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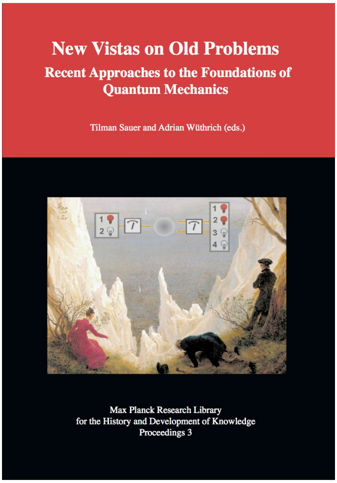
*Tilman Sauer and Adrian Wüthrich:*

# Introduction

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# Introduction

*Tilman Sauer and Adrian Wüthrich*

This volume presents a collection of contributions to the current debate on the interpretation of quantum theory. The collection is neither intended to give a comprehensive overview of a highly active field of philosophical research, nor is it intended to provide a representative collection. The contributions gathered here raise problems, probe alleys of exploration, and try to look at old problems from new or unusual perspectives. We believe that quantum theory by its theoretical structure and empirical validity raises problems that should and can be addressed in a dialogue between physicists and philosophers: we believe that quantum mechanics is in need of interpretation.

The papers of this volume were prepared for a symposium on current interpretational problems of quantum theory held at the University of Bern in June 2011. The symposium was a little bit more specific in its focus. It was announced under the title "Decoherence and No-Signalling." Let us expand a bit on the idea behind the symposium.

As a matter of historical fact, quantum theory has been a subject of interpretational debates ever since its inception. Physicists were puzzled by the quantization of energy that seemed necessary in order to understand black-body radiation, and they were troubled about the status of Niels Bohr's mysteriously successful, yet, axiomatically stipulated quantum postulates. The emergence of modern quantum mechanics is a process of reinterpreting old classical concepts and of trying to come to an understanding of new quantum concepts in a situation that was often explicitly perceived as one of theoretical crisis. Even after the establishment of quantum mechanics in the mid-twenties interpretational questions kept raising their heads. Why does quantum theory often not predict the outcome of a measurement but only give the probability distribution over possible outcomes? Does this reflect our ignorance of some relevant features of the system, do quantum systems not always evolve deterministically? This is just one complex of questions which came up early on in the development of quantum theory.

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The development of quantum mechanics, from about 1900 to the mid-1930s, was intimately linked to discussions of its consequences for our scientific world view. Albert Einstein, John von Neumann, and Erwin Schrödinger were among those who pointed out in particularly sharp ways the conceptual concerns of many physicists and philosophers with determinism, causality, and observability in quantum mechanical contexts.

In 1932, von Neumann laid down the principles of quantum theory in a concise axiomatic formulation. He also formulated what is, in fact, the common core of most of the aforementioned concerns: quantum mechanics exhibits a “measurement problem.” According to quantum mechanics, a “collapse” of the wavefunction unpredictably interrupts the deterministic evolution of a quantum mechanical system in the course of a measurement process. However, quantum mechanics does not provide any criterion of what constitutes a measurement. Quantum mechanics does not tell us to which domain we should restrict the application of the Schrödinger equation. When is the interaction of two systems a “measurement” (which is described by the Schrödinger equation) or an interaction of two quantum systems (which is not)?

In 1935, Schrödinger took the measurement problem to extremes by showing that the unrestricted application of his eponymous equation leads to superpositions of macroscopic objects, such as cats, which should be neither dead nor alive, nor both, nor none of the two. It seems hard to reconcile superposed states of macroscopic objects, such as cats, with our experience, and, insofar, there has to be something which distinguishes the interaction of macroscopically observable objects with quantum systems from the interaction among quantum systems themselves.

Also in 1935, in a joint paper with Nathan Rosen and Boris Podolsky, Einstein challenged the completeness of the quantum mechanical description of composed systems. They considered two sub-systems, say 1 and 2, which, on reasonable grounds, have ceased to interact. They find quantum mechanical descriptions which assign a definite position and momentum to sub-system 2 only if a measurement is performed on sub-system 1. However, they assume, the measurement operations on one sub-system does not influence the physical processes of the other. Sub-system 2 should, therefore, be assigned a definite position and momentum even before a measurement on sub-system 1 has taken place. Because quantum mechanics does not make this assignment, they conclude that it is incomplete.

