Annalen der Physik

Founded in 1790

WILEY-VCH

www.ann-phys.org

Ann. Phys. (Berlin) **522**, No. 11, 783 – 801 (2010) / **DOI** 10.1002/andp.201000064

A categorical framework for quantum theory

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Received 28 May 2010, revised and accepted 26 July 2010 by A. Wipf
Published online 17 September 2010

Key words Foundation of physics, quantum theory, categorial framework, time.

Underlying any physical theory is a layer of conceptual frames. They connect the mathematical structures used in theoretical models with the phenomena, but they also constitute our fundamental assumptions about reality. Many of the discrepancies between quantum physics and classical physics (including Maxwell's electrodynamics and relativity) can be traced back to these categorical foundations. We argue that classical physics corresponds to the factual aspects of reality and requires a categorical framework which consists of four interdependent components: boolean logic, the linear-sequential notion of time, the principle of sufficient reason, and the dichotomy between observer and observed. None of these can be dropped without affecting the others.

However, quantum theory also addresses the "status nascendi" of facts, i.e., their coming into being. Therefore, quantum physics requires a different conceptual framework which will be elaborated in this article. It is shown that many of its components are already present in the standard formalisms of quantum physics, but in most cases they are highlighted not so much from a conceptual perspective but more from their mathematical structures. The categorical frame underlying quantum physics includes a profoundly different notion of time which encompasses a crucial role for the present.

The article introduces the concept of a categorical apparatus (a framework of interdependent categories), explores the appropriate apparatus for classical and quantum theory, and elaborates in particular on the category of non-sequential time and an extended present which seems to be relevant for a quantum theory of (space)-time.

1 Introduction

Even today, many scientists and philosophers of science still struggle with the fundamental concepts of quantum theory. It is not the mathematical formalism which is at the center of this struggle – apart from technical details the formalism is relatively simple – but it is more the conceptual questions and the physical intuition related to this mathematical framework which is unsatisfactory. It has often been argued that our ways of thinking rely on our every-day experiences, and, therefore, may not fit to the realm of microscopic systems. But on the other hand, we have far less problems dealing with geometry in 26 dimensions or with the topology of infinite dimensional spaces. It is not so much a lack of imagination and visualization which is at the heart of the problems, but rather an apparent contradiction of certain aspects of quantum theory with our most basic assumptions about reality.

What are some of these aspects of quantum theory which scientists struggle with? Surely, one aspect is related to the intrinsic indeterminacy of quantum theory. In every-day situations we accept indeterminacy as a lack of knowledge, but we are reluctant to give up Leibniz' principle of sufficient reason which states that "nothing happens without a sufficient reason; that is to say, that nothing happens without its being

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possible for him who should sufficiently understand things to give a reason sufficient to determine why it is so and not otherwise." [1] This principle seems to be violated in quantum theory, at least in those interpretations which include the reduction postulate. The violation of Bell's inequalities [2] in quantum physics [3] indicates that in some cases even the mere assumption of a predeterminded cause for the behavior of quantum systems leads to contradictions.

Another conundrum of quantum theory is related to its non-locality, in particular in the context of EPR-scenarios [4], i.e., in cases which involve entangled states. Quantum states can be highly non-local, but local measurements can lead to an instantaneous reduction of the whole state. If we attribute an ontology to a quantum state and the reduction process, two fundamental concepts seem to contradict each other: the locality principle of relativity and the reduction postulate of quantum theory. In addition to its non-local aspects, entanglement expresses a type of relationship which is unknown in classical physics. The concept of facticity is put into question when entangled states are involved. Rovelli in his relational interpretation of quantum theory describes this situation as: "... a physical fact, its being true, or not true, must be understood as relative to an observer..." [5].

Still another weird aspect of quantum theory are "superpositions" or, more general, the non-existence of dispersive-free states with respect to all observables. This statement is trivial for mixed states, but it also refers to pure states. In other words, for any state there exist observables such that repeated measurements of the same observable on systems prepared in this same state do not always yield the same results. Again, the formalism does not allow to attribute this fact to an imperfect preparation of the state (e.g., as not beeing separated with respect to certain "hidden" variables), but it is something intrinsic to quantum states.

As a final aspect we mention the lack of a rigid spatiotemporal ordering of events. Events do not happen at a particular location in space and at a particular moment in time. Spatially non-local states describing particles are well known and partially related to the non-boolean aspect of quantum theory. Usually less emphasized is the temporal aspect of this phenomenon: a lack of sequentiality of events. This partial loss of a sequential time will be one of the major subjects of this article.

Various interpretations of quantum theory have addressed the problems mentioned above. Physicists favouring a more formal or positivistic approach may deny any conceptual problems of quantum theory because the mathematical concepts are well defined and free of contradictions, and the associations of mathematical structures with physical observables are equally well defined and in full agreement with all experiments. However, in this framework any question related an ontology beyond the formalism is put aside.

Protagonists of the many-world interpretation [6, 7] may deny a problem with the indeterminism in the reduction process, because in the many-world interpretation there is no reduction. However, the non-locality problem of quantum theory is not solved by the many-worlds interpretation (along with other problems, like the pointer basis problem or the assignments of probabilities).

Supporters of a subjective or an information based interpretation of quantum states see no problem in the reduction process, because according to their understanding, reduction is merely a change of knowledge about a system. Still, for many physicists the alternatives offered by these interpretations are unacceptable for reasons of their own.

Two major assumptions about quantum theory will be made in this article: (1) the quantum state of a system is related to an ontic element of reality (thus excluding purely information based and subjective interpretations of a quantum state), and (2) the reduction process too is related to an ontic element of reality (hence, we will mention but not focus onto the implications which the many-world interpretation has for the applicability of our approach). Furthermore, we will also not discuss explicit alterations of the standard formalism of quantum theory, like the approaches of Karolyhazy [8] and Penrose [9], which attribute the reduction process to an influence of gravity, or the GRW formalism [10] and relativistic extensions [11], which alter the Schrödinger equation by adding a non-linear stochastic term. In these cases the reduction of the wave function is attributed to collapse centers. We will also not discuss interpretations which invole a causation into the past (like, e.g., in [12]) or which are "superdeterministic" by including future decisions related to the set-up of experiments into the initial conditions of quantum systems (like, e.g., the approach of Palmer [13]). The reason why we will not elaborate our conceptual framework in the context of these approaches is not so much that our framework is not applicable, but rather that it would require a refinement and adaptation for each single case which would go far beyond the scope of a single article.

Our approach to address the counterintuitive aspects of quantum theory is less formal and more conceptual. First, we want to analyse, which "hidden assumptions" we often make when we try to interpret quantum mechanical issues and why these hidden assumptions in the context of quantum theory seem to lead to contradictions with our understanding of how reality "should be". We apply these assumptions successfully in the context of classical physics, and we know that they lead to contradictions with quantum theory, but we often do not see the conceptual alternatives. Therefore, as a second step, we will suggest a replacement of these concepts which work so well in the context of classical physics. This replacement will not be on the formal mathematical level – such concepts exist, e.g., the axiomatic algebraic approach [14] or the notion of non-boolean lattices [15] – but rather on the level of conceptual thinking. Therefore, our approach does not aim at a replacement of the existing mathematical formalism, but instead it elaborates the underlying categorical assumptions thus allowing for a coherent interpretation.

