QUESTION 2

BIG ISSUES

What are the most pressing problems in the foundations of quantum mechanics today?

While science churns out a relentless series of quantum leaps within a matter of years (if not months), philosophy is accustomed to a much more leisurely ride. As a philosopher friend of mine recently remarked, “Major advances in philosophy happen in units of centuries, and even that might be an optimistic assessment.” And indeed, by their very nature, many of the questions that perplexed Kant or even Plato continue to engage the contemporary philosopher. Clearly, the pace of progress is a matter of perspective.

The foundations of quantum mechanics occupy a comfortable middle ground between these two extremes. The field is relatively young and dynamic. And because its object of interest is a physical theory, the field is rooted quite firmly in science, despite the host of metaphysical questions quantum mechanics seems to generate. At the same time, the issues that the founders of the theory already agonized over have not visibly aged in the passing decades. Schrödinger’s cat is alive and well fed and not inclined to having its fate decided anytime soon. The ripples of EPR are still felt everywhere. Bohr’s interpretation of quantum mechanics keeps flexing its muscles, inspiring a new generation of epistemic and informational viewpoints while sending other people scrambling for an antidote.

But to say that the time-honored themes of quantum theory’s first generation are on everyone’s lips today as ever is not to suggest that the field of quantum foundations has turned stagnant, or that it has become akin to a dog chasing its tail, or that is has been reduced to little more than an autoerotic enterprise with no hope or desire for escape from bachelorhood. Quite the opposite, actually. As already mentioned in the prologue, there’s been a dramatic refinement over time in the way people think and talk about the central issues. Post-war developments—such as the stream of new interpretations, the various no-go theorems, experiments at the quantum level, and more recently quantum information—have not only put a distinctly new spin on old debates, but have also given rise to a flurry of new questions (and even a few precious answers).

In fact, it is now far from obvious what a contemporary foundationalist would regard as the key issues awaiting resolution. There are no hard-and-fast rules. What one person may experience as a genuine and pivotal difficulty—to be disregard only

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at our peril—may be perceived by someone else as a petty concern or mere pseudo-issue. And even once you find two people settling on the same problem, you can bet that they'll hold divergent views of what the problem is really all about and what the best course of action might be.

To get a good sense, then, of a representative range of present-day foundational priorities, let's ask our interviewees to lay out the playing field for us.

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Guido Bacciagaluppi · I think recent progress in various fields within foundations has brought up, or renewed, interest in a number of very important questions—although maybe none are so pressing as to impede further progress pending their resolution.

Hidden-variables programs, that is, pilot-wave theories of the de Broglie–Bohm type, have progressed enough in recent years that the question of direct experimental evidence that might decide between them and quantum mechanics has become meaningful. The central idea is the analogy between pilot-wave theories and classical statistical mechanics, in particular the possibility of observable nonequilibrium effects. The range of application of pilot-wave theories is now large enough that they can be applied to quite exotic phenomena that might reveal systematic violations of the Born rule. Antony Valentini in particular has been pioneering the exploration of these possibilities. Such violations would be the most direct evidence in favor of a revision of quantum mechanics.

Within collapse theories, recent work—especially by Pearle and by Nicrosini and Rimini in physics, and by Wayne Myrvold in philosophy—has brought us very close to finally deciding whether a satisfactory relativistic collapse theory is possible. That is a very big question, and it is surprising that so few researchers actively engage in it. (Maybe this is a side effect of an apparent shift in the preoccupations of the community, partially away from more traditional approaches and more toward the new field of quantum information. Indeed, at the Sixteenth U.K. Foundations Meeting just a few months ago, it was quite noticeable that only a handful of talks were in the subject areas of hidden variables, collapse theories, and Everett interpretations.) The experimental question of deciding between collapse theories and quantum mechanics has also made progress, but it is not quite as promising as in the case of pilot-wave theories. This is due to the fact that the appearance of spontaneous collapse can be always mimicked by decoherence induced by some appropriate environment (coupled with one's favorite no-collapse interpretation). What is particularly worrisome is the suspicion that a rival no-collapse theory might not even need to invoke some hitherto unobserved, mysterious environment to do the job, but that once gravitation is quantized, it might provide just the right kind of environment to reproduce some of the currently best candidates for collapse theories (which tend to be mass-density based). A paper by Bernard Kay some twelve years ago or so made this point in a particularly striking manner.

Everett interpretations have also made quite spectacular progress in recent years, principally thanks to work by Simon Saunders in the 1990s, and by David Deutsch, David Wallace, and others in the 2000s. They appear, in fact, to have solved—or to have convincing strategies for solving—all the classic questions that used to trouble them. There are still a few question marks, but I would not say there are very pressing questions for Everett. (Personally, I think there are some questions about the details of relativistic locality and of the various accounts of mentality, which I am exploring with Laura Felline, and some lingering issues about probabilities, as raised, for instance, by Peter Lewis.)

The development of the cluster of approaches around quantum information has brought renewed interest in axiomatic foundations of standard quantum mechanics, and the reconstruction problem of quantum mechanics has seen a sudden flood of very impressive and diverse results from a number of researchers (among others, Hardy, Goyal, and Chiribella–D'Ariano–Perinotti—quoting just the ones I happen to be most familiar with). Among these developments, one particular instance that never ceases to amaze me is Rob Spekkens's "toy theory," which reproduces qualitative analogues of scores of quantum effects (excepting computational speedup, Bell-inequality violation, and Kochen–Specker theorems), based purely on a notion of an epistemic limitation on the description of system states. These and similar results carry with them insights into what the truly crucial difference might be between classical and quantum theories, and decisive progress along these lines would be a truly splendid thing.

Some of the other questions I would be most intrigued to see resolved are those surrounding the relation between standard quantum field theory and the axiomatic approach of algebraic quantum field theory, but I am not sure I am competent enough to comment in detail.

Finally, if I may mention a particular interest of mine, I believe that the relation between quantum mechanics and the direction of time needs to be explored further and may yet have surprises in store. Part of this interest, of course, stems from my period at Huw Price's Centre for Time in Sydney, but part is rooted in my interest in decoherence, and is related to ideas I am exploring jointly with Max!

Časlav Brukner · Quantum theory makes the most accurate empirical predictions. Yet it lacks simple, comprehensible physical principles from which it could be uniquely derived. Without such principles, we can have no serious understanding of quantum theory and cannot hope to offer an honest answer—one that's different from a mere "The world just happens to be that way"—to students' penetrating questions of why there is indeterminism in quantum physics, or of where Schrödinger's equation comes from. The standard textbook axioms for the quantum formalism are of a highly abstract nature, involving terms such as "rays in Hilbert space" and "self-adjoint operators." And a vast majority of alternative approaches that attempt to find a set of physical principles behind quantum theory either fall short of uniquely deriving quantum theory from these principles, or are based on abstract mathematical assumptions that themselves call for a more conclusive physical motivation.

One strategy for progress on this front is to view quantum theory within the context of general theories that conform to reasonable axioms about probabilities, and then to contrast the alternatives. Surprisingly, in the last decade it was found that what one might have expected to be uniquely quantum features—such as probabilistic predictions for individual outcomes (indeterminism), the impossibility of copying unknown states (no cloning), or the violation of "local realism"—are actually highly generic for general probabilistic theories. So, is there any reason why we see phenomena obeying the laws of quantum theory rather than of any other possible probabilistic theory?

Most recently, there have been several approaches to reconstructing quantum theory on the basis of a small set of reasonable physical axioms that demarcate phenomena that are exclusively quantum from those that are common to more general probabilistic theories (see my answer to Question 3, page 66, for my own reconstruction attempt). Typically, however, the proposed axioms partially use abstract mathematical language. One should, in my opinion, insist on reducing this language as far as possible to a phenomenological meaning, and not be afraid to combine these simple elements of everybody's experience with abstract concepts such as "information" or "knowledge."

Modern reconstructions of quantum theory partially meet this demand by being entirely developed in terms of primitive laboratory operations, such as preparations, transformations, and measurements. Bohr's insistence on the usage of classical terms is respected insofar as these operations are classically describable, but they are not linked to the concepts of time, position, momentum, or energy of "traditional" physics. As a result, one derives a finite-dimensional, or countably infinite-dimensional, Hilbert space as an operationally testable, abstract formalism concerned with predictions of future experiments and frequency counts, which are ultimately based on clicks of detectors and nothing more. While I consider the quantum state to be a tool for calculating the probabilities of whatever future measurements we may choose to carry out, I want to make the point that we do appoint physical labels to the states in any particular orthonormal basis, and that we do deal with notions of position, momentum, fields, specific forms of Hamiltonians, and so forth. The abstract quantum formalism, however, tells us nothing about how we should go about building a useful instrument for measuring, say, position, as opposed to any other observable.

In my opinion, the clue for this will not be obtained without an understanding of the concept of distance—or of the more abstract idea of nearness—of points lying in ordinary real space. In the abstract quantum formalism, any two different eigenvalues of the position observable correspond to orthogonal quantum states, without any concept of closeness or distance. The terms "close" and "distant" make sense only in a *classical* context, where those eigenvalues are treated as close when they correspond to neighboring outcomes in real space. Is it possible to arrive at notions of nearness, distance, and space—and, furthermore, at the theories referring to these notions, such as the theory of relativity, quantum field theory, and elementary-particle theory—merely on the basis of clicks in detectors? Or is it necessary to presuppose these notions, prior to the construction of physical theories? To me, this is one of the most pressing contemporary questions in the foundations of quantum mechanics.

Preferred tensor factorizations, coarse-grained observables, and symmetries might help to indeed demonstrate that all known basic theories of physics are a consequence of abstract quantum theory. The most elementary system, or qubit, lives in an abstract state space with $SU(2)$ symmetry, which is locally isomorphic to the group $SO(3)$ of rotations in three-dimensional space. Thinking about directional degrees of freedom—i.e., about spin—this symmetry finds its operational justification in the symmetry of the configuration of macroscopic instruments by which the spin state is prepared and measured. But from where have the macroscopic instruments acquired this symmetry in the first place?

I would like to suggest that under the everyday conditions of coarse-grained measurements, the systems consisting of a large number of elementary systems, such as macroscopic instruments, acquire the symmetry of their elementary constituents. For example, in 2007 Johannes Kofler and I derived the following result. Suppose we mimic restricted measurement precision by bunching together eigenvalues of spin projections into slots. Then the spin coherence states—which are states of many identical elementary spins—acquire an effective description as a classical spin embedded in ordinary three-dimensional space. The orientation of this classical spin requires two angles to be defined, which gives rise, through the relative angle, to the notion of "neighboring" orientations. Thus, the reason for three-dimensional real space being *the* space of the inferred world is offered through a circular but *consistent* movement in the reconstruction, in which it is legitimate to recover the elements with which one started the reconstruction. Von Weizsäcker coined the name *Kreisgang* ("circle walk") for such movements. The epistemological framework of classical physics and three-dimensional ordinary space are required at the "beginning" of the *Kreisgang* to specify the configuration of macroscopic instruments by which the quantum state is prepared and measured. The *Kreisgang* is "closed" by showing that under the everyday conditions of coarse-grained measurements, a description of macroscopic instruments emerges in the terminology of classical physics, and three-dimensional ordinary space emerges from within quantum theory. I conclude by remarking that this program is not completed—and perhaps not completable.

JEFFREY BUB · We don't really understand the notion of a quantum state, in particular an entangled quantum state, and the peculiar role of measurement in taking the description of events from the quantum level, where you have interference and entanglement, to an effectively classical level where you don't. In a 1935 article responding to the EPR argument, Schrödinger characterized entanglement as "*the* characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought." I would say that understanding the nonlocality associated with entangled quantum states, and understanding measurement, in a deep sense, are still the most pressing problems in the foundations of quantum mechanics today.

Having said that, I don't think we are going to get anywhere by sitting back and reflecting on the meaning of measurement or the notion of state in physics, or in trying to "solve the measurement problem." It's not that we don't know how to solve the measurement problem: Bohm's theory is a solution, so-called modal interpretations provide formal solutions, the Everett interpretation is another solution, the Ghirardi–Rimini–Weber theory is a rival theory that avoids the measurement problem. It's rather that there's nothing like a general consensus that any of these proposals are getting it right. Einstein commented in a letter to Max Born that Bohm's theory "seems too cheap to me." He was referring to the deterministic character of Bohm's theory. My feeling is that all these ways of thinking about quantum mechanics are "too cheap," because they all attempt to explain away the irreducible indeterminism of quantum mechanics—rather than providing a conceptual framework for thinking about a universe in which, to put it somewhat anthropomorphically, a particle is free to choose its own response to a measurement, subject only to probabilistic constraints, which might be nonlocal.

I think the way forward is to consider the sort of question raised by Wheeler: why the quantum? Or, the more focused question posed by Popescu and Rohrlich in their 1994 article, in which they introduced the notion of a nonlocal box: why is quantum theory not more nonlocal, given that you can have more nonlocality without thereby allowing the possibility of instantaneous signaling between the parties? This question has been extraordinarily fruitful in leading to new insights about quantum nonlocality and seems to me the most promising route to advancing our understanding of what is really involved in the transition from classical to quantum physics.

ARTHUR FINE · My general attitude toward science is pluralistic, in the sense that I regard every major theory in science as open to reasonable interpretations that differ from one another over some essentials. This is certainly true in the case of quantum theory, where interpretations differ over collapse and the need for an external observer, over determinism and indeterminism, over whether Lorentz invariance is merely phenomenological, over realism and instrumentalism, and so on. Faced with this array, one might experience a pressing need to sort things out so as to narrow the options, hopefully, to the one "correct" interpretation. I do not share that attitude. Rather, I see the interpretive array as part of a healthy freedom of choice whose payoff comes from the different heuristic paths suggested by the differing interpretations. So I don't think that finding the "right" interpretation of quantum mechanics is a pressing problem at all.

Still, there are problems that we would all like to understand better. One is the whole question of locality. Reflections that stem from the Bell theorem have suggested that quantum phenomena exemplify nonlocality: acting here can immediately influence happenings way over there. I have never seen an argument for this conclusion that does not involve assumptions that go well beyond reliable theory and data. Indeed, several generations now of excellent experimental investigations have not yet produced a conclusive verdict concerning the violation of the Bell inequalities themselves. The problem remains as to whether one can satisfy efficiency requirements (both on detection and on synchronization of coincidence) and, in the same experiment, manage to rule out communication between the two (or more) wings where the measurements are made. Although there are plans for experiments that claim to do this, none seem to work. It may be that none can work, since modern simulation techniques suggest that statistics in violation of the Bell inequalities can be generated classically in a wide range of circumstances, including the conditions proposed in most experimental designs. Thus, entanglement may turn out to be a significant resource in quantum information theory, but not of such significance foundationally as has been supposed.

One general issue raised by the debates over locality is to understand the connection between stochastic independence (probabilities multiply) and genuine physical independence (no mutual influence). It is the latter that is at issue in "locality," but it is the former that goes proxy for it in the Bell-like calculations. We need to press harder and deeper in our analysis here.

CHRISTOPHER FUCHS · John Wheeler would ask, "Why the quantum?" To him, that was the single most pressing question in all of physics. You can guess that with the high regard I have for him, it would be the most pressing question for me as well. And it is. But it's not a case of hero worship; it's a case of it just being the right question. The quantum stands up and says, "I am different!" If you really want to get to the depths of physics, then that's the place to look.

Where I see almost all the other interpretive efforts for quantum theory at an impasse is that despite all the posturing and grimacing over the "measurement problem" and the "mysteries of nonlocality" and what have you, none of them ask in any serious way, "Why do we have this theory in the first place?" They see the task as one of patching a leaking boat, not one of seeking the principle that has kept the boat floating this long (for at least this well). My guess is that if we can understand what has kept the theory afloat, we'll understand that it was never leaky to begin with. The only source of leaks was the strategy of trying to tack a preconception onto the theory that shouldn't have been there.