On the other hand, if the quantum mechanical description is taken to be complete, sub-system 2 is changed from a state with no definite position and momentum to a state with definite position and momentum by the measurement operations on sub-system 1. If the quantum mechanical description is taken to be complete, the collapse of the wave function has to be considered a real physical process.[1]

But the collapse of sub-system 2 is caused *instantaneously* by the measurement of the distant sub-system 1—certainly a "spooky action-at-a-distance." Einstein thus revealed another problematic aspect of the collapse of the wave-function: Not only does quantum mechanics not specify how and why a collapse happens but, also, the collapse of the wave-function is difficult to reconcile with the special theory of relativity and with more general established principles of the separability of composed systems.

In particular through the work of Niels Bohr, an "orthodox" response to all these problems was established as a received view. The so-called Copenhagen interpretation held that those worries by Einstein and others about the interpretational consequences of the theory were unfounded. Although quantum mechanical phenomena continued to attract the attention of philosophers and physicists concerned with foundational issues, several events and developments contributed to the confirmation of this increasingly widely accepted response to quantum mechanics' interpretational problems.

Many physicists regard the theoretical description of decoherence processes as a mere elaboration of the Copenhagen interpretation. The measurement problem is claimed to be overcome by taking into account how superposed quantum mechanical systems disentangle rapidly through the interaction with a many-particle environment. Numerical models and estimates show that decoherence times are much shorter than the resolution of presently feasible measurement techniques.

In a similar vein, the empirical violation of Bell's inequality is taken as a crucial experiment showing the quantum mechanical description may be complete, notwithstanding Einstein's challenge. On this reading, Einstein, together with Podolsky and Rosen, argued that if physical systems interact only locally, the quantum mechanics is an incomplete description of physical systems and their interaction.

[1] The most recent and precise versions of arguments, along these lines, for the reality of the collapse of the wave function have been given by Pusey et al. (2012) and Colbeck and Renner (2012).

However, in 1964, John S. Bell spelled out the notion of locality, which Einstein seems to have had in mind, and showed that any such local theory satisfies an empirically testable inequality. Quantum mechanics, on the other hand, predicted a violation of these inequalities. In the early 1980s, experiments showed Bell's inequality to be violated, a result that vindicated quantum mechanics and, at the same time, ruled out any local alternative. Einstein's reasoning to think quantum mechanics is incomplete was thereby neutralized.

Moreover, it has been proven that the kind of non-locality which the empirical violation of Bell's inequality requires cannot be exploited to send signals faster than light. These no-signalling proofs seem to guarantee a "peaceful coexistence" (Abner Shimony) between quantum mechanics and the special theory of relativity.

Recent philosophical arguments, however, challenge the "new orthodoxy" (Jeffrey Bub) and its appeal to decoherence and no-signalling theorems. As a linear type of evolution, decoherence cannot make superpositions of quantum mechanical states disappear. Therefore, even when complemented by theorems and models of decoherence, quantum mechanics cannot dispense with the need for a collapse of the wave-function, or the need for an explanation of how superposed states are compatible with our experience.

This still generates the essential conundrum of the measurement problem. Similarly, the no-signalling theorems cannot provide what the new orthodoxy requires. The impossibility of sending signals faster than light does not ensure that the core principle of special relativity, Lorentz-invariance, can be satisfied by theories which describe the violation of Bell's inequality. Also, if the non-locality of quantum mechanics is accepted, there is no straightforward reason to dismiss non-local hidden variable theories, such as Bohm's. They are not excluded by the violation of Bell's inequality. If non-locality is accepted, there is no straightforward and sound argument any more why quantum mechanics should be regarded complete. (As mentioned before, there is also no straightforward and sound argument any more why quantum mechanics should be regarded *incomplete*.)

The objective of the symposium was to critically assess whether there still is today a problem of interpretation of quantum mechanics. Taking into account the most recent pertinent developments in philosophy and physics, invited speakers updated an audience interested in both philosophy and physics on the current state of research. Speakers and the audience engaged in a discussion, which challenged the different positions.

