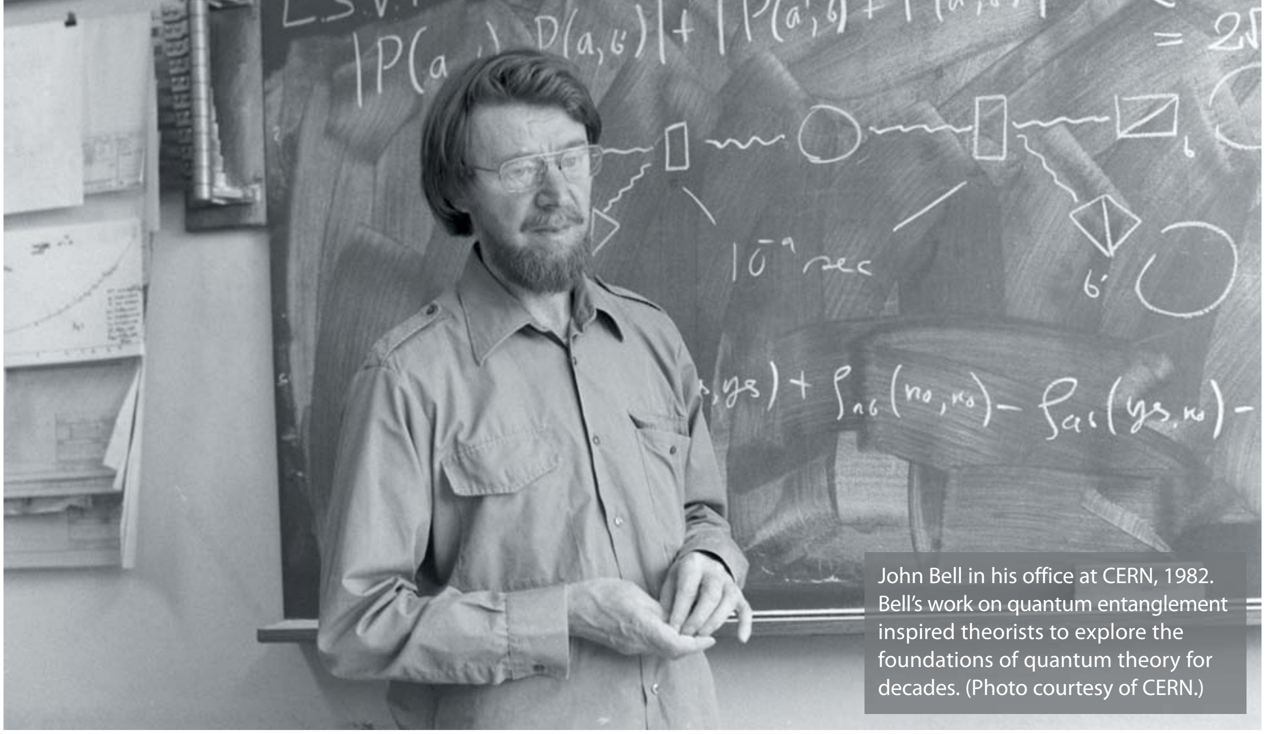

John Bell in his office at CERN, 1982. Bell's work on quantum entanglement inspired theorists to explore the foundations of quantum theory for decades. (Photo courtesy of CERN.)

Quantum foundations

David P. DiVincenzo and Christopher A. Fuchs

More than a century after the birth of quantum mechanics, physicists and philosophers are still debating what a "measurement" really means.

It's sometimes said that the field of quantum information and computing ought to be called applied quantum foundations. That's because so many of the ideas that first arose when scientists began thinking deeply about the mysteries of quantum theory—entanglement, Bell inequality violations, parallel worlds, interference of probabilities, and quantum contextuality—are now seen to be resources for attaining feats in information processing unimaginable in a classical world. Not only has *Reviews of Modern Physics* (*RMP*) nurtured that vibrant young field, it deserves credit for laying its very foundation.

