time in quantum thermodynamics cannot be understood as fundamental itself but as a necessarily occurring by–product of a more fundamental cosmological time asymmetry. I shall argue that the behaviour of some specific entropy values in cosmic time will be intrinsically asymmetric in our particular (and similar) spacetime(s); hence, with decreasing cosmic time, the entropy value will also decrease, and with increasing cosmic time, the entropy value will increase (apart from fluctuations). Additionally, and independent of an epistemic or ontic interpretation of entropy itself, I will show that the *origin* of the time asymmetry in the behaviour of entropy is physically effective, whether or not entropy itself is understood as a purely epistemic content. Thus, I think the analysis of the thermodynamic time arrow in Chapt. V provides new views and advantages for the understanding of this prominent time arrow and the second law of thermodynamics itself.

1.1.1.4. Quantum mechanics

According to the standard formulation and interpretation of ordinary quantum mechanics, the time arrow in this field is mostly understood as a result of quantum measurements. Without considering any attempts to resolve the measurement problem, the most traditional understanding of this time arrow seems to be the following: the time evolution of a quantum system is described according to the time reversal invariant (according to the view that an complex conjugated equation is physical equivalent to the original equation) Schrödinger equation (or the Klein–Gordon equation and the Dirac equation regarding relativistic quantum mechanics, but they do not add anything to this discussion, so I focus on ordinary non–relativistic quantum mechanics here). Thus, it does not favour one particular time direction. However, the Schrödinger dynamics breaks down when a measurement or an analogous physical process is performed on a quantum system. In this case, we observe classical states. In the traditional formulation of quantum mechanics, this fact is attributed to the collapse of the wave function, which is time asymmetric, at least according to the traditional formulation and interpretation. This means that time evolution, if begun in a classical state, will guide the measured classical state of the system slowly to one in which quantum effects become stronger. However, if a measurement is performed on a quantum state, the quantum state collapses into one classical state at the moment when the measurement is performed, and not slowly but on a very short (or infinitely short) time scale.

I shall argue in Chapt. VI, motivated partly by the physical analysis of Castagnino, Lara and Lombardi (Castagnino, Lara, Lombardi 2003), that, because it seems totally outside the scope of this investigation to provide a solution to the measurement problem, I divide the fields of applications of quantum physics into three levels. The first consists of laboratory experiments, in which we can deal only with measured physical entities. At this level, we can treat a quantum measurement as a black box in order to avoid the measurement problem and to define subsystems. The second level covers quantum measurements or analogous physical processes, and the third level is that of a pure von Neumann–Schrödinger quantum dynamics where no measurement is assumed. In the third level, the measurement problem is avoided by simply ignoring the possibility of quantum measurements or analogous physical processes at all. Using this distinction between "levels" of quantum physical descriptions, I show in Chapt. VI that at the levels of laboratory experiments, as well as at the level of a pure von Neumann–Schrödinger dynamics, we find an arrow of time as an intrinsic property of the physical processes themselves. These arrows will be understandable as by–products of an energetic time asymmetry whereby the connection between those local asymmetries and cosmic time asymmetries will, again, be unsolved but revealed as the crucial point to understand the arrows in a fundamental sense. Moreover, the time arrow in the pure von Neumann–Schrödinger quantum dynamics provides strong arguments and motivations for a particular time asymmetric formulation of the rigged Hilbert space approach (see Chapt. VI).

Also, I will show that a crucial time asymmetry in one prominent process (often associated with quantum measurements), the decoherence process, is understandable in ways similar to the quantum mechanical time arrows from the other levels of description. Additionally, I mention that I do not go into much detail in the interesting discussion regarding the decoherence account of the measurement problem itself. Thus, I do not discuss all the arguments in favour of or against the view that the decoherence account can "solve" the measurement problem. Here my motivation is only to show that, according to one important quantum process connected with quantum measurements, the description of the decoherence process is time asymmetric, at least in spacetimes similar to ours.

In summary, this subsection has sketched my main motivations and my main claims, which will be discussed in much greater detail in the following Chapters. But before I present an understanding of "fundamentality" in the context of time directions in Chapt. II, I shall briefly mention another general assumption of this investigation.

1.1.2. *The role of quantum gravity*

It could appear puzzling that this investigation claims to understand time directions on the basis of fundamental properties of the physical theories used to describe nature without taking into account the diverse formulations of quantum gravity. The fundamental time asymmetry, which I will define as a structural property of the solution set of crucial dynamic equations in cosmology, appears only in classical cosmology (Chapt. III) and in ordinary "semi–classical" cosmology (with no attempt to quantize gravity; Chapt. V). Thus, the fundamental theory for all the models considered in this investigation is general relativity without a quantisation of gravity. Hence, my claims could be seen as a bit inconsistent. In fact, according to physics, it seems reasonable to assume that the most fundamental physical theory we can think of today is a theory of quantum gravity unified with the quantum dynamical description of the other three fundamental interactions. So, a fundamental time asymmetry should be based on the properties of such a fundamental unified theory of quantum gravity.