What is this preconception? It almost feels like cheating to say anything about it before Question 4 . . . but I have to, or I can't answer the rest of Question 2! The preconception is that a quantum state is a *real thing*—that there were quantum states before there were observers; that quantum states will remain even if all observation is snuffed out by nuclear holocaust. It is that if quantum states are the currency of quantum theory, the world had better have some in the bank. Take the Everett interpretation(s)—the world as a whole has its wave function, darned be it if observership or probability is never actually reconstructed within the theory. The Bohmian interpretation(s)? The wave function is the particle's guiding field; observers never mentioned at all. GRW interpretation(s)? Collapse is what happens when wave functions get too big; of course they're real. Zurek's "let quantum be quantum"? It is, as far as I can tell, a view that starts and ends with the wave function. There is no possibility that two observers might have two distinct (contradicting) wave functions for a system, for the observers are already *in* a big, giant wave function themselves.

So when I say "Why the quantum?" is the most pressing question, I mean this specifically within an interpretive background in which quantum states aren't real in the first place. I mean it within a background where quantum states represent observers' *personal* information, expectations, degrees of belief.

"But that's *just* instrumentalism," the philosopher of science says snidely (see my answer to Question 14, page 253). "You give up the game before you start." Believe me, you've got to stand your ground with these guys when their label guns fly from their holsters! I say this because if one asks "Why the quantum?" in this context, it can only mean that one is being *realist* about the *reasons* for one's instrumentalities. In other words, even if quantum theory is purely a theory for apportioning and structuring degrees of belief, the question of "Why the quantum?" is nonetheless a question of what it is about the actual, real, objective character of the world that compels us to use this framework for reasoning rather than another. We observers are floating in the world, making decisions on all that we experience around us: why are we well-advised to use the formalism of quantum theory for that purpose and not some other formalism? Surely it connotes something about the general character of the world—something that is contingent, something that might have been otherwise, something that goes deeper than our decision-making itself.

With this one gets at the real flavor of this *most pressing problem in the foundations of quantum mechanics* from the point of view of QBism. It takes on two stages. The first is to find a crisp, convincing way to pose quantum theory in such a way that it gets rid of these trouble-making quantum states in the first place. What I mean by this is, if quantum theory is actually about how to structure one's degrees of belief, it should become conceptually the clearest when written in its own native terms. To give an example of how this might go, consider the Born probability rule as it is usually represented: one starts with a quantum state $\hat{\rho}$, say for some d-level system, and some orthogonal set of projection operators $\hat{D}_j$ representing the outcomes of some nondegenerate observable. The rule is that the classical value D_j registered by the measuring device (no hat this time) will occur with probability

$$p\left(D_j\right) = \mathrm{tr}\left(\hat{\rho}\hat{D}_j\right).$$

A recent result of QBism, however, is that if a certain mathematical structure always exists in Hilbert space (we know it does for $d = 2$ to 67 already), then in place of the operator $\hat{\rho}$ one can always identify a *single* probability distribution $p\left(H_i\right)$, and in place of the operators $\hat{D}_j$ one can always identify a set of conditional probability distributions $p\left(D_j \mid H_i\right)$, such that

$$p\left(D_j\right) = (d+1)\sum_i p\left(H_i\right)p\left(D_j \mid H_i\right) - 1.$$

The similarity between this formula and the usual Bayesian sum rule (law of total probability) is uncanny. It says that the Born rule is about degrees of belief going in, and degrees of belief coming out. The use of quantum states in the usual way of stating the rule (that is, rather than degrees of belief directly) would then simply be a relic of an initial bad choice in formalism.

If this program of rewriting quantum theory becomes fully successful (working for all *d*, for instance), thereafter there should be no room for the distracting debates on the substantiality of quantum states—they're not even in the theory now—nor the tired discussions of nonlocality and the "measurement problem" the faulty preconception inevitably engendered. At this point, a second stage of the pressing question would kick in: it will be time to take a hard look at the new equations expressing quantum theory and ask how it is that *they* are mounted onto the world. What about the world compels this kind of structuring for our beliefs? To get at that is to really get at "Why the quantum?" And my guess is, when the answer is in hand, physics will be ready to explore worlds the faulty preconception of quantum states couldn't dream of.

GianCarlo Ghirardi · I believe that the most pressing problems are still those that have been debated for more than eighty years by some of the brightest scientists and deepest thinkers of the past century: Niels Bohr, Werner Heisenberg, John von Neumann, Albert Einstein, Erwin Schrödinger, John Bell. To characterize these problems in a nutshell, I cannot do better than stressing the totally unsatisfactory conceptual status of our best theory by reporting the famous sentence by Bell: "Nobody knows what quantum mechanics says exactly about any situation, for nobody knows where the boundary really is between wavy quantum systems and the world of particular events."

I also share Bell's opinion that the fact that this wonderful and extremely successful theory is radically incapable of accounting for our definite perceptions does not matter in practice, at least not presently. But I cannot accept that the basic theoretical construction for our understanding of natural phenomena is internally inconsistent, and that it is not able to account for the way it postulates measuring processes to take place. I will repeatedly come back to this point in my subsequent comments. But from the very beginning, I want to emphasize with great strength that science, this wonderful and unbelievable creation of the human mind, finds its real reason of existence in its ability to allow for an objective and always-growing understanding of reality. As such, an internally inconsistent theoretical scheme—one that becomes acceptable only by resorting to vague, not well-defined, imprecise, and fundamentally contradictory verbal assertions—cannot be taken as real progress in our grasping *God's thoughts*.

In this spirit, and given that theoretical schemes exist that are logically consistent and predictively equivalent—or even identical—to standard quantum mechanics (here I have in mind particularly the spontaneous-collapse theories and Bohmian mechanics), I am naturally led to share another position of Bell's, which he expressed with great clarity in *Against Measurement* and in his Touschek Lectures. Namely, the great problem now is which one of the existing "exact" theories admits a fully satisfactory relativistic generalization. Here it is useful to recall that Bell used the term "exact" to denote a theory that "neither needs nor is embarrassed by an observer."

Shelly Goldstein · If I were to take this question to be concerned only with the most pressing problems in the foundations of quantum mechanics *today*, then I suppose I would point to the tension between quantum nonlocality and relativity. Relativity is widely regarded both as a fundamental physical principle and as being incompatible with any sort of genuine action-at-a-distance. Quantum nonlocality is arguably (correctly, I believe) an experimentally verified consequence of quantum mechanics that would clearly seem to involve genuine action-at-a-distance. Does relativity then have to be abandoned, or can it be reconciled with quantum nonlocality, appearances to the contrary notwithstanding?

I think it would be better, however, to respond to the following question: what *have been* the most pressing problems in the foundations of quantum mechanics? And to this I suppose the standard answer is the measurement problem, or, more or less equivalently, Schrödinger's cat paradox.

The problem here is that the usual description of the state of a system in a quantum-mechanical universe is of a rather unusual sort. It is given by a rather abstract mathematical object, called the wave function or the quantum state vector (or maybe the density matrix) of the system, an object whose physical meaning is rather obscure in traditional presentations of quantum theory. Moreover, in these presentations we are usually rather emphatically discouraged from supplementing our description of a quantum system with further—possibly more familiar but maybe exotic and elusive—variables, or even from contemplating such a possibility.

If one accepts, however, that the usual quantum-mechanical description of the state of a quantum system is indeed the complete description of that system, it seems hard to avoid the conclusion that quantum measurements typically fail to have results: pointers on measurement devices typically fail to point, computer printouts typically fail to have anything definite written on them, and so on. More generally, macroscopic states of affairs tend to be grotesquely indefinite, with cats seemingly both dead and alive at the same time, and the like. This is not good!

These difficulties can be avoided by invoking the measurement axioms of quantum theory, in particular the collapse postulate. According to this postulate, the usual quantum-mechanical dynamics of the state vector of a system (given by Schrödinger's equation)—the fundamental dynamical equation of quantum theory—is abrogated whenever measurements are performed. The deterministic Schrödinger evolution of the state vector is then replaced by a random collapse to a state vector that can be regarded as corresponding to a definite macroscopic state of affairs: to a pointer pointing in a definite direction, to a cat that is definitely dead or definitely alive, and so on.

But doing so comes at a price: one then has to accept that quantum theory involves special rules for what happens during measurement, rules that are in addition to, and not derivable from, the quantum rules governing all other situations. One has to accept that the notions of measurement and observation play a fundamental role in the very formulation of quantum theory, in sharp conflict with the much more plausible view that what happens during measurement and observation in a quantum universe, like everything else that happens in such a universe, is a consequence of the laws governing the behavior of the constituents of that universe—say the elementary particles and fields. These laws apply directly to the microscopic level of description, and they say nothing directly about measurement and observation, notions that arise and make sense on an entirely different level of description, the macroscopic level.

I believe, however, that the measurement problem, as important as it is, is nonetheless but a symptom of a more basic difficulty with standard quantum mechanics: it is not at all clear what quantum theory is about. Indeed, it is not at all clear what quantum theory actually says. Is quantum mechanics fundamentally about measurement and observation? Is it about the behavior of macroscopic variables? Or is it about our mental states? Is it about the behavior of wave functions? Or is it about the behavior of suitable fundamental microscopic entities, elementary particles and/or fields? Quantum mechanics provides us with formulas for lots of probabilities. What are these the probabilities of? Of results of measurements? Or are they the probabilities for certain unknown details about the state of a system, details that exist and are meaningful prior to measurement?

It is often said that such questions are the concern of the foundations of quantum mechanics, or of the interpretation of quantum mechanics—but not, somehow, of quantum mechanics itself, of quantum mechanics simpliciter. I think this is wrong. I think these, and similar, questions are a reflection of the fact that quantum mechanics, in the words of John Bell, is "unprofessionally vague and ambiguous."

What is usually regarded as a fundamental problem in the *foundations* of quantum mechanics, a problem often described as that of *interpreting* quantum mechanics, is, I believe, better described as the problem of finding a sufficiently precise *formulation* of quantum mechanics: a *version* of quantum mechanics that, while expressed in precise mathematical terms, is also clear as physics.

And it is hard for me to imagine how this can be achieved, in any fundamental physical theory, unless that theory involves, as part of its description of the state of a system, an explicit space-time ontology (for a relativistic version, and a spatial ontology whose state changes with time for the nonrelativistic version). This ontology might be a particle ontology, involving world lines in space-time, or a field ontology, involving a field on space-time, or perhaps both, or perhaps neither but something else. In any case, the space-time ontology amounts to a certain kind of decoration of space-time, to the specification of what Bell has called the local beables of the theory.

Theories involving different local beables, or involving the same local beables but different laws for the local beables, would be different theories—for example, different *versions* rather than merely different *interpretations* of quantum theory.

Daniel Greenberger · For reasons I'll explain in my answer to Question 7 (see page 152), I don't think the measurement problem will be solvable soon, or possibly ever. We will probably have to know more about nature for that. But there are other questions that are intriguing, such as whether a single particle has a wave function, or whether we have to talk about ensembles, and whether the wave function represents solidly observable probabilities, or just subjective information that we have about the system.

I myself have been worrying along different lines. I don't think we treat mass properly in quantum theory. It enters as a parameter, while energy enters as an operator. If $E = mc^2$, then I don't think that's consistent, and there is much evidence for that. In the same vein, the concept of proper time is much more subtle in quantum theory than it is in classical physics. For example, if you send a particle wave packet through a beam splitter, each part has its own proper time. If the two parts then get accelerated differently, their proper times run at different rates. If now the two parts get recombined, say at another beam splitter, what exactly is the proper time of the recombined particle? This is a practical question because the particle can be unstable, and its decay time will be controlled by the proper time that has elapsed. Surely the two parts cannot remember their separate histories. That would violate the essence of how quantum theory works.

Connected to this problem is the serious disconnect between quantum theory and general relativity. Quantum theory works with position and momentum, which intrinsically brings in the mass of the particle, while relativity works with particle trajectories, position and velocity, purely geometrical concepts, and independent of the mass. As a consequence, the weak equivalence principle breaks down in quantum mechanics. I think that these problems are the essence of why we don't have a theory of quantum gravity. It goes way beyond the mathematical complications of a nonlinear theory. I think we don't understand gravity at the simple physical level of the equivalence principle. We don't know nearly enough to even begin to make a theory of quantum gravity. (If someone succeeded in making such a theory mathematically, which certainly could happen, I think it would be a serious step backward—everyone would believe it, and it would probably win a Nobel prize. Nobody could test it, and in my opinion, it would be almost guaranteed to be wrong, since it would be based on ideas that do not fit together on the simplest level.) I'll have more to say about this in my answer to Question 15 (see page 265).

LUCIEN HARDY · The most well-known problem in quantum foundations is the measurement problem—our basic conception of reality depends on how we resolve this. I will address this problem in my answer to Question 7 (see page 153). The measurement problem is tremendously important. But there is another problem that is even more important—and that may well lead to the solution of the measurement problem. This is to find a theory of quantum gravity. The problem of quantum gravity is easy to state: find a theory that reduces to quantum theory and to general relativity in appropriate limits. It is not so easy to solve. The two main approaches are string theory and loop quantum gravity. Both are deeply conservative, in the sense that they assume it will be possible to formulate a theory of quantum gravity within the quantum formalism as it stands. I do not believe this is the right approach. Quantum theory and general relativity are each deeply conservative, and deeply radical, but in complementary respects. Quantum theory is conservative in that it works on a fixed space-time background, but it is radical in that probabilities play an indispensable role. General relativity is conservative in that it is deterministic (probabilities are not necessary), but it is radical in that the space-time background is not fixed but rather depends on the distribution of matter. In my opinion, a theory of quantum gravity will have to take the radical road in each case. It will be probabilistic, and it will have nonfixed causal structure. In fact, we can expect it to be a bit more radical still. It will, most likely, have indefinite causal structure. The reason for this is that in quantum theory, when we have a physical quantity that can vary, we will typically have situations where there is fundamental indefiniteness as to the value of the quantity. Since causal structure is dynamical in general relativity, we therefore expect it to be subject to fundamental indefiniteness in quantum gravity. This means that it will sometimes be the case that there is no matter of fact as to whether a given interval is spacelike or timelike. The basic mathematical apparatus of quantum theory needs a fixed space-time background (at least it requires a background time with respect to which the state evolves), and the basic mathematical apparatus of general relativity is deterministic. Neither framework is likely to be capable of accommodating a theory of quantum gravity, since neither possesses the radical feature of the other, and neither has indefinite causal structure. Hence, we require a deeper framework with new conceptual and mathematical apparatuses.

It is instructive to look at the transition from Newton's theory of gravitation to Einstein's theory of general relativity. We can take a limit to get from Einstein's theory back to Newton's theory. The mathematical apparatus of general relativity, however, is very different from that of Newton's theory. Newtonian gravity suffers from a deep conceptual problem: the force of gravity is not local. In general relativity, locality is restored, because the gravitational force is propagated locally through the space-time continuum (through matter-induced curvature of this very continuum). Even though Newton's theory turned out not to be fundamental, it is interesting to ask what the best interpretation of it is. One reasonable answer is that it should be regarded as a theory of curved space rather than of curved space-time. Such an interpretation of Newton's theory (as formalized by Cartan) only became evident after Einstein had formulated his theory of general relativity in terms of the curvature of space-time. This point, which is due to Wayne Myrvold, raises the possibility that we will best understand quantum theory—which suffers from its own deep conceptual problems—in retrospect as a limiting case of a deeper theory, such as a theory of quantum gravity. If this is true, then we need to work on quantum gravity to have a hope of properly solving the measurement problem.

The problem of quantum gravity requires, in my opinion, the development of a new mathematical framework. This could be as radical a departure from the frameworks of quantum theory (Hilbert spaces) and general relativity (tensor calculus) as the tensor calculus for general relativity is from the mathematics of Newtonian mechanics. The problem of quantum gravity is, I believe, a foundational problem, and the tools and methods of foundational thinking need to be brought to bear on it.

Anthony Leggett · To my mind, within the boundaries of "foundations of quantum mechanics" strictly defined, there is really only one overarching problem: is quantum mechanics the whole truth about the physical world? That is, will the textbook application of the formalism—including the use of the measurement axiom, possibly at a very late stage—continue to describe experimental results adequately for the indefinite future? If the answer should turn out to be no, then, of course, there would be any number of further questions to be raised, but they would no longer be about quantum mechanics. If the answer is yes, then I believe there is really not much left to be asked (see also my answer to Question 3, page 79).

