Abstract

Underlying any theory of physics is a layer of conceptual frames. They connect the mathematical structures used in theoretical models with physical 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, in quantum theory the reduction postulate 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.
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. We are used to indeterminacy in every-day situations, but whenever we refer to probability theory, we consider this indeterminacy as a lack of knowledge. In some way or another we are reluctant to give up Leibniz’ principle of sufficient reason which states that “nothing takes place without a sufficient reason; in other words, that nothing occurs for which it would be impossible for someone who has enough knowledge of things to give a reason adequate to determine why the thing is as it is and not otherwise.”

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 in quantum physics seems to indicate that in some cases even the mere assumption of a predetermined cause for the behavior of quantum systems (e.g., the observed deviation of an atom in a Stern-Gerlach set-up) leads to contradictions.

Another conundrum of quantum theory is related to its non-locality, in particular in the context of EPR-scenarios, 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. 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”. Even though superpositions only refer to vector representations of quantum states, there is a more general phenomenon behind it: In quantum theory there are no states which are non-dispersive 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 (which is not 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. The spatial “smearing out” of particles as expressed by wave functions is well known and partially related to the non-boolean aspect of quantum theory: a particle is not “either” in a certain volume element “or” not, but according to the extension of the wave function it can be to a certain degree inside a volume element “as well as” outside this element. 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. Protagonists of the many-world interpretation [6, 7] may deny a problem with the non-locality of the reduction process or with indeterminacy, because in the many-world interpretation there is no reduction. 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 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 add to the Schrödinger equation a non-linear stochastic term. In these cases the reduction of the wave function is attributed to reduction centers. We will also not discuss interpretations which invoke a causation into the past (like, e.g., in [12]) or which are “superdeterministic” by including the future decisions of experimenters about which experiment to make 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 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 interprete quantum mechanical issues and why this hidden assumptions in the context of quantum theory seem to lead to contradictions with our understanding of how reality “should be”. These hidden assumptions are no surprises: We are aware that, e.g., we tend to apply causality in the sense of Leibniz’ principle of sufficient reason, or that we apply boolean (“either-or”) logic to physical attributes like location, energy, and momentum, or that we like to put ourselves into an external perspective (in contrast to the “participatory universe” of Wheeler[14]). 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 [15] or the notion of non-boolean lattices [16] - 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. The
purpose of this article could in a way be summarized as: Making quantum physics thinkable.

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 (Sec. 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 Sec. 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 Sec. 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 Sec. 5 the categorical assumptions we make in the context of classical, factual physics. In Sec. 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 Sec. 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 develop 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.

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. 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 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 photograph 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 consciousness enters and we are leaving the realm of known physics. (In [18] we elaborated on the similarity between the conceptual frameworks of quantum theory and consciousness.)

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. In the realm of classical physics it is the second law of thermodynamics (the increase of entropy in non-equilibrium systems) which makes it easier for us to deduce events in the past from facts in the present as compared to predicting events in the future from the present situation.

In contrast, quantum theory refers to the transition from possibilities (or potentialities) to facts. A wave function, or, more general, 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 “sum 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.

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 the nodes of the gist of space-time. In most cases, they are idealized to be “point-like”. Events can be a conglomerat 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 [19]. A second type of event will be what in discussions about quantum theory sometimes is called “virtual event”. These type of events often refer 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 categorical 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, 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 [20, 21, 22]):

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 physical 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 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, attempts 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 \textit{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 \textit{E-scheme} will be needed. Both apparatus together, the F-scheme and the E-scheme, constitute the complete \textit{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 photograph, a fossil 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 Sec. 4. The four slots - (1) relation between physical events, (2) combinations of predications, (3) relation between observer and observed, (4) ordering structure of time and space - are filled with the following categories: (1) processes are deterministic (causally closed), (2) a predicate about a physical attribute is either true or false, (3) an observation has no influence on the observed, (4) space and time allow for an ordering structure: events along a world line can be sequentially ordered and for objects in space there exists a metrical and topological ordering. 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 of Maxwell’s theory of electromagnetism and of special and general relativity.

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 \( \Delta t \), 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 \( \Delta t \) 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.