I have much sympathy for this view, but, according to physics, at least as far as I know, there is no well–established theory of quantum gravity that fulfils all the physically motivated requirements for such a theory. For example, as far as I know, there is no formulated theory of quantum gravity that has a well–defined classical limit or that explains the processes of supersymmetry breaking (SUSY) (if SUSY were imbedded in such a theory). Thus, because of the great range of speculations about the formulation of a unified theory of quantum gravity, for this investigation it seemed plausible to consider only the well–established physical theories of general relativity and quantum field theory (QFT). This restriction seems even more attractive considering that most formulations of quantum gravity have serious problems in defining even some sort of time coordinate on which a *fundamental* time asymmetry could be based. Thus, given the situation that we find in fundamental physics and in the scientific attempts to formulate quantum gravity, it seems well–motivated to focus on well–established physical theories. Moreover, I think an independent motivation for avoiding the field of quantum gravity in this investigation is the hope that, if a unified theory of quantum gravity is formulated, at least in their limit solutions, it should provide ordinary QFT and the traditional theory of general relativity as approximations. So, the fundamental time asymmetry in classical and "semi–classical" cosmology (which I show more precisely in Chapt. III and V) could be a property of the approximation of the fundamental unified theory of quantum gravity. However, this is of course a question that can be investigated only after a well–established theory of unified quantum gravity is formulated.

However, even if physics should someday show that all the theories used in our current physical descriptions are inadequate and must be exchanged for others, I think the analysis in Chapt. II, which shows that a fundamental time asymmetry should not be based on the property of time–reversal variance of a fundamental physical law, could still be valid as long as the mathematical language of the theories change not too drastically. In fact, the considerations from Chapt. II are independent of specific physical theories and are basically of a philosophical kind. Thus, the suggested understanding of "fundamentality" in the context of time asymmetries could still be an adequate notion of fundamentality even if the entire field of modern fundamental physics were *basically* inadequate (even in approximation).

1.2. The main claims

a) I will begin this investigation by motivating and defining a new notion of "fundamentality" in the context of time asymmetries. This new notion is not based on the time–reversal variance of fundamental physical laws but instead on the structure of the solution set of a fundamental dynamical equation. This proposal is based and motivated on philosophical, physical and mathematical work in the context of asymmetries in general and time asymmetries in particular. (I shall take the opportunity to mention some crucial research that is important for the motivation for my own suggestion: Boltzmann 1897, Castagnino, Gaioli, Gunzig 1996, Castagnino, Gunzig 1997, Castagnino, Laura 1997, Castagnino 1998, Castagnino, Gunzig 1999, Castagnino, Gueron, Ordonez 2002, Castagnino, Laciana 2002, Castagnino, Catren, Ferraro 2002 and very crucially Castagnino, Lombardi 2009 as well as Feynman 1964);

b) I will consider some accounts regarding the cosmological time arrow (see, for example, Price 1996, Price 2002 as well as Ćirković, Miloševic–Zdjelar 2004), and I shall show that none of them can provide a fundamental understanding of even a cosmological time asymmetry, nor can they rule out the possibility of such an fundamental understanding (see Chapt. III).
Therefore, I will develop my proposal: that the solution set of the crucial dynamical equation in cosmology (analysed similar to Castagnino, Lombardi 2009) provides a situation that is captured and described by my definition of fundamental time asymmetries from Chapt. II (provided some crucial requirements are fulfilled, see Chapt. II and III);

c) additionally, in Chapt. IV I will consider the actual discussion of the arrow of radiation. I will concentrate on crucial attempts to understand its origin (see, for example, Rohrlich 2005, Frisch 2000, Price 1994, Price 1996, Price 2006, Zeh 1989, Zeh 1999). In Chapt. IV, my claim will be:

— that the traditional characterisation of the arrow of radiation is well–motivated for physical reasons, where the characterisation is given by the empirical fact that no fully advanced radiation of a specific kind seems to occur in our particular spacetime region. Moreover, I shall show (motivated in part by the philosophical suggestions of Frisch (Frisch 2000));
— that the arrow of radiation, in the suggested characterisation, can be understood as a simple consequence from time asymmetric energy flows in spacetimes similar to ours (following parts of Castagnino, Lombardi 2009). Thereby, the question of fundamentality of the radiation arrow will depend on the connection of the energy flow (in spacetimes similar to ours) and the cosmological time asymmetry investigated in Chapt. III;

d) because the fundamental time asymmetry in cosmology (described in Chapt. III) was explicated only in the context of classical cosmology, one of the claims of Chapt. V is that the same type of explication is also given in "semi–classical" quantum cosmology (omitting quantum gravity). I shall show that this is the case by considering the Einstein equations in some quantum cosmological models. Here the analysis is motivated in part by the cosmological investigation of Castagnino and Laciana (Castagnino, Laciana 2002) (see Chapt. III and V).
In Chapt. V, I also concentrate on the understanding of the arrow of time in quantum thermodynamics. At the beginning of Chapt. V, I shall discuss an account of this particular time arrow that seems to be guided by artificial definitions and some crucial approximation methods (see Allahverdyan, Gurzadyan 2002). I investigate this account in order to show that my suggestions will not use similar kinds of arguments. Thus, in the second part of Chapt. V, I shall argue that, according to some prominent entropy definitions from Landau and Lifshitz (Landau, Lifshitz 1970) as well as from Glansdorff and Prigogine