One might ask whether such a non-mathematical conceptual foundation is necessary or what the advantages might be of having such a categorical framework at hand. We will address this question in the next section (Sect. 2) but a brief answer will be that the difficulties we have in formulating a consistent and satisfactory unification of general relativity and quantum theory might indicate that some of the basic notions we use in the context of these two theories are incompatible and not yet fully understood. For this reason it not only seems legitimate but necessary to rethink the conceptual underpinnings in these theories.

In Sect. 3 we will address the issue that quantum theory mainly deals with the "coming into being" of reality, while classical Newtonian physics is more about the factual aspect of reality. In our opinion, this is the major difference between classical physics and quantum theory, and it is this difference which makes a richer conceptual framework necessary for quantum theory. In Sect. 4 we introduce the notions of a category, a categorical slot, a categorical apparatus and a categorical framework in the more philosophical meaning which we will use in this article. After these preliminary notions we will describe in Sect. 5 the categorical assumptions we make in the context of classical, factual physics. In Sect. 6 we will introduce the categorical apparatus necessary to address questions related to "reality in the making", i.e. the categorical apparatus of quantum theory. Both apparatus taken together, the categorical apparatus related to factual classical physics and the categorical apparatus related to quantum theory, make up the whole categorical framework necessary to address reality as such.

One category in the apparatus related to quantum theory - the non-sequential "time-space of the present" – is of particular importance. We will argue that certain ingredients in the formalism of quantum theory indicate that for a full understanding we may need a theory of the present. In contrast to the other categories which are well-known from the standard formulation of quantum theory, this aspect is usually less emphasized in the standard presentations of quantum theory. Therefore, we will devote Sect. 7 to this concept. A brief summary as well as an outlook to other applications of our scheme will conclude this article. Because of the unfamiliar approach taken in this article, we will describe some of the physical aspects and their relation to the philosophical concepts in more detail than would otherwise be necessary.

2 Why a categorical framework?

Before we introduce the categorical framework which in our opinion is most appropriate for dealing with classical and quantum physics, and "reality" in general, we want to justify why it might be necessary to develope such categories or concepts and to clarify the relations among these concepts. Why is it not sufficient to refer exclusively to the mathematical formalism which allows to make predictions for the outcomes of future experiments?

A famous answer to this question is known from Einstein: *It has often been said, and certainly not without justification, that the man of science is a poor philosopher. Why then should it not be the right* *thing for the physicist to let the philosopher do the philosophizing? Such might indeed be the right thing to do at a time when the physicist believes he has at his disposal a rigid system of fundamental concepts and fundamental laws which are so well established that waves of doubt can't reach them; but it cannot be right at a time when the very foundations of physics itself have become problematic as they are now. At a time like the present, when experience forces us to seek a newer and more solid foundation, the physicist cannot simply surrender to the philosopher the critical contemplation of theoretical foundations; for he himself knows best and feels more surely where the shoe pinches. In looking for a new foundation, he must try to make clear in his own mind just how far the concepts which he uses are justified, and are necessities.* [16]

A present day example for this necessity can be found in the efforts to find a conceptually satisfying unification of general relativity and quantum theory. One approach to such a unification is to apply and extend the existing mathematical formalism to new areas and to hope that the results are still meaningful. This is done in the context of canonical quantization, loop quantum gravity, Wheeler-DeWitt type of approaches or even string theory (for surveys see, e.g., [17–19] and references therein). Another direction to go is to reconsider the fundamental concepts – space, time, matter, reality etc. – of the existing theories and to clarify the exact meaning in which these concepts are used, why these attributed meanings may be incompatible with each other, and by what concepts we might sensibly replace them. An attempt of this kind is made in this article.

Another reason to analyse the fundamental concepts from a more general perspective and, in particular, to relate them to ideas which are not from mathematical textbooks (later we will use expressions like "autogenesis", "parataxis", "self-referentiality", etc.) is that these concepts actually do occur outside the realm of quantum physics, for instance in the areas of consciousness and selfhood or of literature and art. In these areas we are used to expressions which often refer to a vague feeling or an impression and which lack mathematical rigor. Nevertheless, we often use these concepts with considerable success in the development of ideas and the establishment of relations which we would miss without these concepts. In quantum theory we are in the lucky situation, that we have a rigorous mathematical formalism which we can use in making exact statements or predictions, and which we can also use in making the vague concepts mentioned above more rigorous. What we often lack is the intuitive notion which helps us to develop new ideas. Therefore, our aim is on the one hand to keep the rigorous mathematical formalism for deducing precise conclusions, and, on the other hand, to enlarge this tool by a more intuitive but, nevertheless, equally rich framework of categories which, when being aware of them, can be used to get a deeper understanding of quantum physics and, more general, of reality.

3 Quantum physics – the "status nascendi" of reality

Why does quantum theory need a different set of categories as compared to the classical physical theories like Newtonian mechanics, Maxwells's field theory, or even special and general relativity? Why are already the basic questions addressed by quantum theory of a fundamentally different nature? We argue, and this will be elaborated in more detail in this section, that quantum theory is a theory about how facts come into being, how facts "are born", i.e. the "status nascendi" of reality. In contrast, classical physics deals with facts, not the coming into being of facts. This fundamental difference requires the different categories which we will introduce in the next sections.

In classical physics we mainly talk about facts. By facts we usually mean configurations or constellations of objects which we see (or otherwise detect). From these configurations we can deduce that certain events have happened. Even if we talk about "events" in the context of classical physics, we usually refer to the facts which have evolved from these events. In this sense we will use the word "fact" to denote the traces which events have left behind in the constellation of our present reality. An obvious example for such a trace is a fotograph which shows us a picture of a situation in the past. Similar examples are fossiles or written documents. Less obvious but of a similar kind are the traces left behind in our brain which allow us to remember certain situations. Another example are scattered particles whose momentum or energy carry information about the scattering event. Only what leaves factual traces qualifies for the notion of a "real event".

Even in cases where we seem to observe a certain event, what we perceive and observe are already traces: the photons which have been scattered by objects which took part in an event or the sound waves which have been emitted by a clash of certain objects. Even when we refer to the event of observation itself, by the moment we become aware of this event we are already talking about facts. The closest we come to taking part in an event itself is the phenomenon of becoming aware of something. However, now the problem of consciuosness enters and we are leaving the realm of known physics. (In [20] we elaborated on the similarity between the conceptual frameworks of quantum theory and consciousness. There are numerous approaches to argue for a more direct connection between consciousness and quantum theory, see e.g. [9, 21–23]; for an overview see [24].)

The deterministic nature of classical physics leaves no room for possibilities or alternatives apart from the epistemic uncertainty which arises because of our lack of knowledge about certain situations. In principle, the present state already determines the future states in a similar way as from the present state one can deduce the past. It is the second law of thermodynamics (the increase of entropy in non-equilibrium systems) which makes it easier for us to deduce past events from facts in the present as compared to predicting future events.

