# 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 But perhaps that's an outdated image.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).

# INDEX

*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.