(Glansdorff, Prigogine 1971), time asymmetric behaviours of entropy values appear as a necessarily occurring by–product of the fundamental time asymmetry in cosmology;

e) in Chapt. VI, I will focus on the time arrows in non–relativistic quantum mechanics. Here the distinctions (mentioned above) among three different levels of quantum physics are crucial to deal with the measurement problem. The different levels are given by:
   — the level of laboratory descriptions, where a quantum measurement as well as analogue physical processes can be handled as black boxes;
   — the level of the measurement itself, where only the prominent decoherence approach is considered;
   — the level of the pure von Neumann–Schrödinger quantum mechanics, where no measurement or analogous physical process is assumed.

Adopting parts of the physical analysis of Castagnino, Lara and Lombardi (Castagnino, Lara, Lombardi 2003), I show that at all levels, a time arrow can be found and understood as a consequence of time asym-

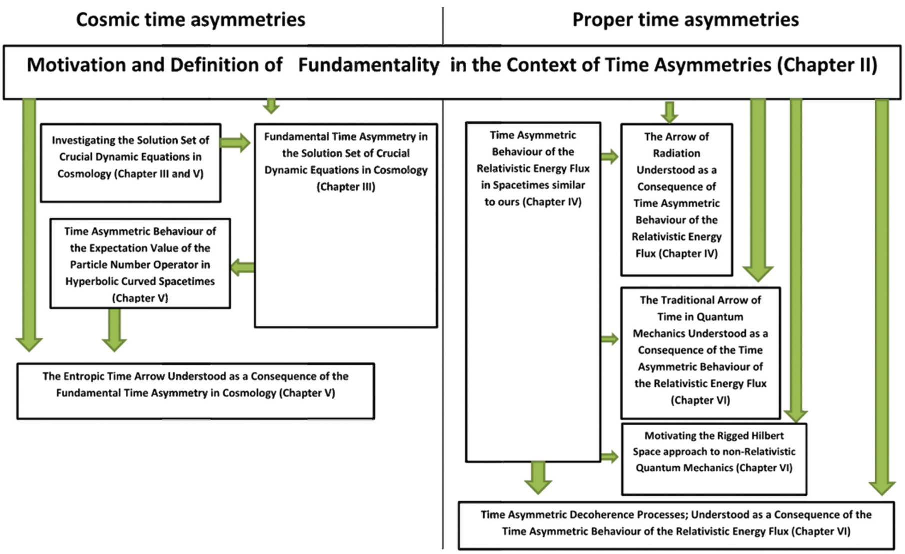


Figure 1.1. Introduction and motivation.

metric energy flows, but, in contrast to Castagnino, Lara and Lombardi (Castagnino, Lara, Lombardi 2003), not depending on the definition of subsystems in general. Thereby, as well as by the radiation arrow, the fundamentality of those time asymmetries depend on the connection to the fundamental time asymmetry of cosmology (which is defined in Chapt. III and V). Moreover, I argue (see also Bishop 2004) that, regarding the pure quantum mechanical level of description, a particular time asymmetric formulation of ordinary quantum mechanics, the rigged Hilbert space formulation in a particular form, is strongly supported.

To summarize the aims of this investigation:

a) I will show that an understanding of time asymmetries based on the properties of fundamental physics is possible without time–reversal variant laws in the fundamental theories of physics;
b) I will show that the fundamentality of time asymmetries can be based on the structure of the solution set of time–reversal invariant physical equations;
c) I will show that this understanding of fundamentality is applicable to physics; in particular, to classical cosmology and "semi–classical" cosmology, which will provide time arrows in QFT and in quantum thermodynamics. Other local time asymmetries and arrows can be understood as time asymmetric consequences, for example in classical electrodynamics and ordinary quantum mechanics, if a particular kind of connection between the cosmological time asymmetry and other local processes is assumed. This point will be clarified in the Chapt. IV and VI.

Moreover, I think the proposed understanding of some time arrows investigated here could provide new arguments in the discussions of:

a) an epistemic or ontic understanding of entropy and the second law of thermodynamics;
b) causality and the asymmetry between causes and effects in fundamental physics as well as in non–fundamental physics and specific sciences.

I shall return to these points briefly in Chapt. VII, where the conclusions of the entire investigation are summarized.

Fig. 1.1 shows a schematic diagram of the coarse structure of the investigation as sketched in this Chapter. At the beginning of each Chapter, I shall return to this diagram to clarify which part of the investigation that particular Chapter covers. The aim of this investigation, which is that the understanding of a difference between two time directions, labelled as "past" and "future", can be based on fundamental considerations in physics, is illustrated in the diagram.