I think that there is, however, one question that—while in some sense more general than being about quantum mechanics as such—may be relevant to our future perceptions of the meaning of the formalism. This is the issue of the basis and status of the conventional viewpoint on the arrow of time. To be more specific, if it were to become accepted in a more general context that this arrow could, as it were, reverse itself locally and temporarily—as has in effect been suggested by a number of thinkers—then I believe this might recolor our thinking about the measurement problem and about other aspects of the formalism.

TIM MAUDLIN · The most pressing problem today is the same as ever it was: to clearly articulate the exact physical content of all proposed "interpretations" of the quantum formalism. This is commonly called the measurement problem, although, as Philip Pearle has rightly noted, it is rather a "reality problem." Physics should aspire to tell us what exists (John Bell's "beables"), and the laws that govern the behavior of what exists. "Observations," "measurements," "macroscopic objects," and "Alice" and "Bob" are all somehow constituted of beables, and the physical characteristics of all things should be determined by that constitution and the fundamental laws.

What are commonly called different "interpretations" of quantum theory are really different theories—or sometimes, no clear theory at all. Accounts that differ in the beables they postulate are different physical theories of the universe, and accounts that are vague or noncommittal about their beables are not precise physical theories at all. Until one understands exactly what is being proposed as the physical structure of the universe, no other foundational problem, however intriguing, can even be raised in a sharp way.

DAVID MERMIN · Here are three.

One: In the words of Chris Fuchs, "quantum states: what the hell are they?" Quantum states are not objective properties of the systems they describe, as mass is an objective property of a stone. Given a single stone, about which you know nothing, you can determine its mass to a high precision. Given a single photon, in a pure polarization state about which you know nothing, you can learn very little about what that polarization was. (I say "was," and not "is," because the effort to learn the polarization generally results in a new state, but that is not the point here.)

But I also find it implausible that (pure) quantum states are nothing more than provisional guesses for what is likely to happen when the system is appropriately probed. Surely they are constrained by known features of the past history of the system to which the state has been assigned, though I grant there is room for maneuver in deciding what it means to "know" a "feature."

Consistent historians (see also my answer to Question 16, page 279) maintain that the quantum state of a system *is* a real property of that system, though its reality is with respect to an appropriate "framework" of projectors that includes the projector on that state. Since the reality of most other physical properties is also only with respect to suitable frameworks, for consistent historians the quantum state of a system is on a similar conceptual footing to most of its other physical properties. Quantum cosmologists maintain that the entire universe has an objective pure quantum state. I do not share this view. Indeed, I do not believe it has a quantum state in any sense, since there is nothing (nobody) outside the entire universe to make that state assignment. Well, I suppose it could be God, but why would he want to make state assignments? Einstein has assured us that he doesn't place bets. (See also my answer to Question 4, page 102.)

Two: How clearly and convincingly to exorcise nonlocality from the foundations of physics in spite of the violations of Bell inequalities. Nonlocality has been egregiously oversold. On the other hand, those who briskly dismiss it as a naive error are evading a direct confrontation with one of the central peculiarities of quantum physics. I would put the issue like this: what can one legitimately require of an *explanation* of correlations between the outcomes of independently selected tests performed on systems that no longer interact? (See also my answer to Question 8, page 176.)

Three: Is the experience of personal consciousness beyond the reach of physical theory as a matter of principle? Is the scope of physics limited to constructing "relations between the manifold aspects of our experience," as Bohr maintained? While I believe that the answer to both question is yes, I list them as problems, because most physicists vehemently reject such views, and I am unable to explain to them why they are wrong in a way that satisfies me, let alone them.

I regard this last issue as a problem in the interpretation of quantum mechanics, even though I do not believe that consciousness (as a physical phenomenon) collapses (as a physical process) the wave packet (as an objective physical entity). But because I do believe that physics is a tool to help us find powerful and concise expressions of correlations among features of our experience, it makes no sense to apply quantum mechanics (or any other form of physics) to our very awareness of that experience. Adherents of the many-worlds interpretation make this mistake. So do those who believe that conscious awareness can ultimately be reduced to physics, unless they believe that the reduction will be to a novel form of physics that transcends our current understanding, in which case, as Rudolf Peierls remarked, whether such an explanation should count as "physical" is just a matter of terminology.

I am also intrigued by the view of Schrödinger (in *Nature and the Greeks*) that it was a mistake dating back to the birth of science to exclude us, the perceiving subjects, from our understanding of the external world. This does not mean that our perceptions must be parts of the world external to us, but that those perceptions underlie everything we can know about that world. (See also my answer to Question 14, page 256.) Until the arrival of quantum mechanics, physics made good sense in spite of this historic exclusion. Quantum mechanics has (or should have) forced us to rethink the importance of the relation between subject and object.

Lee Smolin · The measurement problem—that is to say, the fact that there are two evolution processes, and which one applies depends on whether a measurement is being made. Related to this is the fact that quantum mechanics does not give us a description of what happens in an individual experiment.

To put it differently, the only interpretations of quantum mechanics that make sense to me are those that treat quantum mechanics as a theory of the information that observers in one subsystem of the universe can have about another subsystem. This makes it seem likely that quantum mechanics is an approximation of another theory, which might apply to the whole universe and not just to subsystems of it. The most pressing problem is then to discover this deeper theory and level of description.

Antony Valentini · The interpretation of quantum mechanics is a wide open question, so we can't say in advance what the most pressing problems are. As the history of physics shows, it's only in hindsight that one can say who was looking in the right direction. What's important is that we leave the smoke screen of the Copenhagen interpretation well behind us, and that talented and knowledgeable people think hard about this subject from a realist perspective.

Instead of answering the question, I can offer a list of things I'd like to see done in the near future, as they seem important as far as I can tell.

It would be good if the ongoing controversy over the consistency of the Everett interpretation could be settled. It would be helpful to know if that theory really makes sense (on its own terms) or not. It would also be good to see further experiments searching for wave-function collapse. More generally, I'd like to see more experiments that test quantum theory in genuinely new domains—as in the recent three-slit experiment.

In modern theoretical physics, there are a number of important issues that deserve more attention from a foundations perspective, such as the question of Hawking information loss in black holes, and the problem of time in quantum gravity. The description of the quantum-to-classical transition in the early universe also deserves more foundational scrutiny.

As for my own current line of research—which focuses on the possibility of nonequilibrium violations of quantum theory, in de Broglie–Bohm theory and in deterministic hidden-variables theories generally—there are some outstanding issues that need a lot more work. One is the need for more detailed calculations and numerical simulations of relaxation to quantum equilibrium in the early universe, with the aim of obtaining precise predictions of where residual nonequilibrium violations of quantum theory might be found today—for example, in the cosmic microwave background or in relic cosmological particles. My work so far points in the direction of super-Hubble wavelengths as the area to look at, but much more remains to be done. I have also made some proposals to the effect that Hawking radiation could consist of nonequilibrium particles that violate the Born rule in a way that might avoid information loss, and there are a host of theoretical questions to be investigated to develop that proposal further.

Finally, there is the important general question of whether it's possible to construct a reasonable hidden-variables theory without an ontological wave function.

De Broglie–Bohm theory has several features that have been shown to be common to all hidden-variables theories (under some reasonable assumptions): nonlocality, contextuality, and nonequilibrium superluminal signaling. De Broglie–Bohm theory also has the feature of an ontological wave function, and it would be good to know if this is another common feature of hidden-variables theories or not. Alberto Montina has worked on this recently, but more needs to be done.

DAVID WALLACE · I think anyone's answer to this is going to depend above all on what they think of the quantum measurement problem. After all, the measurement problem threatens to make quantum mechanics incoherent as a scientific theory—to reduce it, at best, to a collection of algorithms to predict measurement results. So the only reason anyone could have not to put the measurement problem right at the top of the list would be if they think it's solvable within ordinary quantum mechanics. (Someone who thinks it's solvable in some modified version of quantum mechanics—in a dynamical-collapse or hidden-variables theory, say—ought to think that the most pressing problem is generalizing that modified version to account for all of quantum phenomena, including the phenomena of relativistic field theory.)

As it happens, though, I *do* think the measurement problem is solvable within ordinary quantum mechanics: I think the Everett ("many worlds") interpretation solves it in a fully satisfactory way, and while I think there are some philosophical puzzles thrown up by that solution—mostly concerned with probability and with emergence—that would benefit from more thought, I wouldn't call them *pressing*. Not from the point of view of physics, at any rate.

So from my point of view, the "most pressing problems" aren't going to be ultra-broad problems like, "What does quantum mechanics as a whole mean?" They're going to be a bit more detailed, a bit more concerned with particular puzzling features of the conceptual and mathematical structure of quantum mechanics. (The advantage of the Everett interpretation—the main *scientific* benefit it's brought, I'd say—is that it allows us to ask those questions without getting tangled up in worries about whether there are hidden variables or dynamical collapses or whatever not included in our equations, and without all sorts of doubletalk about "experimental contexts" and "the role of observers" and "subjective quantum states" and so on.)

All that said, here's the problem that leaps out for me. Just how are we to understand the apparently greater efficiency of quantum computers over classical ones? When I started as a physics grad student in the late 1990s, we had two really great quantum algorithms—Shor's algorithm, which factorizes large numbers, and Grover's algorithm, which finds the biggest number in a list—and both of them were dramatically more efficient than the best-known classical algorithms. Shor's algorithm in particular had had a huge impact, because the problem of factorizing large numbers *both* is one of the standard examples of a difficult computational problem, *and* is crucial in decoding a lot of codes that were and are thought to be basically undecodable by classical computers. So everyone who was working in quantum information—including me at the time—was very excited by this, and pretty much all of us thought that Shor's and Grover's algorithms were going to be the tip of the iceberg, that there were going to be dozens or hundreds of these amazing quantum algorithms. But actually, ten years and more later, and those algorithms are still pretty much all we've got. Even if you could solve the technical problems involved in making a quantum computer that would fit on your desktop, at the moment there's not much you could do with it that you can't do with your existing classical desktop.

Now that's embarrassing for people writing grant applications. But it's also bizarre from a foundational point of view. It's one thing to discover that quantum mechanics has a completely different computer-complexity theory from classical mechanics. It's quite another to discover that it's almost identical but *not quite*. My hunch is that we're missing something pretty profound here.

The second problem I'd identify is a bit easier to attack, and indeed we've got quite a long way with it already, but there's further to go. It's fairly clear now that the really big mysteries in quantum theory come not so much from superposition as from entanglement (after all, classical electromagnetism admits superpositions). But getting a detailed quantitative grasp of what's going on in multipartite entanglement is really hard. We've got a variety of tools, and a variety of results, but it feels as if we still haven't found the right way of thinking about it, or maybe the right mathematical framework to use, such that it all becomes less opaque and less mysterious. (I think the very graphical "language" that Bob Coecke and his coworkers are developing is really promising here, but it's early days.)

I'll mention one more thing, which might not normally be classified as "quantum foundations"—and which I guess isn't exactly "pressing," because we've been stuck with it for decades. The last twenty or thirty years have made it really clear that quantum mechanics is way, way different from classical mechanics, and that it's possible to understand why the world looks classical without having to keep classical concepts as basic. (I'm thinking, in particular, of the role of decoherence theory, and the way we've basically managed to wean ourselves of the correspondence principle.) But the way we construct quantum theories, particularly in quantum field theory, is still almost invariably to start with a classical theory and then "quantize" it. That really, really shouldn't be necessary, but it seems to be. We need to find some way of thinking about quantum fields that doesn't require this link to classical fields.

Anton Zeilinger · We have learned from quantum mechanics that naive realism is not tenable anymore. That is, it is not always possible to assume that the results of observation are always given prior to and independent of observation. To me, the most important question is to find out what exactly the limitations are. This can only be found out by carefully exploring quantum phenomena in more complex situations than we do today.

A deep reanalysis of the fundamental concepts underlying quantum mechanics is also necessary, analogous to the careful analysis of the notions of space and time by the Viennese philosopher–physicist Ernst Mach. Mach's analysis paved the way for the abandonment of the notions of absolute space and time, and for their replacement by the modern notions in special and general relativity.

WOJCIECH ZUREK · Understanding the role of information; or, to be more precise, clarifying the relation between information and existence. I think that this was always—that is to say, since about 1925—the key. It is the essence of the measurement problem.

When you read Bohr, von Neumann, Wigner, Everett, or Wheeler, it is clear that they were aware of this. Bohr may not have had information theory at hand when he was thinking about matters of interpretation, but his insistence on the communicability of the measurement outcomes in everyday language points in that direction. Von Neumann and Wigner worried about the role of the conscious observer in the process, and the precondition for (and maybe even the essence of) consciousness is information acquisition and processing. Everett has long passages on information and quantum theory in his thesis, and he even devises an information-theoretic version of Heisenberg's indeterminacy principle. Wheeler's "It from Bit" goes further, by turning tables on the usual understanding of information as representing what exists and proposing that it might be the material that reality—the "It"—is made out of.

In a sense, the interplay between information and existence—between what is known and what exists—is older than quantum theory: it was central to physics since at least Boltzmann and Maxwell. The origin of the second law and the threat posed by Maxwell's demon are a premonition of the problems that are central in quantum theory. Indeed, one may defend the thesis that the quantum discoveries of Planck and Einstein (for example, stimulated emission) that paved the way for modern quantum theory happened because thermodynamics "knew" that information plays a central role in physics. One of the best illustrations of this interdependence is the famous (classical and thermodynamic) discussion of Szilárd, who in effect deduced—years before Shannon—some of the key ideas of information theory. It also puts the observer (the demon) squarely in the center of the action. This theme of the physical significance of information persists in quantum measurements.

So, already thermodynamics made it clear that "information is physical." Newtonian mechanics, however, allowed for a separation of what *is*—what exists—from what *is known*: a point in phase space is a legal representation of the state of a classical system, and it need not be altered by the observation aimed at making its location precise.

This separation of information from states was tenable in classical physics, but it breaks down in quantum theory—it breaks down in our universe. I think that by now many people recognize how central information is to quantum physics. On a technical level, this started with Heisenberg and his indeterminacy principle. But even with all that we know now about the interplay of quantum physics and information (including Bell's theorem, the no-cloning theorem, quantum error correction, and so on), I sense that the real mystery is still barely touched.

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Elegance and Enigma
The Quantum Interviews
(Ed.)M. Schlosshauer
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EPILOGUE

Seventeen questions and close to three hundred responses later, what have we learned? Trying to draw objective conclusions would be like trying to propose a definitive interpretation of David Lynch's *Mulholland Drive*. With both the film and this interview book, everyone will take away something different. It's a freedom as deliberate as desired.

Neither do I intend to launch into a tedious question-by-question summary, nor a grand analysis complete with pie charts. Instead, let me focus on one particular observation. In my introductions to Questions 3 and 12, I talked a lot about warring interpretive factions. But perhaps that's an outdated image. I think the interviews make it overwhelmingly clear that what's happening today is more accurately described as a sharp contrast, in mindset and approach, between an interpretation-focused, realist, ontological camp on the one hand, and a reconstruction-focused, epistemic-informational camp on the other.

The people in the first camp are wedded to the idea that we ought to exorcise observers from the picture and make quantum mechanics, as Bub (page 67) puts it, "conform to some ideal of classical comprehensibility," by embedding quantum mechanics into a realist interpretive framework with an explicit ontology. The people in the second camp pursue some form of reconstructive approach infused with the spirit of quantum information, heeding Wheeler's why-the-quantum call and taking an epistemic view of the formalism.

Let me expand these characterizations a little. The interpretation-focused, realist, ontological camp roughly thinks like this. Let's take standard quantum mechanics as our starting point, because we already know that its (statistical) predictions match our observations. In particular, we won't attempt to rederive the formalism from deeper principles. But we cannot accept the standard textbook presentation of quantum mechanics: it makes quantum mechanics into a ragtag creature, studded with severe deformities and clinically deluded in its talk of "observers" and "measurements." We are appalled that hardly anyone else seems to notice or care. And so we take it upon ourselves to fashion some new clothes for quantum mechanics, such that it may better match our expectations and join the ranks of what we consider proper physical theories.