In contrast, quantum theory refers to the transition from possibilities (or potentialities) to facts. A quantum state carries information about the past of the system, but with respect to possible events in the future it only allows to make probabilistic predictions. In quantum theory, this probabilistic nature is intrinsic, not a lack of knowledge about the present state. The transition from this "set of possibilities" to a single factual result is what we define as the "event", and in this sense quantum theory addresses the coming into being – or the "status nascendi" – of facts. (The relation between quantum possibilities and classical facts has been elaborated, e.g., in [25].)

At this stage some remarks about our notion of "event" are in order. Whenever we are referring to non-quantum physics, the expression "event" is used in the same sense as it is used, e.g., in the context of special or general relativity: Events are identifiable elements of space-time. They are considered to be objective constellations of matter, like the event when a pointer of a clock points to a certain mark, when two particles collide, when a light source is turned on or off, etc. In most cases, they are idealized to be "point-like". Events can be a conglumerat of more elementary events and in many cases we even assume that there are "basic" events which cannot be separated into subevents anymore.

When we talk about events in the context of quantum theory we should, strictly speaking, distinguish two types of events. One type of event refers to the transition from possibilities to facts in the reduction process. When there is a danger of confusion, we will use the expression "transgressive event", emphasizing the transitional aspect of "becoming a fact". An attempt to give a more precise meaning to this type of event can be found in [26]. A second type of event is what in discussions about quantum theory sometimes is called "virtual event". This type of events often refers to an interpretation of aspects of the formalism (e.g., the terms in a perturbative expansion, like the emission of a photon by an electron in a scattering process). They do not lead to facts individually, but only as parts of a transgressive event.

4 A categorical framework

In this section we will introduce the notion of a catgeorical apparatus and a categorical framework. Loosely speaking, a categorical apparatus consists of a set of categories which are mutually interdependent, and a categorical framework consists of two (or more) categorical apparatus which, taken as a whole, allow to formulate any meaningful statement with respect to the realm addressed by the categories. The notions of "category" and "categorical" are not used in a mathematical but a philosophical sense.

The notion of a category has a long history in philosophy, and different thinkers have often attributed different meanings to this notion. Fortunately, we will not need a rigorous definition but only the general idea (actually, in the context of the approach developed here, a comprehensively well-defined notion of "category" may not even be possible). *Categories* are the most fundamental interface between reality and cognition. They constitute primordial assumptions about the nature of phenomena. For instance, the assumption that all physical processes are deterministic and can be described by an equation of motion is a categorical assumption which holds in Newtonian physics but not in quantum physics. As we shall see, however, and this will be one of the main hypotheses of this article, categories do not come as isolated entities, but they are mutually interrelated. For such a set of interdependent categories we introduce the notion of a *categorical apparatus*.

The general structure of a categorical apparatus consists of various slots that are to be filled with specific, interrelated categories. This means that categories which we insert into a certain slot have consequences with respect to the other categories. These interdependencies of categories are so rigid, that one category predetermines the other categories, and any attempt to substitute a given category by a different assumption leads to inconsistencies with the other categories. The slots within a categorical apparatus will be called a *categorical template*.

To make the idea more crisp let us give an example which we will study in more detail in Sect. 5: the categorical apparatus of classical (non-quantum) physics, by which we mean Newtonian mechanics, Maxwell's field theory and relativity. We argue that the following four slots make up a categorical template (for a more philosophical account of this structure see [27, 28]):

1. What is the relation between physical events?
2. How can we combine predications about physical observables?
3. What is the relation between the observer and the observed?
4. Which ordering structures are attributed to space and time?

Underlying classical physics are the following four categorical assumptions:

1. The events which make up physical processes are causally deterministic.
2. For all physical attributes the *tertium on datur* holds, i.e., in a given context only one of the predicates, "a" or "not a", can be true.
3. The observer can be considered as separated from the observed and the acquisition of information is possible without influencing the observed system.
4. At each instant in time, the location of physical bodies is determined by their relative distances. Along any world-line, events are sequentially ordered.

It seems obvious that if we change one of the categories, e.g., the sequentiality of time ("for any two events a and b along a world-line either $a < b$ or $b < a$ holds") this has a huge impact on the other categories. E.g., the standard notions of causality or determinism can no longer hold if this assumption is dropped.

We claim that all scientific theories imply certain underlying categorical assumptions. This refers only partially to the mathematical formalism per se but more to its association with physical phenomena. It will turn out, however, that not all questions related to reality can be formulated meaningfully within only one categorical apparatus, e.g., the frame defined by the classical categorical apparatus given above. Quantum physics, in particular as far as the transition from potentialities to facts are concerned, requires a different categorical apparatus. None of the four classical categories holds in quantum physics, i.e., all categories have to be changed. For this reason, attemps which try to cope with quantum theory by relaxing only one of the categories listed above are bound to fail. The categorical apparatus given above will be applicable whenever we make statements about the factual aspect of reality, therefore we will refer to it as the *F-scheme*. On the other hand, quantum theory also deals with the "coming into being" of facts. Whenever we address the "statu nascendi" aspect of reality, i.e., make "event-related" statements, the second categorical apparatus, the so-called *E-scheme* will be needed. Both apparatus together, the F-scheme and the E-scheme, constitute the complete *categorical framework* that allows to address physical reality in a comprehensive way.

5 The categorical apparatus of factual reality

As we have mentioned before, facts are traces left behind by events. In some extreme cases the trace-character is immediately obvious (like in a fotograph, a fossile or the connectivities in the brain leading to a memory). Other examples are the click of an electron in a detector or the polarization of a photon which scattered from some surface. In general, the traces of even a single event become distributed over a huge number of degrees of freedom and may in practice never be observed in their totality. But when we observe reality we mostly look at facts, and classical physics is essentially a theory about facts. Even though the equations of motion allow to make predictions about future states of a system, classical physics is not concerned with the event of "coming into being" itself. Actually, in the framework of all variants of classical physics (including relativity) this problem cannot even be addressed. The deterministic character of the equations of motion lead in an almost automatic way to a block type universe in which everything which is, was, or will be has the same degree of facticity.

For addressing questions related to the factual aspects of reality, we refer to the categorical apparatus mentioned in Sect. 4. In the following sections we shall discuss these categories in more detail.

5.1 The deterministic nature of physical processes

In the context of classical physics, the changes in state space are described by equations of motion. If the state of a closed physical system is given at a certain instant t, the equations of motion determine the state for any other instant t'. This is also true for Maxwell's theory of electromagnetism as well as special and general relativity[1].

At this point we should emphasize that we are not so much concerned with actual predictability but only with determinism. In the framework of relativity we even can speak of a local determinism, i.e., the state of a system at point x and time t is determined by the configuration of the state at time $t - \Delta t$ (for sufficiently small Δt, in order to avoid the singularities mentioned in the footnote of the previous paragraph) within a volume of radius $c\Delta t$. In classical physics we may choose Δt to be as small as we like (keeping it positive and non-zero). This local determinism (which is always present in the absence of an action at a distance) extends to a global determinism (at least within a finite part of our universe) and is independent of the actual impossibility to make predictions due to the complexity of a system. For this reason this notion of determinism extends also to non-linear systems with chaotic behavior.