Arguably the most far-reaching article on quantum foundations to come through the pages of *RMP* was also its first: Richard Feynman's 1948 "Space-time approach to non-relativistic quantum mechanics."[1] Well-known for introducing the technique of path integrals, the paper goes deeper in presenting what Feynman considered the distinguishing mark between classical and quantum physics. At issue was how probabilities for the outcomes of an actual measurement are calculated in terms of the probabilities given by unperformed measurements. Feynman's resolution was to introduce the amplitude calculus, but the foundational statement on which it was based was quite clear: "We are led to say that the statement, '*B* had some value,' may be meaningless whenever we make no attempt to measure *B*."

Hidden variables

But maybe there is a way to preserve the notion that unperformed measurements have unrevealed values after all, perhaps at the cost of giving up some less-cherished classical intuition. That was the subject of three groundbreaking papers in *RMP*'s 1966 volume.[2–4] In a 1952 non-*RMP* paper, David Bohm proposed the first hidden-variable extension of nonrelativistic quantum theory:[5] A spinless particle actually could be modeled as having a preexistent position and momentum despite Niels Bohr's edict of "complementarity." Indeed, researchers showed in the years since that there are many ways to supplement quantum theory with hidden variables; Bohm and Jeffrey Bub wrote in *RMP* about one such way.[3] The only deciding factors seemed to be the inventors' intuitions and their hopes that the new hidden-variable models might lead to new physics.

Yet in 1952 a young John Bell was already thinking "How could this be?" For John von Neumann had "proved" years earlier the impossibility of hidden-variable extensions of quantum theory. Bell's paper[2] (which had accidentally languished for two years in the *RMP* editorial office!) and Bohm and Bub's papers[3,4] tackled the

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question head-on. The common conclusion was that von Neumann's theorem and later refinements of it rested on overly restrictive assumptions that the various hidden-variable models simply shrugged off. Most portentous was a line at the end of Bell's paper: "It would . . . be interesting . . . to pursue some further 'impossibility proofs,' replacing the arbitrary axioms [I] objected to . . . by some condition of locality, or of separability of distant systems." In fact, Bell had already settled his question in the intervening years: No local hidden-variable model could ever be up to the job of reproducing quantum theory's statistics, he concluded. In other words, all successful hidden-variable models must have what Albert Einstein dubbed "spooky action at a distance."

Is locality a less cherished principle to give up than the idea that unperformed measurements have preexistent (but yet to be seen) outcomes? Einstein in 1948 had already expressed the conundrum with admirable clarity: "Without . . . an assumption of the mutually independent existence . . . of spatially distant things . . . physical thought in the sense familiar to us would not be possible. Nor does one see how physical laws could be formulated and tested without such a clean separation."[6] In the years after Bell, the points were made increasingly sharp, culminating 45 years after Einstein's statement with one of the most powerful and thorough presentations of what is at stake with those considerations: David Mermin's *RMP* analysis of the then newly discovered three-particle Greenberger-Horne-Zeilinger paradox.[7]

It from bit

Unperformed measurements either have no outcomes or they have some but with spooky action at a distance. Is there any other option besides those? Might unperformed measurements have all possible outcomes? As strange as it might seem, that question too was first explored in the pages of *RMP*—through Hugh Everett III's seminal paper on the many-worlds interpretation of quantum theory.[8] His idea was that the universe obeys a giant Schrödinger equation, and there is no such thing as "measurement" in any preferred or fundamental sense. There is only physical interaction as specified by the Hamiltonian of the universe, and that interaction leads the universe to continuously branch into parallel worlds.