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Take the interview responses from people partial to de Broglie–Bohm and collapse approaches as an example. Many of these responses display an outspoken disdain for textbook quantum mechanics, which is denounced as "internally inconsistent" (Ghirardi, page 47) and "unprofessionally vague and ambiguous" (Goldstein, quoting Bell, page 49). The goal becomes to lift the "smokescreen of the Copenhagen interpretation" (Valentini, page 54). This entails, among other things, a firm commitment to "beables," that is, to an ontology, because "accounts that are vague or noncommittal about their beables are not precise physical theories at all" (Maudlin, page 52). So building a satisfactory quantum theory requires, first of all, the specification of a definite ontology—particles in de Broglie–Bohm, mass densities (or "flashes") in collapse theories—and the specification of its dynamics. Crucially, statements referring to observers and measurements are to be purged from the formulation of the theory, based on the reductionist argument that such structures cannot have fundamental status but must instead be understood in terms of the beables of the theory. The pre-Socratic philosopher Democritus believed that "in truth, there is nothing but atoms and the void." For a Bohmian, then, "in truth," there is nothing but particles and guiding fields. For a collapsist, "in truth," there is nothing but mass densities and their nonlinear evolution. For an Everettian, "in truth," there is nothing but the global wave function and the Schrödinger equation. Quantum theory is thus made to largely feel like a classical, materialistic theory, save for some interpretation-specific idiosyncrasies, such as the abstract, nonlocal ontology of the Everett picture.

The reconstruction-focused, epistemic-informational camp, in contrast, thinks like this. Let's start neither from the ready-made quantum formalism, nor from some kind of prejudice about a prerequisite ontology that's to be mounted onto quantum mechanics like a luggage rack on a car. Crucially, we see the prominent, fundamental role of observers and measurements in quantum theory not as a critical flaw to be remedied at all costs, but as a constructive starting point. We see it as something suggestive of fundamentally new ways of thinking about physics, about nature, about the role and status of physical theories, and about the relationship between subject and object. The fact that observers and measurements prominently appear in the axioms of quantum mechanics doesn't mean that they're to be regarded as entities *physically* different from other objects in our world, as is often suggested (usually by critics of Copenhagen-style quantum mechanics). Rather, it is the *application* of the quantum formalism that requires a split between observed and observer, because this formalism is essentially a kind of map for observers navigating the world; it is not the world itself. Our goal, then, is to pick out the features of the world that inform the structure of the formalism—the features that make quantum theory such an excellent map. On this reading, we consider it misguided to try to turn quantum theory into an all-inclusive nothing-but-atoms-and-the-void picture. It can be done, but it comes at a high price (think many worlds and Bohmian nonlocality), and, most of all, we will likely not have learned one deep thing about nature in the process.

I'll be the first to admit that this characterization of the two camps is oversimplified. The interviews in this book display all the nuances and fill in all the blanks I couldn't capture here. For example, there are reconstructionists who emphasize the importance of giving an ontological account, or who lean toward an ontological concept of information. There are also people who embrace epistemic or informational attitudes toward the quantum formalism but stay clear of the business of reconstruction.

Be that as it may, I think an overall dichotomy is evident from the interview responses, and it makes for a recurring, overarching theme in this book. It's a dichotomy that's not altogether new, but one that has definitely become increasingly pronounced as ever more people approach foundational questions through reconstructions and information theory. The interview responses also make clear that we're witnessing not just a superficial methodological difference, but a separation that runs much deeper—all the way down to fundamentally distinct attitudes toward theory building, toward what a physical theory is, can be, and should strive to be. The puzzles of quantum mechanics, it seems, spur people into two diametrically opposed forms of action. That's not to imply a profound incompatibility or antagonism between the two camps. They each have their merits and shortcomings, and perhaps they are best regarded as complementary, as Bacciagaluppi suggests (page 202). Yet these approaches and their proponents still correlate to radically different temperaments.

If this book has shown one thing, then it is that the field of quantum foundations is humming with more activity than ever. The subject has clearly outgrown its popular image as some sort of idle philosophical exercise without cash return, as feel-good poetry not befitting a scientifically-minded person eager for clear answers. From technical results to experiments, quantum foundations has come of age.

Are we today any closer to answering the grand questions? Or are we simply caught in a web of more opinions, approaches, and infinitesimal increments of understanding? I think what can be said with reasonable confidence—something that I've already hinted at in the prologue and that the interviews in this book have hopefully amply demonstrated—is that we have acquired a more nuanced grasp of those grand questions than a contemporary of, say, Bohr or Einstein had. We have also assembled a larger, and continuously expanding, toolbox for tackling these questions. At the same time, at the deeper level, we may still feel stuck in a morass of the kind that had already stopped the founding fathers of quantum mechanics in their tracks. This may be frustrating, but it is also an enduring testament to the theory's depth and enigmatic beauty.

GLOSSARY

This glossary lists some of the key terms appearing in this book. A much more detailed discussion of many of these terms can be found in the *Compendium of Quantum Physics: Concepts, Experiments, History and Philosophy*, edited by Daniel Greenberger, Klaus Hentschel, and Friedel Weinert (Springer, 2009). The *Stanford Encyclopedia of Philosophy*, online at http://plato.stanford.edu, is also an authoritative source of information. It has comprehensive entries—some written by our interviewees—on staples such as EPR, the Bell and Kochen–Specker theorems, the measurement problem, entanglement, quantum information, decoherence, quantum logic, and the common interpretations (Copenhagen, Everett, collapse theories, Bohmian mechanics, and modal and relational interpretations).

beable A term coined by John Bell for the observer-independent ontological entity that, in Bell's view, a physical theory ought to make reference to. Bell intended the term and concept of beables as a counterbalance to the prevalent notion of a primacy of observables and observation in quantum theory:

> In particular, we will exclude the notion of "observable" in favour of that of "*be*able." The beables of the theory are those elements which might correspond to elements of reality, to things which exist. Their existence does not depend on "observation." Indeed observation and observers must be made out of beables.

Beables are a hobbyhorse of adherents of Bohmian mechanics and, to a lesser extent, collapse theories—theories that had enjoyed Bell's personal endorsement.

Bell–Kochen–Specker theorem See KOCHEN–SPECKER THEOREM.

Bell's inequalities First derived by John Bell in the 1960s, these mathematical expressions show that no local hidden-variables theory—as defined by Bell in terms of a set of locality assumptions—can fully reproduce the predictions of quantum theory (Bell's theorem). A Bell inequality involves combinations of expectation values for measurements on a bipartite system prepared in an entangled quantum state. If the probability functions used to calculate these expectation values are assumed to obey certain locality conditions, then the expression will be bounded from above. If, however, the expectation values are computed using the usual rules of quantum mechanics, the bound can be violated. Experiments have so far ruled in favor of quantum mechanics, though loopholes remain. See Question 8, *Bell's Inequalities*, for more.

Bell's theorem See BELL'S INEQUALITIES.

Bohmian mechanics A hidden-variables interpretation of quantum mechanics, developed by David Bohm in the 1950s as a modification of Louis de Broglie's original pilot-wave proposal. Bohmian mechanics describes the deterministic motion of particles along determinate trajectories. The distribution of the trajectories is given by the quantum equilibrium distribution $|\psi|^2$. This choice ensures that statistical predictions agree with those of standard quantum mechanics. While the wave function is transformed via the Schrödinger equation, the particle positions evolve according to the so-called guiding equation. The wave function acts as a "guiding field" that generates a velocity field followed by the particles. There are also versions using nonequilibrium initial distributions and de Broglie's original equation of motion. Therefore, the more general term "de Broglie–Bohm theory" is sometimes used. See also HIDDEN-VARIABLES INTERPRETATION and PILOT-WAVE THEORY.

Born rule One of the axioms of standard quantum mechanics. In its most elementary form, it states that the probability of finding the value o_i in a measurement of an observable with eigenstates $\{|o_i\rangle\}$ and spectrum $\{o_i\}$ is given by $|\langle o_i|\psi\rangle|^2$, where $|\psi\rangle$ is the state vector of the measured system immediately prior to measurement.

coherence See SUPERPOSITION.

collapse postulate One of the axioms of standard quantum mechanics. It states that a measurement (introduced axiomatically in standard quantum mechanics) instantaneously changes the quantum state of the measured system into one of the eigenstates of the measured observable. See also BORN RULE.

collapse theory An umbrella term for theories that add to quantum mechanics an explicit mechanism for wave-function collapse. As such, they make predictions different from standard quantum mechanics for certain situations. Collapse can be implemented by adding stochastic terms to the Schrödinger equation, or by postulating the occurrence of instantaneous, stochastic wave-function "hits" (or by combining these ideas). A well-known collapse theory is the GRW THEORY.

Copenhagen interpretation An umbrella term for a variety of viewpoints associated with members and disciples of the "Copenhagen circle" of Niels Bohr, Werner Heisenberg, Nathan Rosenfeld, and others. Don Howard has argued that "[u]ntil Heisenberg coined the term in 1955, there was no unitary Copenhagen interpretation of quantum mechanics." According to Jan Faye, "today the Copenhagen interpretation is mostly regarded as synonymous with indeterminism, Bohr's correspondence principle, Born's statistical interpretation of the wave function, and Bohr's complementarity interpretation of certain atomic phenomena." It has also become popular to throw wave-function collapse, positivism, subjectivism, and the fundamental role of the human observer into the mix, even though such concepts are mostly alien to the spirit of Bohr's own philosophy, which focused on the complementarity principle and the irreducibility of classical concepts.

de Broglie–Bohm theory See BOHMIAN MECHANICS.

decoherence A quantum-mechanical process whereby interactions of a quantum system with its environment lead to uncontrollable and practically irreversible entanglement between the two partners. Decoherence explains why it is so difficult in practice to prepare certain quantum states and to observe interference effects—especially in the case of mesoscopic and macroscopic systems, for which decoherence is extremely fast and virtually inescapable. Decoherence is an application of the standard quantum formalism to open quantum systems; as such, it is neither an interpretation nor a new theory. Yet it is often invoked in foundational discussions, for example, when addressing aspects of the measurement problem. It's also a cornerstone of Everett-style interpretations. Decoherence is a lively subject of experimental investigation and a feared enemy of quantum computers.

density matrix See QUANTUM STATE.

dynamical-reduction theory See COLLAPSE THEORY.

Einstein–Podolsky–Rosen paradox See EPR PARADOX.

EPR paradox An argument presented in a seminal 1935 paper by Albert Einstein, Boris Podolsky, and Nathan Rosen, claiming to demonstrate the incompleteness of quantum mechanics. See page 162 for a brief introduction.

entanglement A genuine quantum phenomenon whereby two systems become "quantum-correlated." Formally, two systems are said to be entangled if they cannot be afforded with their own state vectors. Entanglement is sometimes described as a process by which systems lose their individuality and fuse into a quantum-mechanical whole ("quantum holism"), but there is disagreement about whether this metaphysical picture is actually appropriate. Suffice to say, entanglement implies that there exist physical properties that can be measured on the composite system but not be inferred from measurements on the subsystems. Entanglement underlies classic quantum paradoxes, such as EPR and Schrödinger's cat, and is a cornerstone of quantum information theory.

Everett interpretation Also known as the relative-state interpretation of quantum mechanics, it was proposed in the 1950s by Hugh Everett, then a Ph.D. student of John Wheeler's. Everett wanted to address the measurement problem and rid the theory of its system–observer dualism. He disposed of the collapse postulate and tried to show that nonetheless—even when no particular measurement outcome is singled out—our *subjective* experience of definite measurement outcomes (as well as their correct quantum statistics) could be recovered. Everett emphasized the principle of relativity of quantum states: each component in the uncollapsed superposition state at the conclusion of a von Neumann measurement describes a correlation between a definite state of the system and a definite state of the observer, with the latter state then interpreted as *relative* to the system's being in a particular state. Serious gaps in Everett's argument motivated later efforts to develop Everett's ideas into a coherent, satisfactory interpretation; see MANY-WORLDS INTERPRETATION.

gedankenexperiment A thought experiment (from the German word *Gedanke*, meaning "thought"). Famous examples relevant to the theme of this book are SCHRÖDINGER'S CAT and WIGNER'S FRIEND.

GRW theory A collapse theory postulating a spontaneous, stochastic spatial localization of the wave function. Named after its inventors GianCarlo Ghirardi, Alberto Rimini, and Tullio Weber. See also COLLAPSE THEORY.

hidden-variables interpretation An interpretation of quantum mechanics that adds to the wave function additional variables that specify the physical state of the system more accurately than the wave function alone could do. To avoid a clash with the predictions of quantum mechanics, the hidden variables must remain experimentally inaccessible. A well-known hidden-variables interpretation is BOHMIAN MECHANICS. See also Question 8, *Bell's Inequalities*.

interference In quantum mechanics, the phenomenon that observed distributions of events may have a distinctly nonclassical shape in (typically) space or time. The most famous example is the spatial interference pattern observed in the double-slit experiment with particles. Classically, the expected pattern would be two partially overlapping peaks (the sum of the contributions from each individual slit). The observed quantum-mechanical pattern, however, has an oscillatory shape ("interference fringes"). The formal account of interference rests on the fact that a quantum superposition represents a linear combination of probability *amplitudes* rather than actual probabilities. This means that the corresponding probability distribution contains additional crossterms ("interference terms"), which modulate the classically expected distribution.

Kochen–Specker theorem A no-go theorem that, together with Bell's theorem, imposes severe constraints on the structure of a viable hidden-variables theory. Derived by Simon Kochen and Ernst Specker in 1967, it may also be read as a powerful argument against naive realism, by implying that measurements cannot in general be construed as simply revealing objectively preexisting properties of the world. Specifically, the theorem proves that in quantum mechanics, it is not possible in general to assign values to a set of observables defined for a quantum system of Hilbert-space dimension greater than two such that (1) all these values are definite at all times, and (2) the value assignment is independent of how the value is eventually measured—say, independent of the choice of other co-measured observables ("noncontextuality"). Some authors prefer the term "Bell–Kochen–Specker theorem," arguing that the derivation of the Kochen–Specker theorem shares a key step with the (earlier) proof of Bell's theorem.

many-minds interpretation See MANY-WORLDS INTERPRETATION.

many-worlds interpretation An interpretation that develops the basic ideas of Everett's relative-state interpretation into the full-blown picture of a single quantum universe—represented by an all-encompassing wave function—containing a myriad of constantly branching, effectively classical worlds. "Our" observed world then corresponds to one such branch. Many-worlds interpretations were popularized by Bryce DeWitt in the 1970s and by David Deutsch in the 1980s. A variant is the class of "many-minds" interpretations proposed by David Albert and Barry Loewer, Dieter Zeh, Michael Lockwood, and others. See also EVERETT INTERPRETATION.

measurement problem The difficulty of reconciling the smooth, linear, reversible Schrödinger evolution of quantum states with the occurrence of definite events in the world of our experience. The measurement problem is one of the classic problems in the foundations of quantum mechanics. See Question 7, *The Measurement Problem*.

modal interpretation A class of interpretations of quantum mechanics. One characteristic feature is the definition of rules that permit the assignment of a definite value to a system even when the system is not in an eigenstate of the corresponding observable. The first modal interpretation was proposed in the 1970s by Bas van Fraassen. There, a system is described by the following two different states. (1) The *value state*, which specifies the values of physical quantities possessed by the system at a given time. (2) The *dynamical state*, which determines the evolution of the system—that is, the possible future value states. It coincides with the ordinary quantum state vector, but it never collapses.

no-cloning theorem A theorem of quantum mechanics showing that it is impossible (except by sheer luck) to duplicate an unknown quantum state.

no-go theorem An umbrella term for theorems that demonstrate an incompatibility between what quantum mechanics *allows* us to do and what we'd *like* to do—be it implementing particular actions, constructing particular hidden-variables models, or continuing to believe in particular worldviews. For examples, see BELL'S INEQUALITIES, KOCHEN–SPECKER THEOREM, NO-CLONING THEOREM, and NO-SIGNALING THEOREM.

nonlocality In the context of quantum mechanics, this term chiefly has two meanings. (1) The impossibility of describing correlations between outcomes of local measurements, performed at two different locations, in terms of a local hidden-variables model. (2) Actual physical action-at-a-distance, where the physical situation in one region instantaneously influences the physical situation in another, arbitrarily distant region.

no-signaling theorem A theorem showing that quantum mechanics does not enable us to use entangled quantum states for the instantaneous transmission of information between distant partners.

philosophy The art of skillfully questioning and analyzing subtle yet fundamental matters that the man on the street either takes for granted or does not regard as having practical bearing on his survival. The term is also sometimes employed by toughminded scientists to dismiss issues that they do not regard as having any practical bearing on their survival.

physics The art of skillfully observing, analyzing, and quantifying patterns and relationships in the universe, and of formulating laws that capture and correctly predict these patterns.

pilot-wave theory A hidden-variables interpretation presented by Louis de Broglie at the 1927 Solvay meeting. De Broglie derived an equation for the motion of particles, each endowed with definite position and momentum values (which are the hidden variables), and demonstrated how interference effects could be understood on the basis of such particle trajectories. De Broglie's theory was later revived by David Bohm and developed into BOHMIAN MECHANICS. See also HIDDEN-VARIABLES INTERPRETATION.