5.2 The *tertium non datur* of predications

In physics, a predication about a system prepared in a certain state is a statement about the value of an observable, if the corresponding measurement of this system would be made. In the following we will talk about pure states only. Algebraically, a state can be defined as a positive, normalized, linear functional on the algebra of observables. These states form a convex set and pure states are the states on the boundary of this set. On an operational level, a state can be defined by the equivalence class of the history of the system, where the history includes the preparation process. Two histories are equivalent, if the corresponding states have identical expectation values for all observables. For a pure state the history cannot be refined in such a way that the variances of some observables become smaller without increasing the variances of other observables.

For a pure state in classical physics any observable has a well-defined value. Therefore one can say, that in this situation the system has a certain property. (There are technical problems when this property belongs to a continuous set, in which case one usually refers to intervals.) In this sense the *terium non*

[1] In particular with respect to general relativity we should mention, that certain initial conditions may lead to singularities in the solutions which make a determination of this solution of the equations beyond the singularity impossible or even meaningless. Such singularities indicate a break-down of the classical theory and, thereby, of the classical categorical apparatus or F-scheme. Effects of quantum gravity may become relevant.

datur – the exclusion of a third possibility – holds: for a system in a pure state a predication is either true or false.

In most cases we actually do observe variances of observables but in the context of classical physics it is taken for granted that these variances are either due to a mixture of states or due to an experimental error, i.e., the uncertainties in the measuring procedure and the limits in the precision of the measuring instruments lead to a spreading of the data. A pure system is assumed to have a definite value with respect to any observable.

5.3 The separability of observer and observed

A further assumption which is implicitly made in the context of classical physics is the separability of observer and observed. In the idealized case an observation (measurement) has no influence on the observed system. In other words, the increase of knowledge about a system on the side of the observer is not accompanied by a change of the state of the observed system.

At first sight this assumption seems to contradict Newton's third law – "actio" equals "reactio". Expressed differently, the energy loss of one system is equal to the energy gain of the other system. Any observation obviously changes the state of the observing system: the sensor of the measuring device, the transformation to a change of the pointer of a measuring device up to the change of knowledge on the side of the observer. Therefore, according to Newton's third law, this should be accompanied by a corresponding change in the observed system.

The more rigorous statement of the classical assumption of a separation between observer and observed is: The influence of the observing system on the observed system due to the observation (measurement) can be made arbitrarily small, independent of the precision of the measurement. In classical physics the flow of informational is not accompanied by a corresponding flow of energy. The changes on the side of the observing system may be large and involve a macroscopic amount of energy, however, this energy comes from an amplification mechanism not from the observed system.

The independence of the observer from the observed system should not be confused with a "God's-eye" perspective on the side of the observer, even though these two concepts are closely related. A God's-eye perspective (in contrast to an intrinsic perspective) not only assumes that the observation is done without disturbance of the observed system, but it also assumes a preferred set of measuring devices (clocks, rulers, etc.) which are not subject to the standard laws of physics. Most prominent in the realm of classical physics is the "God's-eye" perspective in the context of relativity: clocks are synchronized with respect to a prefered system, the perception of events is not subject to the delay due to the finite velocity of light, etc.

5.4 Sequential ordering of time

Newtonian mechanics (excluding for a moment Maxwell's theory or the theory of relativity) assumes a universal time with a universal concept of simultaneity: For any two events a and b in the universe one of the following statements is true: $a < b$, $a > b$ or $a = b$, where "$<$", "$>$" and "$=$" refer to "before", "after" and "simultaneous", respectively.

In the context of special or general relativity this is no longer true. We may still define $a < b$ and $a > b$ as "a is in the backward lightcone of b" or "a is in the future lightcone of b", but there is no universal notion of simultaneity. The most one can say from an objective, universal level is that two events a and b are causally unrelated (i.e., they are in the causal complement of each other as defined by the future and backward light-cones). In special relativity the notion of simultaneity is used with respect to a given inertial system. However, this requires a (to a large extend arbitrary) synchronization convention for clocks within the same reference system but at different positions.

What still is true even in relativity is the total sequential ordering of events *along a world-line*[2]. For any two events on a single world-line the statements $a < b$, $a > b$ or $a = b$ are unambiguous. This is a consequence of the necessary condition for a world-line to be time-like. In this sense, time is sequential along any world-line. (This statement has to be modified for light-like world-lines corresponding to particles of zero rest mass; in this case all events along this world line "happen" simultaneously.)

We should remark that there is a corresponding ordering structure for space. In Sect. 4, the fourth slot of our template of categories refered to the ordering structure of space and time. However, in most cases we will only talk about the ordering structure of time (the sequentiality of time). The reason is that the topological ordering structure of space (giving meaning to "inside" and "outside" with respect to closed 2-spaces etc.) and even more its metric structure (giving rise to relative distances) is closely related to the localization of objects. The position of an object is generally considered as a property and, therefore, can be treated in the context of the *terium non datur*. The difference is due to an asymmetry in physics with respect to the nature of space and time: while we attribute observables to the location or position of an object, we usually do not introduce a "time-observable".

6 The categorical apparatus of the statu nascendi aspect of reality

In the previous section we have briefly summarized the categories (conceptual assumptions) applied in the context of classical (non-quantum) physics, i.e. the F-scheme. When dealing with the quantum world, we encounter situations where none of these categories holds anymore. We should emphasize that we do *not* imply that none of the categories of the F-scheme *ever* applies to quantum systems. A large part of quantum theory relates to facts or to a deterministic "prefactual" behavior (e.g., the deterministic time evolution of states according to Schrödinger's equation), and whenever this is the case, the F-scheme applies. However, quantum theory also addresses the problem of the transition from a prefactual world of possibilities to the world of facts (in the classical Copenhagen interpretation, this is expressed in the reduction postulate, and it is also here that the intrinsically probabilistic nature of quantum theory enters). For this transition, the F-scheme is not applicable. We claim that for these cases none of the categories of the F-scheme hold, but they all have to be replaced by a dual categorical scheme which we shall introduce now.

The four slots of our categorical template will be filled with the following categories:

1. Nature of processes: autogenetic.
2. Combination of predications: paratactic.
3. Relation between the observer and observed: self-referential.
4. Temporal ordering structure: time-space of the present.

At first sight, these concepts may sound unfamiliar, strange, and even undefinable. However, we will show that essentially all of these concepts are already contained in the standard mathematical formalism used in quantum theory. We will use these more general terms in order to emphasize that many of these concepts can also be found outside the realm of quantum theory. Furthermore, various aspects related to these concepts have been emphasized in the literature, in particular the non-separability of observer and observed and the henadic or holistic nature of reality (see, e.g., [22, 23]; for a more philosophical account of these concepts see [27] and [29]). The emphasis in this article is that these concepts should not be seen in isolation but as one inseparable categorical apparatus.