\footnote{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.}
5.2 The *tertium non datur* of predcations

In physics a predication about a system is a statement about the values of observables which can be measured for this system. In the following we will talk about pure states only. Algebraically, a state can be defined as a positive, normalized, linear functional on the set 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.

In classical physics any observable has a well-defined value for a pure state in the following sense: Each measurement of the same observable $F$ in the same state $\omega$ yields the same result $f$ which is identical to the expectation value: $f = \omega(F)$. There is no spreading of results, the variance of the results for a sample of measurements of the same observable is zero. Therefore one can say, that in this situation the system has the property \textit{`f'}. (There are technical problems when $f$ is a continuous variable, in which case one usually refers to intervals.) In this sense the *tertium non 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, i.e., the systems under consideration are not prepared in a pure state, 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 of the observer about a system does not lead to a change of state of this system.
At first sight this assumption seems to contradict Newton’s third law - “actio” equals “reactio”: the force of system 1 on system 2 equals (in opposite direction) the force of system 2 on system 1. In a slightly different setting one can also say that 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 and is independent of the precision of the measurement. Equivalently, one may say that in classical physics informational flow does not need a corresponding flow of energy. The changes on the side of the observing system may be large and accompanied by a macroscopic amount of energy, however, this energy comes from an amplification mechanism. A measuring device can be prepared in such a way that an arbitrarily small change of one component (a detecting device) is amplified in such a way as to give rise to a macroscopically large change of another component (the pointer).

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 preferred system, the perception of events is not subject to the delay due to the finite expansion 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 Section \( \[4 \] \) 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”.

\(^2\)At this point we explicitly exclude non-causal solutions of Einstein’s equations which allow for closed time-like loops like the Goedel universe.
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. None of these categories holds anymore in the context of quantum theory. We now introduce the corresponding categorical apparatus of quantum theory.

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. However, 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. (For a more philosophical account of these concepts see [20] and [23].)

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

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 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 (see Everett [6] and deWitt [7]) 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 construct observables which are able to interpolate between sufficiently different branches of the wave function and, 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. Presumably this is the strongest assumption about the interpretation of quantum theory which we make in this context. 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 sys-
tem. 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 in the form of “as well as”. We will refer to this property of the predication space as “parataxis”, and its realization in quantum theory is the superposition principle. In the context of a predication calculus, this category may be realized by non-boolean lattices (see, e.g., [16]).

The concept of superpositions is most easily formulated when quantum states are expressed as (normalized) vectors in a Hilbert space. Often it is stated in the form that with any two vectors \( |\psi_1\rangle \) and \( |\psi_2\rangle \) also the (normalized) linear combination

\[
|\psi\rangle = \alpha|\psi_1\rangle + \beta|\psi_2\rangle \quad \text{with} \quad |\alpha|^2 + |\beta|^2 = 1
\]

is a quantum state\(^3\). Another formulation of the same principle is that a state \( |\psi\rangle \) can be expanded in terms of the eigenstates \( |\psi_i\rangle \) of any self-adjoint observable \( A \):

\[
|\psi\rangle = \sum_i \alpha_i |\psi_i\rangle \quad \text{with} \quad \sum_i |\alpha_i|^2 = 1,
\]

where

\[
A|\psi_i\rangle = a_i |\psi_i\rangle.
\]

In this formulation the superposition principle seems to depend on the representation of pure quantum states as vectors of a Hilbert space. However, strictly speaking, pure quantum states rather correspond to the one-dimensional rays in a Hilbert space, or, in other representations, to the set of one-dimensional projection operators on a Hilbert space or to the (convex) boundary of the set of normalized, positive density matrices. For these

\(^3\)Superselection rules may put restrictions onto this rule but this shall not concern us here.
objects one cannot define a unique addition. (The normalized addition of
projection operators or density matrices leads to mixed states while the superposition of pure states is again a pure state.)