As John Wheeler argued in a companion piece to the paper, a key attraction to the many-worlds view is that it seems to offer a way forward for quantizing general relativity.[9] Yet the Everett interpretation has not been without its problems. Most prominent among them is how one can justify the particular probability calculus of quantum theory from its completely deterministic picture. Since 1957 a surprising number of distinct potential solutions have been proposed for that fundamental problem, with still no consensus at hand. But *RMP* has been there too, with Wojciech Zurek's comprehensive analysis of what the notion of decoherence brings to the table.[10]

Wheeler eventually had his own problems with Everett's interpretation,[11] but the influence he had on all the interpretations discussed here is interesting in its own way. Wheeler was the PhD adviser of both Feynman and Everett when they were doing their foundational work, and Zurek was his postdoc. In the last 25 years of his life, Wheeler landed on a peculiar thought. He desperately wanted to know "Why the quantum?" and it was his conjecture that whatever the answer, it should be of an "information-theoretic color."

In fact, Wheeler's perspective was in no small part responsible for the field of quantum information. One of us (Fuchs) was lucky enough to be under Wheeler's tutelage at the time, and it led to a quest for how to think about quantum states consistently as (subjective) information. The end point was a view of quantum theory called quantum Bayesianism, or QBism, which also made its debut in *RMP*.[12] One of the things that sets QBism apart from the other interpretations is its reliance on the technical details of quantum information to amplify Feynman's point—that the modification of the probability calculus in quantum theory indicates that something new is created in the universe with each quantum measurement. Only it takes the formalism of quantum information to see it with the greatest clarity. (See the Commentary by N. David Mermin, PHYSICS TODAY, July 2012, page 8.)

Indeed, by the example of QBism, one might wonder whether quantum foundations is "applied quantum information" instead. So the subject comes full circle. Whatever the future directions in quantum foundations research, history bears out that *RMP* will be there publishing the deepest and most far-reaching articles on the subject.

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David Mermin has collected his 1988–2014 PHYSICS TODAY essays, with further remarks, in *Why Quark Rhymes with Pork, and Other Scientific Diversions* (2016). Much biographical information is cited in its index.

There is no quantum measurement problem

N. David Mermin

The idea that the collapse of a quantum state is a physical process stems from a misunderstanding of probability and the role it plays in quantum mechanics.

There are three types of quantum physicists: (1) those who think quantum mechanics is defaced by a so-called measurement problem; (2) those who think, as I do, that there is no measurement problem; and (3) those who think the issue is not worth serious thought. You can find the diverse views of 17 physicists and philosophers from the first two groups in chapter 7 of Maximilian Schlosshauer's *Elegance and Enigma.*

Most people in all three groups would agree on the following: Quantum mechanics describes a physical system entirely in terms of states. A state is a compendium of probabilities of all possible answers to all possible questions one can ask of the system. Quantum mechanics is inherently statistical. There is no deeper underlying theory that gives a fuller description.

The state assigned to a system can change in time in two ways. If no question is asked of the system, then its state evolves in time deterministically: continuously and according to fixed rules. If a question is asked of the system—called making a measurement—then when the question is answered, the state changes discontinuously into a state that depends both on the state just before the question was asked and on the particular answer the system gives to that question. The second process is called the collapse of the state. Collapse is generally abrupt, discontinuous, and stochastic.

A physical system together with another physical system that carries out a particular measurement—an apparatus—can be treated by quantum mechanics as a single composite system. If the composite system is not questioned, then quantum mechanics gives a deterministic time evolution to the state assigned to it. If the entire composite system is questioned, however, the state assigned to the composite system gives probabilities that correlate the possible answers given by the state assigned to the original system with states assigned to the apparatus that indicate those possible answers. The associated probabilities are just those that quantum mechanics would give for the original system alone. So as far as probabilities are concerned, it makes no difference whether one applies quantum mechanics to the original system alone or to the composite original system + apparatus.