When we refer to quantum physical phenomena related to the intrinsically probabilistic nature of quantum theory, usually all four components of the second categorical apparatus apply in combination. However, we see a particular close relationship between the following concepts of standard quantum theory with the expressions above:

[2] At this point we explicitly exclude non-causal solutions of Einstein's equations which allow for closed time-like loops like the Goedel universe.

1. Autogenesis – the non-deterministic state reduction.
2. Parataxis – the superposition principle.
3. Self-referentiality – entanglement.
4. Time-space of the present – the loss of temporal sequentiality for events.

In the following sections we will make these concepts as well as some of the relations between them more transparent.

6.1 Autogenesis – the non-determinism in state reduction

The classical Copenhagen interpretation of quantum theory includes two processes by which the state of a quantum system can change in time: (1) the deterministic evolution of a closed quantum system according to Schrödinger's equation, and (2) the non-deterministic state reduction of a quantum system as the result of a measurement.

While the first process of temporal change is largely undisputed, the second one is subject of ongoing debates. In particular protagonists of the many-worlds interpretation [6, 7] (for a more recent summary and critical remarks see [30]) deny the existence of an ontic collapse even though they usually ascribe an ontic reality to the wave function (in contrast to information based interpretations of quantum theory for which the quantum state itself has only an epistemic meaning). The fact that we seem to experience a non-deterministic reduction of the quantum state is explained by a rapid decoherence which makes it impossible to make measurements related to observables which are able to interpolate between sufficiently different branches of the wave function. Therefore, it becomes increasingly impossible to observe interferences between these branches.

As mentioned before, we will assume that the reduction of a quantum state is related to an ontic part of our reality. According to this assumption, quantum theory is intrinsically non-deterministic. This non-determinism is not the consequence of a lack of knowledge, and in this sense Leibniz' principle of sufficient reason is violated in quantum theory.

The relation of the non-determinism of quantum theory with the "status nascendi" of quantum theory becomes obvious when we notice that it is exactly the reduction process which marks the transition from possibilities to facts. The reduction process corresponds to a genuine event and the results of this event are the facts which we ultimately observe.

Why did we name this category "autogenesis"? In its original meaning, autogenesis means "self generation". By using this expression we want to emphasize that the results of certain processes are not predetermined by any external or internal cause. In the reduction process, one of several possibilities becomes a fact and there is no cause whatsoever, which among these possibilities will be realised. We should emphasize that "autogenesis" also excludes any internal cause in the sense of hidden variables within the system. It is the event itself, not some predetermined structure inside or outside the system, which leads to a particular outcome.

6.2 Parataxis – the superposition principle

The second slot of our categorical template refers to predications about physical attributes and, in particular, how these predications may be combined. As we have mentioned before, in the F-scheme predications follow the standard form of binary "either-or" logic (true or false). Formally, this corresponds to a boolean lattice. Now we argue that in the second apparatus, the E-scheme, even contradicting predications can stand side by side. Different scientists prefer different ways to express this fact. Some say, that for certain states certain predications are "neither true nor false", others prefer to say that they are "as well true as false", and again others would argue that for certain states certain predications do not apply at all, or at best in a probabilistic sense. In any case the rigorous *tertium non datur* is lost. We will refer to this property of the predication space as "parataxis", and its realization in quantum theory is most clearly expressed in the superposition principle. In the context of a predication calculus, this category can be realized by non-boolean lattices (see, e.g., [15]).

The concept of superpositions is most easily formulated when quantum states are represented by (normalized) vectors in a Hilbert space. We should emphasize, however, that in a more abstract formulation (where general states are linear mappings on an observable algebra and can be represented as density matrices, and pure states correspond to the convex boundary of general states and can be represented as one-dimensional projection operators or rays in a Hilbert space), the superposition principle corresponds to the fact, that there are no dispersive free states with respect to all observables. (An abstract state ω is called *dispersion-free* with respect to an observable A, if $\omega(A^2) = \omega(A)^2$.) When this property holds, a measurement of A always yields the same result $a = \omega(A)$. In the F-scheme of classical physics any pure state is dispersion-free with respect to any observable. In quantum mechanics it is impossible to construct pure states which are dispersion-free with respect to all observables [31].

Parataxis is an expression which is used in philosophy to denote that predications "stand side by side" and that the *tertium on datur* does not hold. It is also used in the science of literatur where it refers to a text in which a situation, phenomenon or object is described by a collection of (sometimes even contradictory) attributes. Apart from the violation of the *tertium non datur*, two more properties characterize paratactic predications:

1. The overall meaning of a paratactic predication unfolds itself out of the constellation of its components. In the vector representation this is reflected by the fact that the transition amplitudes $\alpha_i = \langle\psi_i|\psi\rangle$ between the state ψ and the states ψ_i, which correspond to the paratactic predicates $\{a_i\}$, determine ψ uniquely.
2. Formal conclusions are not possible and thus the *ex falso quot libet* catastrophy (from one contradiction one can derive any statement) is avoided. Almost symbolic for this aspect in quantum theory is the famous citation of Richard Feynman referring to the double slit experiment: "... *[The electron] always is going through one hole or the other – when you look. But when you have no apparatus to determine through which hole the thing goes, then you cannot say that it either goes through one hole or the other. (You can always* say *it – provided you stop thinking immediately and make no deductions from it. Physicists prefer not to say it, rather than to stop thinking at the moment.) To conclude that it goes either through one hole or the other when you are not looking is to produce an error in prediction. ...*" ([32] p.144). Given the absence of formal truth criteria, actual experience is the only way to verify a proposition.

6.3 Self-referentiality – the nonseparability of observer and observed

One of the most significant and in it's consequences most dramatic features of quantum theory is the phenomenon of entanglement (for a recent review on entanglement, entanglement measures, and physical effects related to entanglement see, e.g., [33]). It has to be kept in mind, however, that entanglement can only be defined with respect to a tensor product representation of a Hilbert space $\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2$. A state is called *separable* if it can be written as a tensor product state of states in $\mathcal{H}_1$ and $\mathcal{H}_2$, otherwise it is called *entangled*.

Famous examples of entangled states are *EPR-states*

$$|\Phi_{\mathrm{EPR}}\rangle = \frac{1}{\sqrt{2}} \left(|\psi_1\rangle \otimes |\varphi_2\rangle - |\psi_2\rangle \otimes |\varphi_1\rangle \right) \, , \tag{1}$$

or, for three particle systems, GHZ-states [34].

In the context of quantum theory, the tensor product representation is interpreted as a splitting or a partition of the system described by $\mathcal{H}$ into two subsystems which are described by $\mathcal{H}_1$ and $\mathcal{H}_2$, respectively. In many cases, such a partition seems natural, e.g., when the total system consists of two particles and the subsystems refer to the single particles, in other cases the splitting is less obvious. In any case, the splitting is always a creative act on the side of the observer who describes the system, it is not given by the theory or the system itself.