PR box A model for studying the properties of (hypothetical) "superquantum" theories. Named after its inventors Sandu Popescu and Daniel Rohrlich. See Jeffrey Bub's introduction to PR boxes, page 68.

QBism Christopher Fuchs's term for his research program of elucidating the larger metaphysical implications of Quantum Bayesianism.

QBit A variant spelling of *qubit*, preferred and promoted by David Mermin. See QUBIT.

Quantum Bayesianism At the core, the view that quantum states encapsulate the subjective degrees of belief of an agent and are nothing but a tool the agent uses in navigating the world he is immersed in. Developed by Carl Caves, Christopher Fuchs, and Rüdiger Schack, the approach is grounded in personalist Bayesian probability theory and is nourished by insights from quantum information theory. See also QBISM.

quantum computer A device that exploits the laws of quantum mechanics to speed up a computation. There are several known quantum algorithms for solving certain problems faster than any classical (i.e., nonquantum) computer could do. The most famous examples are Shor's algorithm for factoring large numbers and Grover's algorithm for finding an element in a list. The heart of a quantum computer is an array of qubits, which can be physically realized in various ways (photons, trapped ions, two-level atoms, nuclear spins, coupled quantum dots, and so on). Gates are implemented via unitary operations acting on the qubits; one- and two-qubit gates are sufficient to perform any quantum computation. (There's an alternative equivalent approach—called measurement-based, or cluster-state, computation—which proceeds from a highly entangled initial state and implements the computation via a series of projective measurements.) Building a quantum computer is one of the holy grails of quantum science and engineering; to date, only proof-of-principle devices containing a handful of qubits have been realized.

quantum gravity An area of research devoted to finding a satisfactory physical theory that would unify quantum mechanics and general relativity. String theory is currently the most popular approach, followed by loop quantum gravity. All of the existing theories, however, have their problems, and so the field is best described as work in progress.

quantum information theory A recasting of quantum mechanics as a theory concerned with the flow, processing, and manipulation of information. It provides a new lens for looking at the structure and capabilities of quantum mechanics. It has also led to practical offshoots, such as protocols for completely secure communication. There is, moreover, the promise of a quantum computer. In absence of a clarifying hyphen, the term "quantum information theory" may be read as both "a theory of quantum information" and "a quantum-mechanical information theory." This is a healthy ambiguity. See also QUANTUM COMPUTER and Question 9, *Quantum Information.*

quantum state The mathematical object for describing the state of an individual quantum system. So-called pure states are represented by complex vectors or functions ("wave functions") in a Hilbert space; they provide, at least according to standard quantum mechanics, a complete description of the physical state of an individual system. Mixed states, formally represented by density matrices, are used in the following two situations. (1) To represent a classical, ignorance-interpretable probability distribution (ensemble) of pure states, one of which is actually realized by the system. (2) To encapsulate the statistics of all possible measurements that can be carried out on a system that is entangled with another system. In this case, the mixture is *not* ignorance-interpretable, because the presence of entanglement prohibits the assignment of a pure state to the system. See also WAVE FUNCTION and Question 4, *Quantum States.*

qubit Short for *quantum bit*, it refers to any quantum system with a two-dimensional Hilbert space. It is a prominent player in quantum information theory and the building block of quantum computers. While a classical bit has a value of either 0 ("off") or 1 ("on"), the state of a qubit will in general be a linear superposition of the form $\alpha|0\rangle + \beta|1\rangle$.

reconstruction A rederivation of the structure of quantum mechanics from a set of fundamental principles. Several such principles have been suggested to date; the challenge is to find principles that are sufficiently basic *and* uniquely specify quantum theory. Reconstructions are work in progress and may be considered either a complement or an alternative to the program of interpreting quantum mechanics. See Question 10, *Reconstructions.*

relative-state interpretation See EVERETT INTERPRETATION.

Schrödinger equation An equation specifying the evolution of the quantum state of an isolated, unmeasured system.

Schrödinger's cat A thought experiment devised by Schrödinger in 1935. It can be seen as a particularly vivid illustration of the measurement problem. The setup consists of a cat confined to a box together with an unstable atom that, at the moment of its decay, triggers a hammer breaking a vial of poison. According to quantum mechanics, the state of the atom is at all times described by a superposition of "not decayed" and "decayed." Unitary evolution leads to entanglement between all systems present, resulting in a seemingly grotesque superposition of two states that our experience deems mutually exclusive: one component of the superposition contains a live cat (together with an undecayed atom, untriggered hammer, and the vial intact), while the other component describes a dead cat (together with a decayed atom, triggered hammer, and the poison released). The second part of the paradox is established when an outside observer opens the box to look at the cat. According to the collapse postulate, such an act of observation will instantaneously reduce the superposition to one of its components. In Schrödinger's words, the "indeterminacy originally restricted to the atomic domain becomes transformed into macroscopic indeterminacy, which can then be *resolved* by direct observation." This raises the question of the state of the cat *before* the observer opens the box. See Arthur Fine's *The Shaky Game: Einstein, Realism, and the Quantum Theory* (Chicago, 1996) for an in-depth analysis of the history of Schrödinger's cat paradox and Einstein's influence.

SQUID An abbreviation for *superconducting quantum interference device*. A SQUID is a macroscopic quantum system consisting of a ring of superconducting material interrupted by thin, insulating barriers called Josephson junctions. At low temperatures, pairs of electrons of opposite spin condense into bosons ("Cooper pairs") and tunnel through the junctions. This leads to the flow of a persistent, resistance-free "supercurrent," which induces a magnetic flux threading the ring. In 1980 Anthony Leggett suggested that SQUIDs could be used to create quantum superpositions of macroscopically distinct flux states. In 2000 coherent superpositions of microampere supercurrents traveling in opposite directions around the loop were experimentally observed by Jonathan Friedman et al. and Caspar van der Wal et al.

state vector A normalized complex vector in a Hilbert space, representing a pure quantum state. See also QUANTUM STATE.

superposition A (pure) quantum state that is written as a linear combination of other (pure) quantum states. Such a quantum-mechanical superposition is often referred to as *coherent*, to emphasize the fact that it defines a new physical state of an individual system—rather than a statistical ("classical") distribution of the component states, with one of the states realized in the system. See also INTERFERENCE and SUPERPOSITION PRINCIPLE.

superposition principle A kinematical concept of quantum mechanics, grounded in the linearity of Hilbert space. It states that any linear combination $\sum_n \alpha_n |\psi_n\rangle$ of quantum states $|\psi_n\rangle$ is again a valid quantum state. See also SUPERPOSITION.

von Neumann measurement A formal scheme describing the entangling interaction between two quantum systems. It is often used to formalize a "measurement-like" unitary interaction between a system and an apparatus, both treated as quantum systems. Since no definite outcome is singled out at the conclusion of a von Neumann measurement, the scheme is sometimes referred to as *premeasurement* and serves as a classic—albeit not the most general—illustration of the measurement problem.

wave function A complex vector or function in a Hilbert space, representing a pure quantum state. In traditional parlance, wave functions are mostly associated with a continuous function of real parameters that refer to the relevant degrees of freedom of the system (usually position, momentum, or spin). A wave function describes a probability amplitude; its mod-squared value $|\psi(x,t)|^2$ specifies the probability of finding the value x in an appropriate measurement at time t (Born rule). See also QUANTUM STATE.

wave packet A wave function that is peaked in the relevant variable. An example is a coherent state, which is narrowly peaked in both position and momentum space.

Wigner's friend A variant of the Schrödinger-cat gedankenexperiment, devised by Eugene Wigner in the early 1960s. The cat is replaced by a human observer ("Wigner's friend") inside a sealed laboratory. The decay of the atom triggers now merely a flash of light. The observer is instructed to assign a definite quantum state depending on whether she has seen a flash. On the other hand, from the perspective of a second, outside observer, the contents of the laboratory will evolve into a superposition of states associated, in particular, with different states of *consciousness* of Wigner's friend. For Wigner, this was a particularly absurd and unacceptable state of affairs. For more, see page 90, Časlav Brukner's answer to Question 11 (page 217), and Christopher Fuchs's answer to Question 5 (page 114).

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Note: A page reference to a person's name means that the corresponding text makes significant mention of that person—say, in the form of a quote, an anecdote, or a substantial description and acknowledgment of the person's work.

Preface

Over the course of the past decade, decoherence has become a ubiquitous scientific term popular in all kinds of research, from fundamental theories of quantum physics to applications in nanoengineering. Decoherence has been hailed as the solution to long-standing foundational problems dating back to the beginnings of quantum mechanics. It has been cursed as the key obstacle to next-generation technologies, such as quantum computers (another seemingly omnipresent field of research). And while decoherence has been directly observed in various experiments, its scope and meaning have often been misunderstood and misrepresented. Decoherence makes a fantastic subject of research, as it touches upon many different facets of physics, from philosophically inclined questions of interpretation all the way to down-to-earth problems in experimental settings and engineering applications.

This book will introduce the reader, in an accessible and self-contained manner, to these various fascinating aspects of decoherence. It will focus in particular on the relation of decoherence to the so-called quantum-to-classical transition, i.e., the question of how decoherence may explain the emergence of the classical appearance of the macroscopic world around us from the underlying quantum substrate.

The scope of this book is relatively broad in order to familiarize the reader with the many facets of decoherence, in both the theoretical and experimental domains. Throughout the book, I have sought to maintain a healthy balance between the conceptual ideas associated with the decoherence program on the one hand and the formal and mathematical details on the other hand. This book will establish a proper understanding of decoherence as a pure quantum phenomenon and will emphasize the importance of the correct interpretation of the consequences and achievements of decoherence.

One beautiful thing about learning about decoherence is that, as vast as its implications and applications are, the basic ideas and formal structures are actually quite clear and simple. As a general rule, I will wherever possible avoid muddling important general insights with complicated mathematical exercises. A basic knowledge of the formalism of quantum mechanics should suffice to follow most, if not all, explanations and derivations in this book. While certain sections inevitably contain somewhat lengthy mathematical considerations (the derivation of master equations in Chaps. 4 and 5 is probably the most striking example), readers less interested in these formal structures underlying the decoherence program should be able to just glance over these sections—or even skip them altogether—without significantly compromising their understanding of other parts of the book. At the same time, the more advanced material included in this book will be useful to the working physicist who may already have some knowledge of decoherence and is looking for a self-contained and detailed reference. Philosophers of physics interested in the foundations of quantum mechanics should also find plenty of interesting material throughout this book (especially in Chaps. 1, 2, 8, and 9).

The book is organized as follows. In Chap. 1, we will take a first "bird's-eye look" at decoherence by introducing some of the basic ideas and concepts. We will emphasize the importance of considering "open" quantum systems in addressing some of the long-standing issues of quantum theory, and contemplate why it may have taken over half a century for this realization and the ideas of the decoherence program to take hold.

The core chapter of the book is Chapter 2, in which we will introduce and discuss in detail the key conceptual ideas and formal descriptions of decoherence. First, we will analyze fundamental concepts of quantum mechanics, such as quantum states (and their differences to classical states), the superposition principle, quantum entanglement, and density matrices. A proper grasp of these topics will turn out to be very important for the development of a solid understanding of decoherence. We will then illustrate and discuss different components of what has become known as the "quantum measurement problem." This problem encapsulates many of the fundamental conceptual difficulties that have to this date prevented us from arriving at a commonly agreed-upon understanding of the physical *meaning* of the formalism of quantum mechanics and of how this formalism relates to the perceived world around us. The measurement problem is also intimately related to decoherence, since decoherence has direct implications for the different components of the problem.

We will then illustrate basic concepts of decoherence in the context of the well-known double-slit experiment. This approach will allow the reader to develop a rather natural understanding of decoherence as a consequence of environmental "monitoring" and quantum entanglement. It will also establish a modern view of Bohr's famous "complementarity principle." We will formalize decoherence in terms of system–environment entanglement and reduced density matrices and discuss the two main consequences of decoherence, the environment-induced suppression of quantum interference and the selection of preferred "pointer" states through the interaction with the environment.

After the reader has thus become familiar with the ideas and formalism of decoherence, the subsequent chapters can either be read in order, or the reader may focus on particular chapters of interest. Each chapter is designed to present a fairly self-contained discussion of a particular aspect of decoherence.

In Chap. 3, we will consider a very important model that describes decoherence of quantum objects due to collisions with environmental particles such as photons and air molecules. This scattering-induced decoherence is ubiquitous in nature and of paramount importance in describing the quantum-to-classical transition on macroscopic everyday-world scales.

Next, in Chap. 4, we will introduce the master-equation formalism that provides us with a general method for determining the dynamics of decoherence models in many cases of physical interest. We will spend some time deriving the important Born–Markov master equation that will allow us to treat many decoherence problems in a fairly straightforward and intuitive fashion.

In Chap. 5, we will then show how a large class of system–environment models can be reduced to a few "canonical" decoherence models. We will then analyze these models in detail. In particular, we will discuss so-called quantum Brownian motion, which can be viewed as the quantum approximation to the familiar classical Newtonian trajectories in phase space. We will also introduce the famous spin–boson model which has recently received additional attention in the context of quantum computing.

After so much theoretical material, the reader will certainly be longing for a break. Thus, in Chap. 6, we will describe some fascinating experiments that have made it possible to directly observe in the laboratory the gradual action of decoherence and therefore the transition from the quantum world to the classical domain.

In Chap. 7, we will shift gears somewhat and enter the field of quantum computing that has attracted so much interest over the past decade. We will explain the crucial role that decoherence plays in this field. We will then describe how the effects of decoherence can be mitigated through sophisticated (but ultimately easy to understand) methods such as quantum error correction, decoherence-free subspaces, and environment engineering.

Chapter 8 will discuss the implications of decoherence for several of the main interpretations of quantum mechanics. We will describe how decoherence may enhance, redefine, or challenge the most common interpretations, such as the orthodox and Copenhagen interpretations, relative-state interpretations, physical collapse models, modal interpretations, and Bohmian mechanics.

Finally, in Chap. 9, we will discuss the role of the observer in quantum theory and the question of decoherence processes in the brain. We will explain why this question is of interest in the first place and then review some explicit model calculations that demonstrate the efficiency of decoherence in the brain. The implications of these results will be discussed, in particular with respect to a "subjective" observer-based resolution of the measurement problem.

A brief remark on notation. I have set $\hbar \equiv 1$ throughout most of the book except in situations where explicit numerical estimates play a role. In this way, I hope to have kept the notation as clear as possible without compromising the reader's ability to derive and reproduce numerical values where needed.

There are many people who have contributed to making this book possible. First and foremost, I would like to thank my Ph.D. advisor, Arthur Fine, for giving me both the freedom and guidance to study the field of decoherence. He suggested to me that I write up some "personal notes" on decoherence so that he and I would better understand this area of research (which was, at the time, new to both of us). These notes evolved into a review article on decoherence [1], which in turn motivated this book. In this context, I am deeply indebted to H. Dieter Zeh for many helpful discussions and for bringing the idea for this book to the attention of Angela Lahee, editor at Springer, who has since lent her patient, encouraging, and helpful support to every aspect in the production of this book.

I thank Michael Nielsen and Gerard Milburn for their hospitality at the University of Queensland where parts of this book were written. I would also like to express my gratitude to Stephen Adler for comments on Sect. 8.4, to Erich Joos for feedback on Chap. 3, to Gerard Milburn for introducing me to quantum-electromechanical systems, and to Wojciech Zurek for many valuable comments on the manuscript and for inspiring discussions. Most importantly, though, I would like to thank my wife Kari for all her patience and all-around inspiration during the long process of writing this book.