Needless to say, that the symposium did not solve any one of the outstanding interpretational problems. What it did was to provide a forum of debate and, in this debate, presented a spectrum of problems, difficulties, approaches, and perspectives. It was meant to be and turned out to be an unlimited and an open-minded debate. Neither did the participants succeed in, or even intend to, exhaust the problems in their various aspects and disguises, nor was any one point discussed until proven valid or invalid. But what the participants did do was to seriously engage in specific aspects of their choosing, laying out difficulties to the best of their understanding and presenting approaches up to a point where they could be taken up by others. The spirit of the symposium, and of this anthology, is to open up new vistas, instead of continuing old debates entrenched in old positions.

The symposium, in this spirit, was first and foremost, a forum to raise concerns. After all, we are still facing opposition—mostly in the physics community—by commentators who flatly deny the need for philosophical reflection. The majority of papers therefore may be presented as expositions of problems. The papers fall roughly into two classes: those which are mainly concerned with how and why a collapse could happen (the measurement problem), and those which are mainly concerned with the problems posed by non-local correlations. We have grouped the contributions accordingly.

## 1 Measurement of a Quantum System

Alexei Grinbaum's illuminates the foundations of quantum mechanics by focussing on the problem of the concept of an observer. Indicative of the problematic nature of this concept is the "shifty split" between system and observer in foundational accounts of quantum theory. Grinbaum gives us a historical overview of various positions that have been formulated in order to account for the role and function of the observer in quantum mechanics. He argues that common to all those accounts is the notion that observers define what a physical "system" is. More specifically, observers in quantum theory define systems not qua physical constitution, consciousness, or specific experimental setups, but they do so in an information theoretic sense. Taking his clue from this observation, Grinbaum describes observers using the notion of Kolmogorov complexity. Only sufficiently complex systems with a sufficient number of degress of freedom can function as observers of quantum systems, systems that lack the necessary number of degrees of freedom can only be classical observers. Spelling out this proposal in detail, Grinbaum suggests an experimental test for this interpretation. A C-60 fullerene molecule should have enough degrees of freedom vis-a-vis a photon emitting source in order to act as a quantum observer. But it should be able to do so only up to a certain number of photons observed. When saturated after observing too many photons, the fullerene will turn classical, a transition that should be observable, Grinbaum suggests, by measuring the fullerene's heat capacity.

Michael Esfeld and Antonio Vassallo discuss how canonical quantum gravity faces a dilemma. On the one hand, it seems impossible, in canonical quantum gravity, to treat entities which are localized in space-time as primitive and thus solve the measurement problem as does, for example, the alternative quantum theory by David Bohm. On the other hand, there seems to be no viable theoretical proposal, within canonical quantum gravity, as to how (macroscopic) entities, which are localized in space-time, can be reduced to more fundamental entities which are not localized in space-time. For Esfeld and Vassallo, a solution to the dilemma is best sought through a better understanding of the Wheeler-DeWitt equation, which describes the dynamical evolution of the quantum state of space-time.

Jakob Sprickerhof proposes an interpretation of quantum field theory in terms of entities which are localized in space, possibly in widely extended regions, and causally connected through energy-momentum transfer. He constructs his interpretation by modifying the conserved quantity theory of causation developed mainly by Phil Dowe, which is usually held to be incompatible with modern physics. The notoriously difficult to explain EPR correlations are, on Sprickerhof's account, an instance of the measurement problem rather than a problem of superluminal or otherwise non-relativistic causation. According to Sprickerhof, the initial singlet state of a pair of electrons is a spatially extended entity which interacts with the measurement devices; only from the interaction result two separate entities. Accordingly, the EPR correlations do not come about by a causal relation between two space-like separated entities but, rather, by a peculiar process—the measurement—which transforms the one spatially extended entity into two space-like separated entities. To render the EPR correlations less mysterious, Sprickerhof urges, we need to know what happens during a measurement.

Iñaki San Pedro calls into question that some statistical independence conditions, which are crucial in the derivation of Bell-type inequalities, can be justified by appealing to the experimenter's free choice as to which observable be measured in a given run of an experiment. San Pedro identifies questionable implicit assumptions, which are necessary to maintain the usual view that the freedom of experimental choice indeed justifies the statistical independence conditions. Those assumptions involve the temporal ordering of the events in EPR experiments, and, more generally, the temporal ordering of causes and effects. The implicit assumptions also involve the possibility of expressing causal relations in terms of probabilistic relations, and the assumption that the common causes of EPR correlations cannot even *partially* cause the experimenter's measurement choices. If we give up at least one of these implicit assumptions in our causal theory of EPR-type correlations, we can at the same time maintain that experimenters have free will and permit statistical dependencies of measurement choices and common causes for the correlations.