The "weird" aspects of entanglement enter when the system described by the quantum state is non-local, i.e., when the system consists of two subsystems which are far apart. A measurement performed at one subsystem has immediate consequences for the state of the other subsystem. To be more precise, a measurement performed at one subsystem leads to a reduction of the total state into a separable state, and only this reduction makes it possible to assign definite states to the two subsystems. According to the standard formalism of quantum theory, this state reduction occurs instantaneously. As the resulting correlations do not allow to transmit information or energy, this process does not violate the causality principle of the theory of relativity. Nevertheless, Einstein called this "superluminal" change of the state due to the reduction process a "spooky action at a distance". (It should be mentioned that this "spooky action at a distance" not only occurs for entangled systems but also for highly non-local single particle states.)

In principle, any interaction between two systems leads to entanglement. (On the other hand, subsequent interactions with other systems may partially destroy, or at least distribute these entanglements.) In particular, there is no reason to restrict quantum theory to microsystems. A special case is the situation of a measurement, where a typical quantum system (with few degrees of freedom) interacts with a measuring device (usually a system with many degrees of freedom). If both systems are described in the framework of quantum theory, the measurement process has to be considered as an interaction between the observing as well as the observed system. As a result of this interaction the observed system and the observing system become entangled. (The classical description of the measurement process can be found in [31] and, e.g., [35], for critical remarks see [36]. For a more recent treatment with emphasis on the role of decoherence see [37]). The subsequent reduction leads to separable states and physical facts. Obviously also the other two concepts discussed so far play an essential role: the paratactic predication (expressed in the superposition of possibilities) and the intrinsic non-determinism of the reduction.

So far, the description is purely within the theoretical framework of quantum theory (an interaction between two subsystems leads to entanglement and the interaction of each of the subsystems with an environment leads to decoherence and, eventually, reduction). There is no need to mention concepts like "measurement" or "observer", which belong to a meta-level[3]. Physical systems which, directly or indirectly, have interacted with each other become non-separable. Lifting this loss of dichotomy to the level of "observer" and "observed system" leads to a meta-description, in particular, when the observer is related to an "I" and a first person perspective. When we talk about the non-separability of observer and observed, we refer to the (meta-level) of a second observer who treats the quantum system and the first observer (or the measuring apparatus) in the theoretical framework of quantum theory.

We have attributed the loss of dichotomy to the general concept of self-referentiality. The philosophical reasons for this attribution will be discussed elsewhere [29]. At this stage, the loss of separability together with the autogenetic process of reduction can be interpreted as an action of the total system onto itself. On a meta-level, when we introduce the concept of an observer and an observed, we have the situation that "a system observes itself", which is a strong form of self-referentiality.

The concepts of autogeneity, non-separability, and self-referentiality of reality in the framework of quantum theory have been emphasized by many authors. E. Schrödinger was influenced by the concept of Advaita in Hindu philosophy [38], J. Wheeler coined the expression of a "participatory universe" [39] and T. and B. Görnitz [22] explicitly talk about a "mutual unfolding" and a unity of nature based on information, just to mention a few. Furthermore, the self-referential aspects of the measurement problem, in particular, if the observer is considered as part of the system, and Gödel-type paradoxes resulting from this self-referentiality, have been addressed by T. Breuer [40] and M. L. Dalla Chiara [41]. Further references can be found in [42].

[3] We are grateful to one of the referees for emphasizing this distinction.

Many of these authors emphasize the henadic and self-referential nature of reality even more than we have done in the description given above.

6.4 The non-sequentiality of time

The final slot of the categorical template refers to the ordering structures of space and time. As we have mentioned before, the loss of the relational metrical ordering in space (as defined, e.g., by relative distances) as well as the topological ordering (e.g., the notion of "inside" and "outside" with respect to closed 2-surfaces) is already obvious for systems with spatially extended states. It can be associated with a loss of "either-or" predications with respect to the position. Therefore, we will concentrate in this section on the partial loss of the predominant ordering principle of time – the sequentiallity of events along a world line – in quantum theory. Of course, this loss of sequentiality is restricted to typical quantum phenomena, i.e. in most cases to very short time intervals. Only in special cases are the relevant time intervals of a macroscopic extension.

We first have to specify what is meant by "loss of sequential ordering". In quantum theory, time is treated as a classical 1-parameter variable which, of course, allows for a well-defined ordering. This variable refers to a mathematical time as it may be realized by an idealized classical clock (we will say more about this point later). However, as we have described in Sect. 5, the sequentiality of time in the F-scheme refers to the sequentiality of events along world-lines: For any two events a and b on a world-line one can say "a before b" or "b before a". It is this property which is partially lost in quantum theory.

Let us consider the unitary time evolution operator of a system. The idea becomes most transparent in the "sum over histories" representation of Feynman, but the conclusions are independent of this particular choice. So we consider the probability amplitude $K(x, y, t)$, where x denotes the initial state of the system, y the final state, and t the propagation time (as measured by a classical clock). Here x and y may represent the position of a single particle, the collective positions of many particles, the configuration of a field etc. According to Feynman's representation of this propagator as a sum over histories we may write:

$$K(x, y, t) = \sum_{x \to y} \exp\left(\frac{\mathrm{i}}{\hbar} S[x \to y; t]\right) . \tag{2}$$

"$x \to y$" represents a possible (classical) history of how the system can evolve from x to y within the time interval t (which is the same for all histories); $S[x \to y, t]$ is the classical action for this history, and $\sum_{x \to y}$ symbolizes the summation over all such histories. If these histories involve certain events a_1, a_2, ... , and if the general constraints on the set of histories do not forbid a permutation of the temporal ordering of these events, then the summation over histories implies also a summation over all these permutations. In such a case, when a system has propagated from x to y, it is meaningless to state that a certain event a_1 has happened before a second event a_2 or vice versa. The classical sequentiality of events along the world line of the system is lost.

This loss of sequentiality, as it follows from the summation over histories representation, is also obvious in elementary particle physics, where the amplitudes for scattering processes are expressed in terms of Feynman diagrams. This representation includes a summation over all possible types of events as well as an integration over all possible space-time locations of these events. In this form, not only the loss of sequentiality is obvious but also the loss of determinism, the paratactic predication (all possible processes actually contribute), and even the self-referentiality in the sense of a highly interactive and entangled system.

Two objections may come into mind at this point: (1) In the example given above one cannot even say *that* a certain event has happened, therefore, the loss of temporal sequentiality may rather be due to a loss of the facticity of the events. (2) Is the loss of temporal sequentiality not an immediate consequence of the energy-time uncertainty relation in quantum theory? Both issues shall be addressed now.

(1) Let us consider an example where it is known that two different events a and b have happened, but where the temporal order of these events is open. Imagine two different (distinguishable) atoms A and B

in a small box. Both atoms shall be in an exited state, and the transition energy from the excited state to the ground state shall be equal in both cases. We will observe two photons of the same energy emerging from the box, possibly with a large temporal delay between the first and second event. However, without disturbing the system by an additional observation, we cannot tell which of the two observed photons corresponds to the decay of which atom. In fact, in the summation over histories we have to sum over both possibilities (atom A decaying first and B second and vice versa), and again the temporal order of these events (which are now known to have happened) is not defined. This situation resembles the spatial non-separability in the double slit experiment: It is known that a particle has passed through a double slit but there is no information about which of the two slits it has passed through.