A word concerning our notation: $\psi$ often refers to a quantum state independent of its mathematical representation. If we want to emphasize that the state is a positive, normalized, linear functional on the set of observables, we write $\omega_\psi$, and $\omega_\psi(A)$ denotes the expectation value of the observable $A$ in this state. When $\psi$ is represented by a normalized vector, we write $|\psi\rangle$, and the expectation value of the observable $A$ is

$$\omega_\psi(A) = \langle\psi|A|\psi\rangle. \quad (4)$$

Finally, if we represent the state by a projection operator onto the ray defined by the vector $|\psi\rangle$, we write $P_\psi$, and the expectation value of an observable $A$ is

$$\omega_\psi(A) = \text{tr}(P_\psi A). \quad (5)$$

The superposition principle of quantum theory expresses a property which is independent of the representation of pure states. We define a state $\omega$ to be dispersion-free with respect to an observable $A$, if

$$\omega(A^2) = \omega(A)^2. \quad (6)$$

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.

If a vector can be expanded according to eq. (2), the corresponding state is not dispersion-free with respect to the operator $A$, unless all the expansion coefficients $\alpha_i$ are zero except one coefficient (which is one), in which case $|\psi\rangle$ is itself an eigenstate of $A$. More general, let

$$A = \sum_i a_i P_i \quad (7)$$

be the spectral decomposition of the observable $A$, then

$$\omega(A) = \sum_i a_i \omega(P_i) \quad (8)$$

and

$$\omega(P_i) = |\alpha_i|^2. \quad (9)$$
These values can be obtained from a distribution measurement of \( \{a_i\} \). The relative phases between these coefficients require measurements of complementary observables (observables which do not commute with \( A \)). In quantum mechanics it is impossible to construct pure states which are dispersion-free with respect to all observables \([24]\).

Let \( \psi \) be a state which is not dispersion-free with respect to an observable \( A \). In this case, the same measurement (of observable \( A \)) performed on the same state \( \psi \) may sometimes yield the result \( a_1 \) and sometimes a different result \( a_2 \), where \( a_1 \) and \( a_2 \) are eigenvalues of \( A \). (For simplicity, we consider only two possible outcomes.) In this case, we can neither say that the state has the property \( a_1 \), nor that is does not have this property. In this sense the *tertium non datur* does not hold. Some scientists prefer to say that this state \( \psi \) is not compatible with properties related to the observable \( A \), others will say that it has property \( a_1 \) "as well as" property \( a_2 \). Fact is that measurements of observable \( A \) for the same state \( \psi \) sometimes yield the result \( a_1 \) and sometimes the result \( a_2 \), and in this sense both properties can be attributed to the state \( \psi \).

Parataxis is an expression which is used in philosophy to denote that predications “stand side by side” and that the *tertium non datur* does not hold. It is also used in the science of literature 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 predication:

1. The overall meaning of a paractic predication unfolds itself out of the constellations of components. This is reflected in the mathematical formalism by the fact that the transition amplitudes \( \alpha_i = \langle \psi_i | \psi \rangle \) between the state \( \psi \) and the states \( \psi_i \), which correspond to the paratactic predicates \( \{a_i\} \), determine \( \psi \) uniquely.

2. Formal conclusions are not possible and thus the *ex falso quot libet* catastrophe (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. ...” ([25] p.144).

Given the absence of formal truth criteria, actual experience is the only way to verify a proposition.

As we have seen, in classical physics either \( a \) or \( \neg a \) is true, but in quantum theory \( a \) as well as \( \neg a \) may be true in the sense, that we find states \( |\psi\rangle \) which are a linear superposition of an eigenstate \( |\psi_a\rangle \) with the (dispersion-free) property \( a \) and an eigenstate \( |\psi_{\neg a}\rangle \) with the (dispersion-free) property \( \neg a \):

\[
|\psi\rangle = \alpha|\psi_a\rangle + \beta|\psi_{\neg a}\rangle \quad \text{with} \quad |\alpha|^2 + |\beta|^2 = 1.
\]

This property of quantum states is what we will denote by “paratactic”, and \( \alpha \) and \( \beta \) are manifestations of the relative constellation of the components.

### 6.3 Self-Referentiality - the nonseparability of observer and observed

One of the most significant and in its consequences most dramatic features of quantum theory is the phenomenon of entanglement. 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 \( \mathcal{H} \):

\[
\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2.
\]

A state \( |\Psi\rangle \) (represented by a normalized vector) in \( \mathcal{H} \) is called separable if it can be written in the form

\[
|\Psi\rangle = |\psi\rangle \otimes |\varphi\rangle,
\]

where \( |\psi\rangle \in \mathcal{H}_1 \) and \( |\varphi\rangle \in \mathcal{H}_2 \). A state which is not separable is called entangled (with respect to the tensor product representation).