## 2 Collapse and Non-Locality

Tilman Sauer discusses several lesser known formulations, by Einstein himself, of the EPR paradox. Sauer uses these formulations to bring to the fore what Einstein's particular concern was: Quantum mechanics ascribes two different states to the same physical matters of fact. This seems to be a different concern than that of the EPR paper of 1935, or it is there much less clearly expressed. The last formulation which Sauer discusses, however, confronts us with a puzzle. He either seems not to have mastered the quantum mechanical formalism as applied to the spin properties of particles, or else he was cryptically expressing some idea that needs explication. Was Einstein slowly losing his intellectual faculties, or was he after an innovative solution of the paradox which he had already exposed sufficiently clearly a long time ago?

Simon Friederich localizes the source of both the measurement problem and the problem of quantum non-locality in the ontic conception of a quantum state. These problems can be solved, he suggests, by giving up the notion that quantum states are states that quantum systems are in. Rather, he suggests, we should conceive of quantum states epistemically as expressing the agent's knowledge about quantum systems. Discussing the advantages of such an "interpretation without interpretation", Friederich proceeds to spell out what he calls the "rule perspective" of an epistemic conception of quantum states. Drawing on a distinction due to John Searle between "regulative" and "constitutive" rules, he suggests that the rules by which we assign states to quantum systems are "constitutive" in the sense that they constitute the very meaning of a quantum state. Friederich argues that the rule perspective allows us to be neutral with respect to the broader issue of realism in the foundation of quantum mechanics.

Matthias Egg first reminds us that there are good reasons to believe that, if nothing else, scientific theories tell us the true causal relations which obtain in the world. But Bell-type experiments pose a serious challenge to such a position. In particular, several theorems tell us that Bell correlations cannot be used to send signals. Therefore, these theorems prohibit us to be able to manipulate any cause that would allow us to send a signal in a Bell-type experiment. But then again, according to Egg, it is only through some manipulation of causes that we can obtain knowledge about the specific causal structure, i.e., knowledge beyond the simple fact that there are *some* causal relations. This dilemma leads Egg to the conclusion that the causal realist has two options in the face of Bell-type experiments. The first option is to doubt some of the premises of the no-signaling theorems. The second option is to be realist only about the general claim that there is *some* causal relation between the observed events.

The empirical violation of Bell's inequality forces us to reconsider our most basic foundational concepts. It is, on Adrian Wüthrich's account, an even more profound and consequential fact than the theoretical difficulties associated with the measurement problem. Wüthrich undertakes to prepare the ground for an informed revision of our fundamental tenets when faced with the empirical violation of Bell-type inequalities. He takes issue with the all-too-simple alternative between realism and locality posed by quantum theory's empirical validity. Taking up arguments to the effect that realism itself in some not-too-specific sense entails non-locality, Wüthrich argues that giving up realist convictions may not help us save locality. In order to identify with more precision the consequences that need to be drawn, Wüthrich analyzes the premises of a minimal derivation of a class of Bell-type inequalities. Only with a minimal derivation are we in a position to identify the choices that we have to make. Following this program, Wüthrich gives a more fine-grained logical analysis of the structure of the reduction argument that allows him to qualify necessary assumptions and premises in terms of realist or local spirit.

Even though, historically, much of the interpretational quagmire arose in theoretical reflections on the foundations of quantum physics, those foundational problems are nonetheless real and carry observational consequences. Philip Walther presents results of an experiment that puts to the test the predictions of EPR correlations pushed to a subtle but conceptually significant consequence. We know, Walther reminds us, that quantum mechanical entanglement is real and observable. But this statement usually takes entanglement to be a relation between particles. Can entanglement itself be entangled? To answer this question Walther designed an experiment, in which the usual polarization state of a photon is entangled with the entangled state of a photon pair. Deriving a Clauser-Horne-Shimony-Holt inequality for the correlations between Alice's photon and Bob's entangled photon pair, Walther shows that in this case, too, experiment can decide on the nature of quantum reality. Not surprisingly perhaps, but with profound implications, he found that Bell's inequalities are violated also in the case where the entangled object in question is itself a state of entanglement and that quantum mechanical predictions are empirically confirmed even in this case. Entanglement is real even in the sense that it can itself be entangled.

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