(2) The uncertainty relation between time and energy, $\Delta t \cdot \Delta E \geq \hbar/2$, refers to a limitation in the precision of measurements of these two quantities on the same system: ΔE is the uncertainty in an energy measurement during a time interval Δt, or, vice versa, Δt is the maximal precission for the determination of the moment of an event in which an energy is transfered of which the value can be known up to ΔE. Of course, in both cases these limitations in precision are not due to imperfect experimental set-ups but they are intrinsic.

The example given above (the decay of two atoms) involves the energy of the emitted photons. For each single atom the uncertainty of the energy of the emitted photon is related to the precision with which the moment of the decay can be determined. If both decays happen within these time ranges, the loss of sequentiality can be attributed to the uncertainty relation between time and energy. (For similar examples related to the loss of sequentiality see, e.g., [43–45].)

However, concerning the sequentiality of the two decays, what is relevant is the indistinguishability of the emitted photons. If the photons have the same energy, it is impossible to attribute one of the photons to one of the events, and the sequence of events cannot be determined. If, however, for some reason, system A only emits photons with a left circular polarisation and system B only emitts photons with a right circular polarisation, it would be possible to attribute an emitted photon to a certain event a or b, and the sequentializability indeed only depends on the precision of how exact the moments of emission can be measured, which again would be subject to the energy-time uncertainty relation. The two cases – polarized or unpolarized photons – involve the same energies, however, the loss of sequentiality only refers to the unpolarized case. The measurement of a polarization selects a particular class of histories for which the sequentiality of events becomes a fact, while in the unpolarized case the measurements do not constrain the histories enough in order to make the sequentiality of events into a fact.

7 The time-space of the present

In the previous section, we have described the loss of sequentiality of events within certain time limits. In this section we will draw some conclusions from this observation and, in particular, emphasize that in our opinion the quantum mechanical formalism strongly indicates that a theory which unites the principles of space-time with the principles of quantum theory may not be possible without a theory of the present.

The paratactic predication with respect to the location of objects together with the loss of temporal sequentiality of events make it difficult if not impossible to obtain a "block universe" picture of reality. By "block universe" we mean a well-defined and fixed space-time representation of the universe. (Famous is the description of a block universe by Sir Arthur Eddington: "Events don't happen; events are simply there" [46].) The fact that the locations of particles and the sequentiality of events are not determined within certain limits leaves "bubbles" in a block universe description for which, due to the inherent inseparability, a higher resolution description is not possible. Similar bubbles occur also in the "consistent histories" descriptions of quantum theory [47, 48] where it becomes obvious that a refinement of the set of possible histories to one single history describing the facts in our universe is impossible.

Of course, such bubbles only remain when one tries to represent the histories in terms of classicle particle trajectories. If, instead, one considers the wave function (or, equivalently, the quantum state) as the essential entity, a block universe representation is possible, but due to the indeterminacy of quantum theory and the reduction process, certain branches of the wave function may come to an end while other branches become enhanced. In both cases a prediction of the future state of the universe in terms of a present state is impossible. Within the many-worlds interpretation of Everett [6, 7] this problem is circumvented, because there is no collapse of the quantum state and the block universe representation in terms of quantum states is deterministic.

However, one problem remains for all of these representations. The standard formalism of quantum theory seems to indicate the existence of a prefered simultaneity – quantum theory is non-local. Consider an EPR-state (in Bohm's formulation, i.e., entanglement refers to the spin degrees of freedom) where the two entangled particles are far apart. A measurement of the spin of one of the particles leads to an instantaneous non-local reduction of the quantum state (in the many-worlds representation, the wave function splits non-locally into two branches). If we assign an objective (ontic) meaning to a quantum state, this non-local reduction would be a non-local event which distinguishes a prefered simultaneity at two distant locations. One could even imagine an entangled state consisting of many particles densely distributed over the whole universe,

$$|\Psi\rangle = \frac{1}{\sqrt{2}} \left(|+,+,+,+,...\rangle + |-,-,-,-,...\rangle \right) , \tag{3}$$

where "$+$" and "$-$" refer to some spin orientation of the single particles. A measurement of one particle leads to the reduction of the state of all particles and, therefore, to a global notion of simultaneity.

Among the standard interpretations of quantum theory, only a strict ensemble interpretation of the quantum state – the state has no meaning for a single system but only for an ensemble of systems – and a subjective interpretation of the quantum state – describing just the information we have about a system – circumvent this problem. In both cases, the quantum state has no ontic correlate[4].

Our formalism circumvents the problems associated with non-local reduction processes. The locality requirement and the causal structure of relativity refer to the factual aspects of reality, i.e. to the traces these events have left in our world. We argue that not the events are subject to this causal structure of relativity but only the propagation of the traces.

When a measurement is made on one of the particles, this becomes a fact in the vicinity of this particle. Even though the state is reduced simultaneously for the second particle, as long as no measurement is made at the second particle, this reduction is not factual in the vicinity of this particle. (Of course, what is relevant here is whether the second particle has sufficient interaction with its environment in order to transfer the information about the reduced state to its environment; in this case this information would become factual. A model for this information transfer has been developed in [25]) On the other hand, if a measurement is made at the second particle, the result coincides with the first measurement. However, as the experimenter has no influence on the result of the measurement, it is impossible to transfer a signal using the reduction process.

Furthermore, if we extend the quantum formalism to space itself, also the metric properties of classical space are subject to this "reduction" process. The question whether certain events happen "close by" or "far apart" only becomes meaningful after this reduction has taken place.

It may be interesting to note that the relevance of the finite propagation velocity of factuality for the interpretation of the reduction process and its consistency with any relativistic locality principle has been emphasized before: Bitbol [49] makes a thorough investigation by emphasizing the event where both results can be known together with the assumptions of retrodiction and locality, and, more recently, Smerlak and Rovelli [50] came to similar conclusions in the context of relational quantum theory. However, in addition we want to emphasize that events do not happen *in* a pre-existing factual space-time, but that factual events

[4] In the GRW-formalism [10] a Lorentz-invariant reduction process has been developed. However, many of the concepts employed in this approach – a multi-time formalism, non-local correlations in the location of reduction points, and a stochastic (non-deterministic) extension of the Schrödinger equation – indicate a close relationship to our E-scheme categories.

constitute factual space-time, and that concepts like "distance" may not be meaningful for two events unless both have "docked" to the factual space-time by becoming facts themselves.

Quantum theory gives us at least two indications that for a full understanding it may become necessary to include a theory of the present: (1) The non-deterministic reduction process describes the transition from potentialities to facts, which is exactly what one would expect to occur in a present. The concept of a present only becomes meaningful if such a transition takes place. For this reason, there can be no concept of a present in the deterministic classical theories. (2) The non-local simultaneity distinguishes a global space-like hyperspace where reduction processes occur simultaneously, and this would be a prerequisite for an ontic "present".

It has been argued at several occasions that a theory of the present contradicts special and general relativity. Einstein himself, in a discussion with R. Carnap, was disappointed that the theory of relativtiy does not allow for a theory of the present [51], and a famous argument in this discussion is due to K. Goedel [52]: For Goedel it was not the Minkowski space itself which contradicted a theory of a present, because a distinguished space-like hyperspace is at least possible. He considered a theory of the present as impossible because of the theoretical existence of solutions of Einstein's equations with light-like closed loops – as, for instance, in the Goedel universe.