Melbourne, Australia *Maximilian Schlosshauer*
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Decoherence and the foundations of quantum mechanics

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This is an introduction to decoherence with an emphasis on the foundational and conceptual aspects of the theory. It explores the extent to which decoherence suggests a solution to the measurement problem, and evaluates the role of decoherence in several different interpretations of quantum mechanics. [This paper is essentially a short version of: M. Schlosshauer, "Decoherence, the measurement problem, and interpretations of quantum mechanics," *Reviews of Modern Physics* **76**: 1267–1305 (2004).]

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I. INTRODUCTION

Over the past quarter-century, decoherence has become an omnipresent term in the literature on quantum mechanics. Even named part of the "new orthodoxy" [18, p. 212] in understanding quantum mechanics, it has attracted widespread attention among experimental and theoretical physicists as well as philosophers of physics. The growing interest in quantum computing has made decoherence a more widely studied field than ever. Although decoherence *per se* does not introduce anything particularly new into the formalism of standard quantum mechanics, it is capable of yielding surprising results that, when properly interpreted, can contribute crucially to a proper understanding of the connection between the quantum-mechanical formalism and the world of our perception. Anyone working in the field of quantum mechanics today needs to know the basics of decoherence and its conceptual implications. This article is intended as a primer that reviews those basics. For a more detailed review of decoherence, we recommend the following articles: Zurek's review paper [69] that deals comprehensively with many of the more technical aspects of decoherence, including an overview of recent experimental advances; the book by Joos *et al.* [41] that provides an extensive description of the decoherence program as a whole; and, maybe most suitable to the audience of this article, a recent review paper of one of us [52] that discusses in great detail the foundational implications of decoherence.

Decoherence studies the ubiquitious interactions between a system and its surrounding environment. These interactions lead to a rapid and strong entanglement between the two partners that has crucial consequences for what we can observe at the level of the system. Studies have shown that even the microwave background radiation can have a significant impact on systems of sizes as small as a dust particle [40, 54]. The decoherence program describes such environmental interactions and evaluates their formal, experimental, and conceptual consequences for the quantum-mechanical description of physical systems. In the following, we will introduce the main concepts of decoherence and discuss some of their implications for foundational aspects and interpretations of quantum mechanics.

II. BASICS OF DECOHERENCE

The key idea promoted by decoherence is rather simple, although its consequences are far-reaching and seem to have been overlooked for a surprisingly long time: To give a correct quantum-mechanical account of the behavior and properties of a physical system, we must include the interactions of this system with its omnipresent environment, which generally involves a large number of degrees of freedom.

Classical physics typically studies systems that are thought of as being separated from their surroundings. The environment is generally viewed as a "disturbance" or "noise." In many cases, the influence of the environment is neglected, usually depending on the relative sizes of system and environment. For instance, the scattering of air molecules on a bowling ball is ignored when the motion of the ball is studied, while surrounding molecules have a crucial influence on the path of a small particle in Brownian motion.

By contrast, in quantum mechanics, environmental interactions amount to more than a simple delivery of "kicks" to the system. They lead to the formation of a nonlocal entangled state for the system–environment combination. Consequently, no individual quantum state can be attributed to the system anymore. Such entanglement corresponds to establishing correlations that imply properties for the system–environment combination that

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are not derivable from features of the individual parts themselves and that change the properties that we can "assign" to the individual system. Thus interactions between a given system and its large, ubiquitous "environment," must not be neglected if the system is to be described properly in quantum-mechanical terms.

The theory of decoherence typically involves two distinct steps: a dynamical step, namely, the interaction of the system with its environment and the resulting entanglement, and a coarse-graining step in form of a restriction to observations of the system only. The latter step can be motivated by the (nontrivial) empirical insight that all observers, measuring devices, and interactions are intrinsically local [43, 60, 64]. In any realistic measurement performed on the system, it is practically impossible to include all degrees of freedom of the system and those of the environment that have interacted with the system at some point. In other words, inclusion of the environment is needed to arrive at a complete description of the time evolution of the system, but we subsequently "ignore" at least a part of the environment by not observing it. For example, light that scatters off a particle will influence the behavior of the particle, but we will intercept (i.e., observe) only a tiny part of the scattered photons with our visual apparatus; the rest will escape our observation. The key question that decoherence investigates can then be put as follows: What are the consequences of *nonlocal* environmental entanglement for *local* measurements?

To formalize matters, let us assume that the system $\mathcal{S}$ can be described by state vectors $|s_k\rangle$, and that the interaction with the environment $\mathcal{E}$ leads to a formation of product states of the form $|s_k\rangle \otimes |e_k\rangle$, where the $|e_k\rangle$ are the corresponding "relative" states of $\mathcal{E}$ (representing a typically very large number of environmental degrees of freedom). If the initial state of the system at $t = 0$ is given by the pure-state superposition $|\Psi_\mathcal{S}\rangle = \sum_k \lambda_k |s_k\rangle$, and that of the environment by $|e_0\rangle$, the initial state of the system–environment combination has the separable form

$$|\Psi\rangle = |\Psi_\mathcal{S}\rangle \otimes |e_0\rangle = \left(\sum_k \lambda_k |s_k\rangle \right) \otimes |e_0\rangle. \tag{1}$$

Here, the system has the well-defined individual quantum state $|\Psi_\mathcal{S}\rangle$. However, the interaction between $\mathcal{S}$ and $\mathcal{E}$ evolves $|\Psi\rangle$ into the nonseparable entangled state

$$|\Psi(t)\rangle = \sum_k \lambda_k(t) |s_k\rangle \otimes |e_k(t)\rangle. \tag{2}$$

In essence, the dynamical evolution $|\Psi\rangle \to |\Psi(t)\rangle$ corresponds to von Neumann's account of quantum measurement [44] that models the measurement process within unitary (non-collapse) quantum mechanics as the formation of appropriate quantum correlations between the system and the measuring apparatus (where the latter is here represented by the environment). Accordingly, decoherence was initially only referred to as "continuous measurement by the environment."

Since the state $|\Psi(t)\rangle$ can in general not be expressed anymore in a separable product form $|\Psi_\mathcal{S}(t)\rangle \otimes |\Psi_\mathcal{E}(t)\rangle$, no individual state vector can be attributed to $\mathcal{S}$. The phase relations λ_k, describing the coherent superposition of $\mathcal{S}$-states $|s_k\rangle$ in the initial state, have been "dislocalized" into the combined state $|\Psi(t)\rangle$ through the interaction, i.e., coherence has been "distributed" over the many degrees of freedom of the system–environment combination and has become unobservable at the level of the system. To paraphrase Joos and Zeh [40], the superposition still *exists* (in fact, it now even pertains to the environment), but it is not *there* (at the individual system). In this sense, we can speak of the decoherence process as describing a local suppression (or rather: inaccessibility) of interference.

Since the interaction is strictly unitary, decoherence can in principle always be reversed. However, due to the large number of degrees of freedom of the environment (that are typically not controlled and/or controllable), decoherence can be considered irreversible for all practical purposes. It also turns out that, for the same reason, the states $|e_k(t)\rangle$ rapidly approach orthogonality (i.e., macroscopic distinguishability) as t increases,

$$\langle e_k(t) | e_{k'}(t) \rangle \longrightarrow 0 \qquad \text{if } k \neq k'. \tag{3}$$

To see more directly the phenomenological consequences of the processes described thus far in the context of actual measurements, let us consider the density matrix corresponding to the state $|\Psi(t)\rangle$ (we shall omit the state-product symbol "$\otimes$" in the following to simplify our notation),

$$\begin{aligned} \rho_{\mathcal{SE}}(t) &= |\Psi(t)\rangle\langle\Psi(t)| \\ &= \sum_{kk'} \lambda_k(t) \lambda^*_{k'}(t) |s_k\rangle |e_k(t)\rangle \langle s_{k'}| \langle e_{k'}(t)|. \end{aligned} \tag{4}$$

The presence of terms $k \neq k'$ represents interference (quantum coherence) between different product states $|s_k\rangle|e_k(t)\rangle$ of the system–environment combination $\mathcal{SE}$. By contrast, if we dealt with a classical ensemble of these states, our density matrix would read

$$\rho^{\text{class}}_{\mathcal{SE}}(t) = \sum_k |\lambda_k(t)|^2 |s_k\rangle |e_k(t)\rangle \langle s_k| \langle e_k(t)|. \tag{5}$$

Such an ensemble is interpreted as describing a state of affairs where $\mathcal{SE}$ is in one of the states $|s_k\rangle|e_k(t)\rangle$ with (ignorance-based) probability $|\lambda_k(t)|^2$.

Let us now include the coarse-graining component, i.e., we assume that we do not (cannot, do not need to) have full observational access to all the many degrees of freedom of the environment interacting with the system. The restriction to the system can be represented by forming the so-called reduced density matrix, obtained by averaging over the degrees of freedom of the environment via the trace operation,

$$\rho_{\mathcal{S}}(t) = \mathrm{Tr}_{\mathcal{E}}\rho_{\mathcal{SE}}(t) = \sum_l \langle e_l|\rho_{\mathcal{SE}}(t)|e_l\rangle$$
$$= \sum_l \sum_{kk'} \lambda_k(t)\lambda^*_{k'}(t)|s_k\rangle\langle s_{k'}|\langle e_l(t)|e_k(t)\rangle\langle e_{k'}(t)|e_l(t)\rangle. \tag{6}$$

This density matrix suffices to compute probabilities and expectation values for all local observables $\widehat{O}_{\mathcal{S}}$ that take into account only the degrees of freedom of $\mathcal{S}$. In this sense, it contains all the relevant information about the "state" of $\mathcal{S}$ that can be found out by measuring $\mathcal{S}$ (while, of course, no individual quantum state vector can be attributed to $\mathcal{S}$).

Now, since the decoherence process makes the environmental states $|e_k(t)\rangle$ approximately mutually orthogonal, see Eq. (3), the reduced density matrix approaches the diagonal limit

$$\rho_{\mathcal{S}}(t) \longrightarrow \sum_k |\lambda_k(t)|^2|s_k\rangle\langle s_k|. \tag{7}$$

Since this density matrix *looks like* a classical ensemble of $\mathcal{S}$-states $|s_k\rangle$ [cf. Eq. (5)], it is often referred to as an "apparent ensemble." As a consequence, the expectation value of observables $\widehat{O}_{\mathcal{S}} = \sum_{kk'} O_{kk'}|s_k\rangle\langle s_{k'}|$ computed via the trace rule $\langle\widehat{O}_{\mathcal{S}}\rangle = \mathrm{Tr}_{\mathcal{S}}\left[\rho_{\mathcal{S}}(t)\widehat{O}_{\mathcal{S}}\right]$ approaches that of a classical average, i.e., the contribution from interference terms $k \neq k'$ becomes vanishingly small.

While the dislocalization of phases can be fully described in terms of unitarily evolving, interacting wavefunctions [see Eq. (2)], the reduced density matrix has been obtained by a nonunitary trace operation. The formalism and interpretation of the trace presuppose the probabilistic interpretation of the wave function and ultimately rely on the assumption of the occurence of an (if only apparent) "collapse" of the wave function at some stage. We must therefore be very careful in interpreting the precise meaning of the reduced density matrix, especially if we would like to evaluate the implications of decoherence for the measurement problem and for non-collapse interpretations of quantum mechanics. It is probably fair to say that early misconceptions in this matter have contributed to the confusion and criticism that has surrounded the decoherence program over the decades. So we will discuss this point in some detail in the next section.

III. DECOHERENCE AND THE MEASUREMENT PROBLEM

The measurement problem relates to the difficulty of accounting for our perception (if not the objective existence) of definite outcomes at the conclusion of a measurement. It follows from the linearity of the Schrödinger equation that when the (usually microscopic) system $\mathcal{S}$ is described by a superposition of states $|s_k\rangle$ which the (typically macrosopic) apparatus $\mathcal{A}$ (with corresponding states $|a_k\rangle$) is designed to measure, the final composite state of the system–apparatus combination $\mathcal{SA}$ will be a superposition of product states $|s_k\rangle|a_k\rangle$. This is basically the state of affairs described by Eqs. (1) and (2) (representing the von Neumann-type measurement scheme), with the environment $\mathcal{E}$ now replaced by the measuring device $\mathcal{A}$.

The usual rules of quantum mechanics then imply that no single, definite state can be attributed to the apparatus, and that in general we have (1) a multitude of possible outcomes (not just one), and (2) interference between these multiple outcomes. That a superposition must not be interpreted as an ensemble has also been widely confirmed in numerous experiments, in which superpositions are observed as individual physical states where all components of the superposition are simultaneously present. Examples for such experiments include mesoscopic "Schrödinger kittens" [8, 34, 37], superconducting quantum interference devices in which superpositions of macroscopic currents running in opposite directions are observable [28], and Bose–Einstein condensates [38].

So how is it then that at the conclusion of a measurement we always observe the pointer of the apparatus to be in a single definite position, but never in a superposition of positions? This "measurement problem" actually contains of two separate questions: (A) Why is it that always a particular quantity (usually position) is selected as the determinate variable (the "preferred-basis problem")? And (B), why do perceive a single "value" (outcome) for the determinate variable (the "problem of outcomes")? We shall discuss these questions and their connection with decoherence in the following.

A. The preferred-basis problem

As a simple example for the preferred-basis problem, consider a system $\mathcal{S}$ consisting of a spin-1/2 particle, with spin states $|{\uparrow_z}\rangle_{\mathcal{S}}$ and $|{\downarrow_z}\rangle_{\mathcal{S}}$ corresponding to the eigenstates of an observable σ_z that measures whether the spin points up or down along the z axis. Now, let $\mathcal{S}$ be measured by an apparatus $\mathcal{A}$ in the following way: If the system is in state $|{\uparrow_z}\rangle_{\mathcal{S}}$, the apparatus ends up in the state $|{\uparrow_z}\rangle_{\mathcal{A}}$ at the conclusion of the measurement, i.e., the final system–apparatus combination can be described by the product state $|{\uparrow_z}\rangle_{\mathcal{S}}|{\uparrow_z}\rangle_{\mathcal{A}}$ (and similarly for $|{\downarrow_z}\rangle_{\mathcal{S}}$). Since we may think of the $|{\uparrow_z}\rangle_{\mathcal{A}}$ and $|{\downarrow_z}\rangle_{\mathcal{A}}$ as representing different pointer positions on a dial (say "pointer up" and "pointer down"), the $|{\uparrow_z}\rangle_{\mathcal{A}}$ and $|{\downarrow_z}\rangle_{\mathcal{A}}$ are often referred to as the "pointer states" of the apparatus.

Suppose now that the state of $\mathcal{S}$ before the measurement is given by the superposition $\frac{1}{\sqrt{2}}(|{\uparrow_z}\rangle_{\mathcal{S}} - |{\downarrow_z}\rangle_{\mathcal{S}})$. Then, at the conclusion of the measurement, the combined (entangled) state of $\mathcal{S}$ and $\mathcal{A}$ is

$$|\Psi\rangle_{\mathcal{SA}} = \frac{1}{\sqrt{2}}(|{\uparrow_z}\rangle_{\mathcal{S}}|{\uparrow_z}\rangle_{\mathcal{A}} - |{\downarrow_z}\rangle_{\mathcal{S}}|{\downarrow_z}\rangle_{\mathcal{A}}). \tag{8}$$

We note that this again represents the final state of a typical von Neumann measurement [cf. Eqs. (1) and (2)]. Looking at the state $|\Psi\rangle_{\mathcal{SA}}$, the answer to the question "what observable has been measured by $\mathcal{A}$?" seems obvious: σ_z, of course, i.e., the spin in z direction. But as the reader may easily verify, $|\Psi\rangle_{\mathcal{SA}}$ can in fact be rewritten using any other basis vectors $\{|{\uparrow_{\hat{n}}}\rangle_{\mathcal{S}}, |{\downarrow_{\hat{n}}}\rangle_{\mathcal{S}}\}$ of $\mathcal{S}$, where now $\hat{n}$ is a unit vector that can point into any arbitrary direction in space, and still $|\Psi\rangle_{\mathcal{SA}}$ will maintain its initial form. For example, if we choose $\hat{n}$ to point along the x axis, Eq. (8) becomes

$$|\Psi\rangle_{\mathcal{SA}} = \frac{1}{\sqrt{2}}(|{\uparrow_x}\rangle_{\mathcal{S}}|{\uparrow_x}\rangle_{\mathcal{A}} - |{\downarrow_x}\rangle_{\mathcal{S}}|{\downarrow_x}\rangle_{\mathcal{A}}). \tag{9}$$

What would we now deduce from this form of $|\Psi\rangle_{\mathcal{SA}}$ as the measured observable? Apparently σ_x, i.e., a measurement of the spin in x direction. So it appears that once we have measured the spin in *one* direction (again, interpreting the formation of correlations between $\mathcal{S}$ and $\mathcal{A}$ as a measurement), we seem to also have measured the spin in *all* directions. But wait, the reader may now object, σ_z and σ_x do not commute, so they can't be measured simultaneously!