Typical entangled states are EPR-states

\[
|\Phi_{\text{EPR}}\rangle = \frac{1}{\sqrt{2}} (|\psi_1\rangle \otimes |\varphi_2\rangle - |\psi_2\rangle \otimes |\varphi_1\rangle),
\]

or, more general, Bell states:

\[
|\Phi_{\text{Bell}}\rangle = \frac{1}{\sqrt{2}} (|\psi_1\rangle \otimes |\varphi_2\rangle \pm |\psi_2\rangle \otimes |\varphi_1\rangle)
\]
and
\[ |\Phi'_{\text{Bell}}\rangle = \frac{1}{\sqrt{2}} \left( |\psi_1\rangle \otimes |\varphi_2\rangle \pm |\psi_2\rangle \otimes |\varphi_1\rangle \right). \tag{15} \]

With respect to measures of entanglement these states are maximally entangled.

In a similar way entanglement can also be defined for higher tensor product representations of the state space. For these higher order tensor products one can even define different types of entanglement. A famous example are the GHZ-states for three particle systems [26].

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 such a splitting may appear arbitrary, e.g., when the description of a single particle is split with respect to the coordinates of its reference system. Another, more relevant, example is a single particle for which the total state space is splitted with respect to the spatial degrees of freedom on the one hand and the spinorial degrees of freedom on the other hand. For an electron which passed a Stern-Gerlach magnet one may speak of an entanglement between the spatial position of this electron and its spin orientation:

\[ \Psi(x,s) = \frac{1}{\sqrt{2}} \left( \psi^+ (x) \otimes |s = +\rangle + \psi^- (x) \otimes |s = -\rangle \right). \tag{16} \]

\( \psi^\pm (x) \) are parts of the spatial wave function which are peaked around different positions.

The weird aspects of entanglement enter when the system described by the quantum state is non-local, e.g., when the system consists of two particles which are far apart. A measurement performed at one particle has immediate consequences for the state of the other particle. To be more precise, a measurement performed at one particle leads to a reduction of the total state in such a way that the state becomes separable, which in turn makes it possible to assign a definite state to the second particle. 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 single particle states with a highly non-local wave function.

In principle, any interaction between two particles - or, more generally, between two systems - leads to entanglement. (On the other hand, subsequent interactions with other systems may destroy these entanglements.) Up to now, we mostly considered the interaction between particles or typical quantum systems. However, according to the standard formalism of quantum theory, this statement remains true for macroscopic systems. A particular case is the situation of a measurement, where a quantum system (a system with few degrees of freedom) interacts with a classical system (a system with many degrees of freedom). In quantum theory the measurement process has to be considered as an interaction which has an influence on both systems, the observing as well as the observed system. As a result of this interaction the observed system and the observing system become entangled. We briefly recall this situation in the usual framework.

Let

\[|\psi_0\rangle\]

be the state of a quantum system, expressed as a superposition of eigenstates with respect to the measured observable. (We are not addressing the “pointer basis problem” here, see e.g. [27], so we assume that these states are uniquely given.) Let \(|\psi_0\rangle\) be the initial state of the measuring device, and \(|\varphi_i\rangle\) be its pointer basis. The initial state of the combined system \(|\Phi_0\rangle\) is separable:

\[|\Phi_0\rangle = |s\rangle|\psi_0\rangle = \sum_i \alpha_i |s_i\rangle|\varphi_0\rangle.\]  

The interaction between the two systems due to the measuring process leads to a superposition of correlated states:

\[|\Phi_1\rangle = \sum_i \alpha_i |s_i\rangle|\varphi_i\rangle.\]  

This state is an entangled state. The observing system and the observed system are no longer separated. It is impossible to assign a separate quantum state to any of these two systems, and only the quantum state corresponding to the combined system is meaningful. In a next step the reduction process
describes the transition from the superposition of possibilities as expressed in eq. (19) to a single fact:

\[ |\Phi_1\rangle \rightarrow |\Phi_2\rangle = |s_k\rangle|\varphi_k\rangle. \]  

(20)

Hence, the process of observation first leads to entanglement and, therefore, an inseparability between observer and observed. In a second step the reduction process results in 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.