We want to indicate now some of the ingredients of such a theory of the present. In accordance with the previous section, the present has an extension. This extension is attributed to events, it depends on the process (i.e., it is not the same for all processes), and it is measured against an external clock. These statements need a clarification which will be given now.

The extension of the present is indicated by the transition from virtual possibilities to facts. This transition is not sharp. Due to certain properties, a particle may interact with its environment and, thereby, transfers the information about these properties to environmental degrees of freedom which now, due to their interaction with ever more degrees of freedom, spread this information to an increasing number of other particles or systems. By this process, events become facts. Facticity is not an either-or property, but it increases gradually. It is closely related to the concept of decoherence. A (qualitative) measure of facticity would be the effort (e.g., the number of degrees of freedom involved) to "undo" a certain event, i.e., to restore all the coherence necessary in order to generate interference effects which indicate that a certain event did not happen. (It has been estimated [48] that in order to "undo" n degrees of freedom which took part in decoherence, a system of the order of $\exp(an^{3/2})$ degrees of freedom is necessary, where a is some positive constant; this indicates a possibility to quantify such a measure.) Therefore, facticity is never absolute but only FAPP ("for all practical purposes", an expression introduced by J. Bell in a similar context [36]).

In some processes the extension of the present is very short (less than nano-seconds), like, e.g., when a particle hits a screen where it is registered. Under special experimental conditions, one can prolong the process of factualization almost arbitrarily long (e.g. in so-called quantum eraser set-ups [53]). An extreme example would be the scenario of the cosmic delayed choice experiment which is attributed to Wheeler [54][5]. Depending on the experimental set-up on earth one can decide to measure whether a photon emitted from a quasar several billion years ago passed by a gravitational lense on both sides (in a double-slit manner) or on one side. Concerning the history of this photon the present extends over billions of years.

Even within a single process, the extension of the present attributed to different events may differ. One can rapidly measure the energy of an electron in an electric field without determining its spin orientation. For atoms one can measure the absolute values of the magnetic moments in an electric field without determining their sign. Therefore, facticity (and hence also the extension of a present) has to be attributed to events and not to systems. (There are certain properties, like the electric charge, which can be attributed

[5] As Max Jammer has pointed out, all the ingredients of delayed choice experiments are already contained in an article of C. F. von Weizsäcker [55] from 1931.

to systems. In general, such properties are related to superselection rules, i.e., not only are these quantities conserved – they commute with the energy operator – but they even commute with any physical observable.)

By an external clock (against which we measure the extension of the present) we mean a system for which the time intervals of the transitions to facticity are extremely short. Today, atomic clocks or fountain clocks can resolve time intervals which are much shorter than the "extension of the present" for many of the systems mentioned above. Presumably there is a principal lower bound for the resolution of such "external clocks" (which might be the Planck scale of roughly 10^{-44} sec), which would be a lower bound for the extension of the present of any event.

We thus arrive at the following picture (see Fig. 1): For each event there is a measure of facticity whose derivative (with respect to the external "classcial" time) gives rise to a measure for the intensitiy of the present of this event. Entanglement leads to a correlation of such curves for different processes and at different locations thus giving rise in a classical limit to a globalized meaning of the present. On the level of quantum processes, this meaning is never absolutely precise.

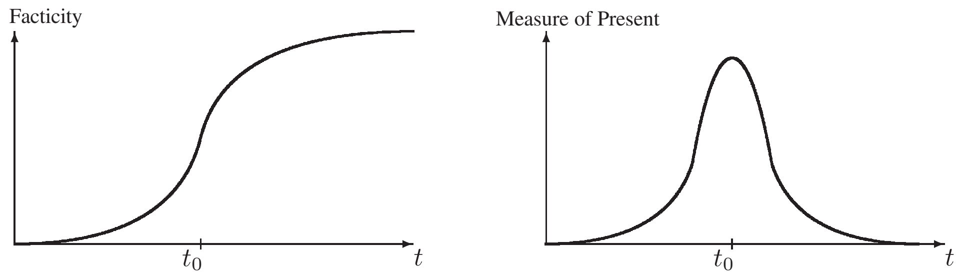

Fig. 1 (Left) Facticity (as measured by the effort to undo an event, see text) against an idealized external time. (Right) The derivative of facticity yields a measure for the intensity of the present. The time t refers to an external classical clock.

We should like to add that an increasing number of authors propagate the idea of reassessing our concepts of time in the context of quantum theory. Some more mathematical models have been developed, e.g., by Primas [56], who uses representation theory of the Weyl algebra in order to develop dual aspects of time which can be related to a theory of the present on the one hand and the standard sequential time on the other hand, and by Hiley [57], who derives time from an algebraic theory of moments and constructs, amongst other concepts, a "time-extension" operator which measures the temporal extension of events.

8 Summary and conclusion

In this arcticle we hoped to achieve two goals: (1) We have clarified the conceptual foundations of quantum theory and put them in opposition to the conceptual foundations of classical physics. In this context we have introduced the concept of a categorical apparatus. (2) We have emphasized the loss of temporal sequentiality in certain quantum processes and it's relevance for a theory which combines quantum theory and (space-)time. (3) We have outlined certain aspects of a "theory of the present". In our opinion such a theory is inherently already incorporated into the existing formalism of quantum theory.

The E-scheme of the conceptual foundations of quantum theory is complementary to the F-scheme of the conceptual foundations of classical physics. Together they constitute the conceptual framework which is necessary to make statements about reality. In the present article we have elaborated the E-scheme only in the context of quantum theory. However, to a certain degree the E-scheme is also relevant for other areas of science. The ingredients – non-determinism, self-referentiality, non-separability between observer and observed, etc. – can also be found in other complex systems (and have been emphasized, e.g., in the books of Görnitz [22,23,25]). In [20] we have argued that both schemes are relevant in addressing the problem of conciousness. In other areas – e.g. in certain evolutionary processes or in addressing the question of "What is life?" – it may also turn out to be relevant that both families of concepts are taken into account.

The concept of a "time-space of the present" which we developed in the last part of this article, should indicate a new approach towards a theory of the present. We believe that an understanding of the fundamental concepts of nature forces us to develope such a theory, and quantum theory already gives us strong hints towards a non-subjective existence of the present. Next to consciousness, the present is one of our most intensive experiences, and without a theory of both we will always lack an understanding of the most profound basis of reality.

Acknowledgements It is a pleasure to acknowledge numerous discussions with friends and collegues about the ideas presented in this article. A list can never be complete, but we are particularly grateful for interesting suggestions from Harald Atmanspacher, Hans-Peter Dürr, Ernst Pöppel, Michael Silberstein, and Eörs Szathmary, as well as from the participants of a Parmenides-Workshop on "Philosophical and Physical Perspectives of Time and the Present" held in October 2006, in particular Domenico Giulini, Michael Drieschner, Erich Joos, Claus Kiefer, and Tejinder P. Singh.

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