The conclusion to be drawn is that quantum mechanics, in the form of the von Neumann measurement scheme applied to the isolated system–apparatus combination, does not automatically specify the observable that has been measured. This is certainly hard to reconcile with our experience of the workings of measuring devices that seem to be designed to measure highly specific physical quantities. We can generalize this problem by asking why (especially macrosopic) objects are usually found in a very small set of eigenstates, most prominently in position eigenstates. In fact, the observation that "things around us" always seem to be in definite spatial locations, whereas the linearity of the Hilbert space of the quantum mechanical formalism would in principle allow for arbitrary superposition of positions, is maybe the most intuitive and direct illustration of the preferred-basis problem.

The inclusion of interactions with an environment suggests a solution to this problem. The system $\mathcal{S}$ and the apparatus $\mathcal{A}$ will, in all realistic situations, never be fully isolated from their surrounding environment $\mathcal{E}$. Thus, in addition to the desired measurement interaction between $\mathcal{S}$ and $\mathcal{A}$, there will also be an interaction between $\mathcal{A}$ (and $\mathcal{S}$) and $\mathcal{E}$, leading to the formation of further correlations. Many such $\mathcal{A}$–$\mathcal{E}$ interactions will, however, result in a disturbance of the initial correlations between $\mathcal{S}$ and $\mathcal{A}$, thus altering, or even destroying, the measurement record, which would render it impossible for an observer to perceive the outcome of the measurement.

Zurek therefore proposed the definition of a "preferred pointer basis" of the apparatus as the basis that "contains a reliable record of the state of the system $\mathcal{S}$" [66, p. 1519], that is, the basis $\{|a_k\rangle\}$ of $\mathcal{A}$ in which the correlations $|s_k\rangle|a_k\rangle$ are least affected by the interaction between $\mathcal{A}$ and $\mathcal{E}$ (for simplicity, we shall assume here that $\mathcal{S}$ interacts directly only with $\mathcal{A}$ but not with $\mathcal{E}$). A sufficient (but not necessary) criterion for such a pointer basis would then be given by requiring all the projectors $|a_k\rangle\langle a_k|$ to commute with the apparatus–environment interaction Hamiltonian $H_{\mathcal{AE}}$ (the so-called "commutativity criterion"), that is,

$$[|a_k\rangle\langle a_k|, H_{\mathcal{AE}}] = 0 \qquad \text{for all } k. \tag{10}$$

In other words, the apparatus would be able to measure (i.e., be designed to measure) observables reliably that are linear combinations of the $|a_k\rangle\langle a_k|$, but not necessarily certain other observables. Thus, the environment—or more precisely, the form of the apparatus–environment interaction Hamiltonian—determines the preferred basis of the apparatus, and in turn also the preferred basis of the system ("environment-induced superselection").

Of course, we can generalize these findings from a setup explicitly containing measuring devices to the more general situation of entanglement between arbitrary systems and their environment. The fact that physical systems are usually observed to have determinate values only with respect to a small number of quantities (typically position for macrosopic objects) can then be explained by the fact that the system–environment interactions depend on precisely these quantities, e.g., distance (relative position). The commutativity criterion then implies that the system will preferably be found in (approximate) eigenstates of observables corresponding to those quantities. Sinc this selection mechanism is based on standard unitary quantum mechanics, it avoids the necessity to postulate *ad hoc* basis selection criteria, and it can therefore also be expected to be in agreement with our observations.

Apart from the most simple toy model cases, the commutativity criterion holds usually only approximately [67, 70], and general operational methods have therefore been proposed to determine (at least in principle) the preferred basis in more complex situations [67–70]. One remaining conceptual problem concerns the question of what counts as the "system" and what as the "environment," and where to place the cut (see the discussion in Sec. IV below). Nonetheless, environment-induced selection can be considered as the most promising approach toward explaining the emergence and stability of preferred states.

B. The problem of outcomes

Let us again consider the situation of von Neumann quantum measurement in form of an interaction that entangles the state of the system with the state of the measuring apparatus. We now also include the environment into the chain of interactions. That is, the apparatus $\mathcal{A}$ interacts with the system $\mathcal{S}$; in turn, the $\mathcal{SA}$ combination then interacts with the environment $\mathcal{E}$. The linearity of the Schrödinger equation yields the following time evolution of the entire system $\mathcal{SAE}$:

$$\begin{aligned}\left(\sum_n \lambda_n |s_n\rangle\right)|a_0\rangle|e_0\rangle &\longrightarrow \left(\sum_n \lambda_n |s_n\rangle|a_n\rangle\right)|e_0\rangle \\ &\longrightarrow \sum_n \lambda_n |s_n\rangle|a_n\rangle|e_n\rangle. \quad (11)\end{aligned}$$

Here $|a_0\rangle$ and $|e_0\rangle$ are the initial states of the apparatus and the environment, respectively. Evidently, after the interaction has taken place, the combined system $\mathcal{SAE}$ is described by a coherent pure-state superposition at all times. While the dislocalization of the phases λ_n into the $\mathcal{SAE}$ combination resulting from the interaction between $\mathcal{S}$, $\mathcal{A}$, and $\mathcal{E}$ "dissolves" local interference into the global system (see Sec. II), this decoherence process by itself does not automatically explain why definite outcomes are perceived. Since superpositions represent individual quantum states in which all components of the superposition "exist" simultaneously, we cannot (and must not) isolate a single apparatus state $|a_m\rangle$ that would indicate an actual outcome of the measurement.

We can break free from the persistence of coherence in the $\mathcal{SAE}$ combination only when the dynamics of the open subsystem $\mathcal{SA}$ in terms of its reduced density matrix is considered. And, of course, all that we really need is the ability to ascribe a definite value to $\mathcal{A}$ (to be precise, to the $\mathcal{SA}$ combination, if the measurement is to be considered faithful), rather than to the total system $\mathcal{SAE}$. The time evolution of the reduced density matrix will in general be nonunitary, since it is not only influenced by the Hamiltonian of $\mathcal{SA}$, but also by the interacting (but averaged-out) environment. As indicated before, decoherence leads to the formation of "classical-looking" density matrices for $\mathcal{SA}$: The reduced density matrix $\rho_{\mathcal{SA}}$ becomes rapidly diagonal in a set of stable, environment-selected basis states. In other words, the decohered density matrix of the local system–apparatus combination becomes *operationally* indistinguishable from that of an ensemble of states, and it correctly describes the time evolution of the open system $\mathcal{SA}$.

It would then seem that decoherence could account for the existence of a local ensemble of potential measurement outcomes with definite probabilities (that in turn could then be related to the occurence of single outcomes in individual measurements). The problem with this argument has already been briefly touched upon earlier: The averaging-out of environmental degrees of freedom by means of the trace operation needed to arrive at the reduced density matrix relies on the probabilitistic interpretation of the state vector (i.e., on the interpretation of $|\langle\varphi_k|\Psi\rangle|^2$ as the probability for the system described by the state vector $|\Psi\rangle$ to be found in the state $|\varphi_k\rangle$ upon measurement). In turn, this is related to the assumption of some form of wavefunction "collapse" at a certain stage of the observational chain. In this sense, taking the trace essentially "amounts to the statistical version of the projection postulate" [49, p. 432]. Of course we do not want to presuppose some sort of collapse that would solve the measurement problem trivially without even necessarily having to worry about the role of decoherence.

We therefore conclude that, by itself, decoherence does not directly solve the measurement problem. After all, this might not come as a surprise, as decoherence simply describes unitary entanglement of wavefunctions — and since the resulting entangled superpositions are precisely the source of the measurement problem, we cannot expect the solution to this problem to be provided by decoherence. However, the fact that the reduced density matrices obtained from decoherence describe observed open-system dynamics and the emergence of quasiclassical properties for these systems perfectly well, decoherence is extremely useful in motivating solutions to the measurement problem. This holds especially when the physical role of the observer is correctly taken into account in quantum-mechanical terms of system–observer correlations, making more precise what the "perception of definite outcomes" and the related measurement problem actually *mean* in terms of physical observations.

Accordingly, we shall describe in Sec. V how decoherence can be put to use in various interpretations of quantum mechanics, especially with respect to a resolution of the measurement problem. Before that, however, we shall discuss in the next section a couple of conceptual issues related to decoherence.

IV. RESOLUTION INTO SUBSYSTEMS AND THE CLOSED-UNIVERSE OBJECTION

The application of the theory of decoherence requires a decomposition of the total Hilbert space into subsystems. As long as we consider the Universe as a whole, it is fully described by its state vector $|\Psi\rangle$ that evolves strictly deterministically according to the Schrödinger equation, and no interpretive problem seems to arise here. The notorious measurement problem only comes into play once we decompose the Universe into subsystems (thus forming the joint product state $|\Psi\rangle = |\psi_1\rangle \otimes |\psi_2\rangle \otimes \cdots$), and attempt to attribute *individual* states to the subsystems.

However, there exists no general criterion that would determine where the splitting cuts are supposed to be placed. Of course, in a standard laboratory-like measurement situation, the physical setup might lead to an easy identification of "the system of interest," "the measuring device," and "the external environment." But this is a rather special and subjective rule for the splitting, and confronted with a more complex state space (encompassing, say, larger contiguous parts of the Universe), there is neither a general rule for decomposition (given, for example, a total Hilbert space and its Hamiltonian) nor a definition for what counts as a "system." This issue becomes particularly important if one would like to use decoherence to define "objective macrofacts" of the Universe as a whole. On the other hand, one might of course adopt the view that all correlations (and the resulting properties) should be considered as intrinsically relative to a given local observer, and that therefore a general rule for "objective" state-space decompositions need not be required.

Also, the ignorance-based coarse-graining procedure required by decoherence to obtain the reduced density matrix requires the openness of the system. But what about if we take this system to be the Universe as a whole? (Quantum cosmology, for example, is all about studying the evolution of the Universe in its entirety.) By definition, the Universe is a closed system, and thus no external environment exists whose "unobserved" degrees of freedom could be averaged over. This has become known as the "closed-Universe problem." From the point of view of talking about "events" or "facts" as the result of observations, this does however not necessarily constitute a problem, since every observation is inherently local and presupposes the ignorance of certain other parts. As Landsman [43, pp. 45–46] put it, "the essence of a 'measurement', 'fact' or 'event' in quantum mechanics lies in the non-observation, or irrelevance, of a certain part of the system in question. (. . .) A world without parts declared or forced to be irrelevant is a world without facts."

V. DECOHERENCE AND INTERPRETATIONS OF QUANTUM MECHANICS

There are numerous interpretive approaches to quantum mechanics. On the "standard" (textbook) side, we have the "orthodox" interpretation with its infamous collapse postulate, together with the similar (and often not distinguished) Copenhagen interpretation. As "alternative" interpretations, we can name several main categories: the relative-state interpretation, introduced by Everett [26] (and further developed as "many-worlds" and "many-minds" interpretations); the class of modal interpretations, first suggested by van Fraassen [58]; physical collapse theories like the Ghirardi–Rimini–Weber (GRW) approach [32]; the consistent-histories approach introduced by Griffiths [33] (for a review, see [45]); and the de Broglie–Bohm pilot-wave theory, a highly nonlocal hidden-variable interpretation [15, 16]. Common to all of the alternative approaches is their attempt to dispose of the collapse postulate of the orthodox (and Copenhagen) interpretation. Some of them are just alternative readings of the formalism of standard quantum mechanics (Everett), others modify the rules that connect the formalism to the actual physical properties (modal interpretations), postulate new physical mechanisms (GRW), and introduce additional governing equations (de Broglie–Bohm).

The necessity to include environmental interactions for a realistic description of the behavior of physical systems is an objective one, independent of any interpretive framework. But the effects (and their proper interpretation) arising from such interactions have much to do with conceptual and interpretive stances. For instance, we might ask whether decoherence effects alone can already solve some of the foundational problems without the need for certain interpretive "additives," or whether decoherence can motivate (or falsify) some approaches – or even lead to a unification of different interpretations. In the following, we discuss some of the connections between decoherence and the main interpretations of quantum mechanics. For a more detailed treatment, we refer the interested reader to Ref. [52].

A. The orthodox and the Copenhagen interpretations

A central element of orthodox interpretations is the well-known collapse (or projection) postulate which prescribes that every measurement, represented by some suitably chosen observable, leads to nonunitary reduction of the total state vector to an eigenstate of the measured observable. To avoid the preferred basis problem, measurements are assumed to be carried out by an "observer" that can freely "choose" an observable before the measurement, and thus determine what properties can be ascribed to the system after the measurement (a strongly positivist, observer-dependent viewpoint).

A major problem with this approach is that it is not clearly defined what counts as a "measurement," and that the measuring process has a strong "black box" character. It does not explain why measuring devices seem to be designed to measure certain quantities but not others. Taking into account environmental interactions can provide the missing physical description of measurements. According to the stability criterion of the decoherence program, for a measurement to count as such, it must lead to the formation of stable records in spite of its immersion into the environment. Therefore, the structure of the interaction between the apparatus and its environment singles out the preferred observables of the apparatus (and thereby also determines what properties can be assigned to the measured system). In this sense, decoherence and environment-induced selection can augment, if not replace, the formal and vague concept of measurement employed by the orthodox interpretation with general observer-independent criteria that specify what observables can actually be measured by a given apparatus.

The most distinctive feature of the Copenhagen interpretation (compared to the orthodox interpretation) is its postulate of the necessity for classical concepts to describe quantum phenomena. Instead of deriving classicality from the quantum world, e.g., by considering the macroscopic limit, the requirement for a classical description of the "phenomena," which comprise the whole experimental arrangement, is taken to be a fundamental and irreducible element of a complete quantum theory. Specifically, the Copenhagen interpretation postulates the existence of intrinsically classical measuring devices that are not to be treated quantum mechanically.

This introduces a quantum–classical dualism into the description of nature and requires the assumption of an essentially nonmovable boundary (the famous "Heisenberg cut") between the "microworld," containing the objects that are to be treated as quantum systems, and the "macroworld" that has to be described by classical physics.

However, the studies of decoherence phenomena demonstrate that quasiclassical properties, across a broad range from microscopic to macroscopic sizes, can emerge directly from the quantum substrate through environmental interactions. This makes the postulate of an *a priori* existence of classicality seem unnecessary, if not mistaken, and it renders unjustifiable the placement of a fixed boundary to separate the quantum from the classical realm on a fundamental level.

B. Relative-state interpretations

The core idea of Everett's original relative-state proposal, and of its interpretive extensions into a many-worlds or many-minds framework, is to assume that the physical state of an isolated system (in particular, that of the entire Universe) is described by a state vector $|\Psi\rangle$, whose time evolution is given by the Schrödinger equation that is assumed to be universally valid. All terms in the superposition of the total state correspond in some way to individual physical states (realized, for instance, in different "branches" of the Universe or "minds" of an observer). One major difficulty of this approach is the preferred basis problem, which is here particularly acute since each term in the state vector expansion is supposed to correspond to some "real state of affairs." Thus, it is crucial to be able to define uniquely a particular basis in which to expand the continuously branching (since new quantum correlations are formed constantly and everywhere) state vector at each instant of time.

It has frequently been suggested to use the environment-selected basis to define the preferred branches. This has several advantages. Instead of having simply to postulate what the preferred basis is, the basis arises through the interaction with the environment and the natural criterion of "robustness." Clashes with empirical evidence are essentially excluded, since the selection mechanism is based on well-confirmed Schrödinger dynamics. Finally, and maybe most importantly, the environment-preferred components of the decohered wavefunction can be reidentified over time, which yields stable, temporally extended branches.