We have attributed the loss of dichotomy between observer and observed to the general concept of self-referentiality. The philosophical reasons for this attribution will be discussed elsewhere [23]. However, it should be obvious that when observer and observed are no longer separated, we have the situation that “a system observes itself”, which is a strong form of self-referentiality.

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 wave functions. 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 sequentiality 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 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 and it is realized by a classical clock (we will say more about this point later). However, as we have described in Sec. 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 quantum propagator of a system, i.e., the probability amplitude \( K(x, y, t) \), where \( x \) is 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:

\[
K(x, y, t) = \sum_{x \rightarrow y} \exp \left( \frac{i}{\hbar} S[x \rightarrow y; t] \right).
\]

(21)

“\( x \rightarrow y \)” represents a possible history of how the system can evolve from state \( x \) to state \( y \) within the time interval \( t \) (which is the same for all histories); \( S[x \rightarrow y, t] \) is the classical action for this history, and \( \sum_{x \rightarrow y} \) symbolizes the summation over all such histories. If these histories involve certain events \( a_1, a_2, \ldots \), and if the general constraints on the set of histories do not forbid a permutation of the temporal order (with respect to the mathematical background time \( t \)) 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 state \( x \) to \( y \), it is meaningless to state that a certain event \( a_1 \) happened before a second event \( a_2 \) or vice versa. The classical sequentiality of events along the world line of the system is lost.

The loss of sequentiality as it follows from the summation over histories representation is most 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 examples 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 facticity. (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: $\Delta E$ is the uncertainty in an energy measurement during a time interval $\Delta t$, or, vice versa, $\Delta t$ is the maximal precision for the determination of the moment of an event in which an energy is transfered of which the value can be known up to $\Delta E$. 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., [28, 29, 30].)

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, atom $A$ only emitts photons with a left circular polarisation and atom $B$ only emitts photons with a right circular polarisation, the association of an emitted photon to a certain event $a$ or $b$ would be possible 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.

7 The time-space of the present

In the previous section we 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 the quantum mechanical formalism gives strong indications that a complete unified theory of space and time on the one side with the principles of quantum theory on the other side 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" [31].) 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 [32, 33] 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 classical 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 preferred simultaneity - quantum theory is non-local. Consider an EPR-state
where the two entangled particles are far apart. A measurement on 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 preferred simultaneity at two distant locations. One could even imagine an entangled state consisting of many particles densely distributed over the whole universe,

\[ |\Psi\rangle = \frac{1}{\sqrt{2}} \left( |+, +, +, +, \ldots \rangle + |-, -, -, -, \ldots \rangle \right), \tag{22} \]

where “+” and “−” refers 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 subjective interpretation of the quantum state - describing just the information we have about a system - circumvents this problem, because in this interpretation the reduction of the quantum state has no observer independent 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. 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 not the measurement as an experimental situation, but the question 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.) 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.

\(^4\)In the GRW-formalism \cite{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.
Quantum theory gives us at least two indications that for a full understanding a theory of the present might be necessary: (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, (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 (global) “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 relativity does not allow for a theory of the present, and a famous argument in this discussion is due to K. Goedel. (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, but due to the theoretical existence of solutions of Einstein’s equations with light-like closed loops - as, for instance, in the Goedel universe - he considered a theory of the present as impossible.)

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 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 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 [37]). An extreme example would be the scenario of the cosmic delayed choice experiment which is attributed to Wheeler [38]. 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 lens 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.

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 $10^{-44}$ s), 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 “classical” time) gives rise to a measure for the intensity 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.

8 Summary and conclusion

In this article we hoped to achieve two goals: (1) We have clarified the conceptual foundations of quantum theory and put them in opposition to
Figure 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.

the conceptual foundations of classical physics. (2) We have outlined certain aspects of a “theory of the present”, which in our opinion is inherently already present in 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. In [18] we have argued that both schemes are relevant in addressing the problem of consciousness. 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 develop 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.
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