There have been several criticisms of this idea. First, as we have pointed out before, there exists no objective rule for what counts as a system and what can be considered as the environment. Therefore, decoherence-induced selection of branches is often promoted in the context of an observer-based (subjective) interpretation (see, for example, [40, 55, 61, 64, 68, 69]). Typically this includes the observer's neuronal (perceptional) apparatus in the full description of observations, instead of assuming the existence of "external" observers that are not treated as interacting quantum systems. Each neuronal state then becomes correlated with the states corresponding to the individual terms in the superposition of the observed system, and decoherence between these different brain states [56] is assumed to prevent the different "outcome records" from interfering and thus to lead to a perception of individual outcomes.

Second, decoherence typically yields only an approximate ("for all practical purposes" [12]) definition of a preferred basis and therefore does not provide an "exact" specification of branches [42, 61]. Responses to this criticism suggest that it is fully sufficient for a physical theory to account for our experiences, which does not entail the necessity for exact rules as long as the emerging theory is empirically adequate [19, 59].

C. Modal interpretations

The main characteristic feature of modal interpretations is to abandon the rule of standard quantum mechanics that a system must be in an eigenstate of an observable in order for that observable to have a definite value. In its place, new rules are introduced that specify lists of possible properties (definite values) that can be ascribed to a system given, for example, its density matrix $\rho(t)$. The results of the theory of decoherence have frequently been used to motivate and define such rules of property ascription. Some [20, 21] have even suggested that one of the main goals of modal interpretations is to provide an interpretation of decoherence. The basic approach consists of using environment-selected preferred bases (in which the decohered reduced density matrix is approximately diagonal) to specify sets of possible quasiclassical properties associated with the correct probabilities. This provides a very general and entirely physical rule for property ascriptions that can be expected to be empirically adequate. The rule could also be used to yield property states with quasiclassical, continuous "trajectory-like" time evolution (since the decohered components of the wavefunction are stable and can thus be reidentified at over time) that is in accordance with unitary quantum mechanics [10, 36].

The difficulty with this approach lies in the fact that determining the environment-selected robust basis states explicitly is nontrivial in more complex systems. The aim of modal interpretations, however, has been to formulate a general rule from which the set of possible properties can be directly and straightforwardly derived. Frequently, instead of explicitly finding preferred states on the basis of the stability criterion (or a similiar measure), the orthogonal decomposition of the decohered density matrix has been used to determine the property states directly. When applied to discrete models of decoherence (that is, for systems described by a finite-dimensional Hilbert space), this method has in most cases been found to yield states with the desired quasiclassical properties, similar to those obtained from the stability criterion, at least when the final composite state was sufficiently nondegenerate [11, 14]. In the continuous case, however, it has been demonstrated that the predictions of decoherence (e.g., as measured by the coherence length of the density matrix) and the properties of the states determined from the orthogonal decomposition do not mesh [9]. Thus decoherence can here be used to indicate that certain methods of property ascription might be physically inadequate [22].

D. Physical collapse theories

These are theories that modify the unitary Schrödinger dynamics to induce an actual collapse of the wavefunction based on a physical mechanism. The most popular version has probably been the one proposed by Ghirardi, Rimini and Weber (GRW) [32] which postulates the existence of instantaneously and spontaneously occurring "hits" that lead to a spatial localization of the wavefunction. The frequency of the hits is chosen such that macroscopic objects are localized faster than any observation could resolve, while preserving an effectively unitary time evolution on microscopic scales.

Decoherence provides a physical motivation for the *a priori* choice of position as the universal preferred basis in the GRW theory. Many physical interactions are described by distance-dependent terms, which according to the stability criterion of the decoherence program leads to the selection of (at least approximate) eigenstates of the position operator as the preferred basis. On the other hand, however, decoherence also demonstrates that in many situations position will *not* be the preferred basis. This occurs most commonly on microscopic scales, where systems are typically found in energy rather than position eigenstates [48], but also for instance in superconducting quantum interference devices [28] that exhibit superpositions of macroscopic currents. As far as microscopic systems are concerned, the GRW theory avoids running into empirical inadequacies by having the spatial localization hits occur so rarely that state vector reduction in the position basis is effectively suppressed. However, this has certainly an *ad hoc* character in comparison with the more sensitive, general, and physically motivated basis selection mechanism of the decoherence program. Furthermore, since decoherence will always be present in any realistic system, the assumption that the GRW theory holds means that we can expect to have two selection mechanisms that either act in the same direction (if decoherence also leads to a spatial localization) or compete with each other (in cases where decoherence predicts a different preferred basis than position).

It also has been found that the governing equations for the time evolution of the density matrix of a system in the GRW theory bear remarkable similarity to the evolution equations obtained from an inclusion of environmental interactions. This has raised the question whether it is necessary to postulate an explicit collapse mechanism, or whether at least the free parameters in the equations of the GRW approach could be directly derived from the study of environmental interactions [39]. (Of course, GRW achieves true state vector reduction, whereas decoherence only leads to improper ensembles, so they are not on the same interpretive footing.) Assuming the simultaneous presence of decoherence and GRW effects, one could imagine an experimental falsification of the GRW theory by means of a system for which GRW predicts a collapse, but decoherence leads to no significant loss of coherence [50, 53]. However, since any realistic system is extremely hard to shield from decoherence effects, such an experiment would presumably be very difficult to carry out [13, 54].

E. Consistent-histories interpretations

The central idea of this approach is to dispose of the fundamental role of measurements (that assume the existence of external observers) in quantum mechanics and instead study quantum "histories," i.e., sequences of quantum events represented by sets of time-ordered projection operators, and to attribute probabilities to such histories. A set of histories is called consistent (judged by an appropriate mathematical criterion) when all its members are independent, that is, when they do not interfere and the classical probability calculus can be applied.

One major problem of this approach has been that the consistency criterion appears to be insufficient to single out the quasiclassical histories that would correspond to the world of our experience—in fact, most consistent-histories turn out to be highly nonclassical [2, 24, 25, 29, 30, 47, 67]. To overcome this difficulty, decoherence has frequently been employed in proposals that would lead to a selection of quasiclassial histories, and also in attempts to provide a physical motivation for the consistency criterion (see, for example, [1, 2, 6, 23, 27, 29, 31, 35, 47, 57, 67]). Interestingly, this move has also introduced a conceptual shift. While the original aim of the consistent-histories program had been to define the time evolution of a single, closed system (often the entire Universe, where standard quantum mechanics runs into problems as no external observers can be present), wedding decoherence to the consistent-histories formalism requires a division of the total Hilbert space into subsystems and the openness of the local subsystems.

The decoherence-based approach commonly consists of using the environment-selected pointer states that (approximately) diagonalize the reduced density matrix as the projectors of histories. This leads typically to the emergence of histories that are stable and exhibit quasiclassical properties, since the pointer basis is "robust" and corresponds well to the determinate quantities of our experience. Moreover, such histories defined by projectors corresponding to the pointer basis also turn out to fulfill the consistency criterion automatically, at least approximately. This has led to the argument that the consistency criterion is both insufficient and overly restrictive in singling out histories with quasiclassical properties, and to a questioning of the fundamental role and relevance of this criterion in consistent-histories interpretations in general [1, 2, 30, 33, 45–47, 57, 67].

F. Bohmian mechanics

Bohm's approach describes the deterministic evolution of a system of particles, where the system is described both by a wavefunction $\psi(t)$, evolving according to the standard Schrödinger equation, and by the particle positions $\mathbf{q}_k(t)$, whose dynamics are determined by a simple "guiding equation" for the velocity field, essentially the gradient of $\psi(t)$. Particles then follow well-defined trajectories in configuration space represented by the configuration $\mathcal{Q}(t) = (\mathbf{q}_k(t), \dots, \mathbf{q}_N(t))$, whose distribution is $|\psi(t)|^2$.

Bohm's theory has been criticized for attributing fundamental ontological status to particles. It has been argued that, since decoherence typically leads to ensembles of wavepackets that are narrowly peaked in position space, one can identify these wavepackets with our (subjective) perception of particles, i.e., spatially localized objects [62, 63, 65]. This suggests that the explicit assumption of the existence of actual particles at a fundamental level of the theory might be rendered superfluous (modulo the basic question of how to go from an apparent to a proper ensemble of wavepackets).

Another problem is how to relate the Bohmian particle trajectories to quasiclassical trajectories that emerge on a macroscopic scale. Going back to studies of Bohm himself [17], it has been suggested that the inclusion of environmental interactions could provide the missing ingredient to arrive at quasiclassical trajectories. Typically the idea has been to identify the Bohmian trajectories $\mathcal{Q}(t)$ with the temporally extended, spatially localized wavepackets of the decohered density matrix that describe macroscopic objects. While this approach is highly intuitive and has been demonstrated to yield promising results in some of the explicitly studied examples, in other cases this identification turns out to be insufficient to sustain the classical limit [3–5, 7, 51, 63].

VI. OUTLOOK

The key idea of the decoherence program relies on the insight that, in order to properly describe the behavior of a physical system in quantum-mechanical terms, the omnipresent interactions of the system with the degrees of freedom of its environment must be taken into account. The application of the formalism of decoherence to numerous model systems has led to many experimentally verified results, so the idea has proven to be very successful. Interestingly, however, the rather straightforward and well-studied approach of decoherence, both experimentally and theoretically, has led to several fundamental interpretive and conceptual questions.

By itself, decoherence simply describes environmental entanglement and the resulting practically irreversible dislocalization of local phase relations (i.e., of quantum-mechanical superpositions). Since the entangled pure state makes it impossible to assign an individual state vector to the system, the dynamics of the system must be described by a nonunitarily evolving reduced density matrix. While decoherence transforms such density matrices into apparent ensembles of quasiclassical states (which, when properly interpreted, may be used to obtain a physically motivated resolution of the measurement problem), the formalism and interpretation of reduced density matrices *presume* the probabilistic interpretation of the wavefunction. Thus decoherence alone (i.e., without being augmented by some additional interpretive elements) cannot solve the measurement problem. Furthermore, the requirement for a division of the Universe into "systems" and "environments" introduces a strong flavor of subjectivity, since no general and objective rule exists for how and where to place the cuts. Also, the necessity for an "external" environment leads to difficulties when one would like to apply the theory to the Universe as a whole, as in quantum cosmology.

This situation requires and motivates interpretive frameworks beyond the "orthodox" interpretation, frameworks that might provide some of the missing steps toward a conceptually complete and consistent interpretation of the decoherence program, and of quantum mechanics as a whole. Conversely, the assumptions made by an interpretation must be consistent with the results obtained from decoherence, thus narrowing down the spectrum of possible (empirically adequate) interpretations—maybe even making the choice between different such interpretations "purely a matter of taste, roughly equivalent to whether one believes mathematical language or human language to be more fundamental," as Tegmark [55, p. 855] put it in a comparison of orthodox and decoherence-based relative-state interpretations. Clearly, the rather simple idea of including environmental interactions as promoted by decoherence has an extremely important impact on the foundations of quantum mechanics, suggesting solutions to fundamental problems as well as posing new conceptual questions.

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Why Did Nature Choose Quantum Theory?

Schrödinger's cat may help reveal why some physical theories are better at describing reality than others.

by Maximilian Schlosshauer

When Jonathan Barrett took his university entrance exam, he was given forty-five minutes to write an essay with the title, "Could things be otherwise?" Now a young lecturer in mathematics at University of London, UK, he keeps returning to the question.

Today, Barrett is particularly fascinated by quantum theory, which describes the physics of the atomic realm. He and his colleague Stefano Pironio, at the Free University of Brussels, are pondering what makes quantum theory, rather than an alternative physical model, the best bet for navigating *our* world. "Why," in Barrett's words, "did nature choose quantum theory?"

Barrett's first encounters with the quantum theory weren't too memorable, however. "It seemed like a perfectly good bit of technical physics," he recalls, "but not the beautiful and poorly understood thing I know it is now." Quantum mechanics has a reputation for being bizarre; its conventional interpretation tells us, for instance, that reality is indeterministic at its core. Physicists cannot calculate the precise outcomes of quantum experiments before they have been performed; they can only work out the probabilities of getting a certain result. But being a probabilistic theory is not enough to define what is special about quantum mechanics. In fact, in recent years, **physicists have come to realize that there is a whole zoo of alternative probabilistic theories sharing many of quantum theory's other mysterious-sounding features—such as entanglement, interference, teleportation, and nonlocality. Yet these alternatives have been rejected by nature.** Studying these alternatives has already told physicists much about what isn't unique to quantum theory. But what *is*?

Barrett and Pironio are proposing a new tack on this subtle problem: "What we want to know is whether facts about time can explain why quantum theory has the structure it does," says Barrett.

Schrödinger's Clock?

The duo's collaboration started when Pironio was a Ph.D. student and shared an office with Barrett, then a postdoc, who was examining the family of probabilistic theories to which quantum physics belongs. Pironio thought that the **key** feature distinguishing quantum theory from its siblings might be ***reversibility***. One of the most puzzling aspects of quantum theory is its built-in tension between reversibility and irreversibility. Take an object not interacting with anything else, and it evolves smoothly, predictably, and reversibly. But whack it with a measurement apparatus, and now the theory prescribes an unpredictable, irreversible jump to a new state. This is often exemplified by the paradox of Schrödinger’s cat, in which an unfortunate feline is trapped in a box with a vial of poison that will be released if a radioactive atom decays, triggering a hammer that smashes the vial. Before the box is opened, the radioactive atom exists in a superposition state of ’decayed’ and ’not decayed’—described by reversible physical equations—and thus the cat is neither alive nor dead. Once the box is opened, however, the cat will be found to be either dead or alive. If dead, you will not be able to turn back the clock and bring Schrödinger’s cat back to life.

With their attention tuned to time and reversibility in quantum mechanics, Barrett and Pironio began to make connections with the arrow of time, which is conventionally thought of in thermodynamic terms. As any child’s toy room illustrates, disorder—or thermodynamic entropy—increases over time. This is codified in the second law of thermodynamics, which thus gives time a preferred direction. The version of quantum theory that physicists know and love obeys the second law of thermodynamics. But what about alternative probabilistic theories? If they violate the second law, could that be the reason that nature favors quantum mechanics?

Talk about time’s arrow also raises questions about cause and effect. In everyday life, we know intuitively that effects cannot occur before the events that caused them. But quantum theory is notoriously fuzzy about which events cause others. Take entanglement for instance, the quantum phenomenon in which two or more particles become inextricably intertwined in such a way that measuring the properties of one seemingly influences the properties of its partners, no matter how far apart they are separated. Physicists shy away from saying that the measurement on the first particle *causes* the change in the others, preferring instead to say that the particles’ properties are correlated. "And as any good scientist knows," Barrett says, "correlation does not imply causation."

In the 1960s, John Bell proposed an experimental test that could explicitly uncover whether quantum-mechanical correlations between two distant events have an intuitive causal origin. Such Bell tests have now been carried out and consistently demonstrate that entangled particles defy simple cause-and-effect explanations. Bell’s work lit many fires, most of them still burning, and Barrett and Pironio want to help clear the smoke. To do so, they have turned to *Bayesian networks*, a tool often used by scientists to model probabilistic relationships, for instance, between the occurrence of certain medical symptoms and the presence of a particular disease. By adapting the standard Bayesian-network formalism to quantum theory, they plan to reinvestigate the connections between Bell’s spooky correlations and causation.

"This is a fruitful topic," says Guido Bacciagaluppi, a philosopher of physics at the University of Aberdeen, UK. "Causality in quantum mechanics and causality in Bayesian networks are now two highly developed areas."

John Cramer, a physicist at the University of Washington in Seattle, adds that examining why alternatives to quantum theory are not realized in nature could have a long-term payoff for those currently struggling to unite the theory with Einstein’s description of gravity. "Such an approach could conceivably provide insights into the structure that a theory of quantum gravity might have to have," he says.

Barrett’s ambitions are more modest, however. When asked what he hopes to have achieved in ten years from now, he chuckles. "If this were a job interview, I would go on about being an international leader in the field, establishing a broad base of research income." He pauses. "I think the honest answer is that I hope to have had an idea. A good one. Something totally different from anything I’m imagining right now."