Many physicists in group 2 would add the following: There are no consequences of a quantum state assignment other than all the probabilities it gives rise to. While many (perhaps most) physicists view probabilities as objective features of the world, most probabilists and statisticians do not. As the celebrated probabilist Bruno de Finetti put it, "The abandonment of superstitious beliefs about the existence of Phlogiston, the Cosmic Ether, Absolute Space and Time, . . . , or Fairies and Witches, was an essential step along the road to scientific thinking. Probability, too, if regarded as something endowed with some kind of objective existence, is no less a misleading misconception, an illusory attempt to exteriorize or materialize our actual probabilistic beliefs."

Physicists who materialize their own probabilistic beliefs must also materialize quantum states, which are nothing more than catalogs of such beliefs. But a physicist who regards probabilities as personal judgments must necessarily view the quantum states he or she assigns as catalogs of his or her own personal judgments. That the quantum state of a system expresses only the belief of the particular physicist who assigns it to the system was emphasized by the theorists Carlton Caves, Christopher Fuchs, and Rüdiger Schack at the turn of the 21st century as being crucial to the interpretation of quantum mechanics.

The quantum measurement problem

The measurement problem stems from the two ways of viewing a measurement: the system alone or the system + apparatus. If the system alone is measured, its state collapses. But the state of the composite system + apparatus does not collapse until the apparatus is examined. Which description is correct? Which is the real state?

The answer from group 2 is that there is no real state of a physical system. What one chooses to regard as the physical system and what state one chooses to assign to it depend on the judgment of the particular physicist who questions the system and who uses quantum mechanics to calculate the probabilities of the answers.

The interplay between continuous and stochastic time evolution is also a feature of ordinary classical probability. When a statistician assigns probabilities to the answers to questions about a system, those probabilities vary in time by rules giving the smooth time evolution of the isolated unquestioned system. But those probabilities also depend on any further information the statistician acquires about the system from any other source. That updating of probabilities is the abrupt and discontinuous part of the classical process. Nobody has ever worried about a classical measurement problem.

ISOLATED EXCERPTS from Niels Bohr can support many diverse views. But a quarter century after publishing my concluding quotation, he wrote that "physics is to be regarded not so much as the study of something *a priori* given, but rather as the development of methods for ordering and surveying human experience." It's the same opinion, and it has the same ambiguity: Is "human experience" individual or collective? (Photograph by A. B. Lagrelius and Westphal, courtesy of the AIP Emilio Segrè Visual Archives, W. F. Meggers Gallery of Nobel Laureates Collection.)

If the entire content of a quantum state is the catalog of probabilities it gives rise to, then each physicist using quantum mechanics is acting as a statistician. The acquisition of further information by that physicist—whether it be through reading the display of an apparatus, or through communication with other physicists, or just through rethinking what that physicist already knows—can lead to an abrupt change in those probabilities and thus to an updating of the quantum state that the physicist uses to represent them. There is no quantum measurement problem.

Physicists in group 1 deal with their measurement problem in a variety of ways: In their otherwise superb quantum mechanics text Lev Landau and Evgeny Lifshitz insist that quantum mechanics is not to be viewed as a conceptual tool used by observers. This leads them to declare that a measurement is an interaction between objects of the quantum and classical types. How to distinguish between the two (which they never explain) is their (unstated) measurement problem.

Others eliminate the physicist from the story by introducing a particular kind of physical noise that interacts significantly only with subsystems that contain a macroscopic number of degrees of freedom. This special noise is designed to provide a physical mechanism for an objective collapse of an objective state. They solve their measurement problem by introducing a new physical process.

Still others remove the personal judgment of each physicist by eliminating collapse entirely. They take quantum states to describe an inconceivably vast multitude of continuously bifurcating universes—the many-worlds interpretation—that contain every possible outcome of every possible measurement.

Such solutions all take quantum states to be objective properties of the physical system they describe and not as catalogs of personal judgments about those physical systems made by each individual user of quantum mechanics.

Keep the scientist in the science

Why does our understanding of scientific laws have to be impersonal? Science is a human activity. Its laws are formulated in human language. As empiricists, most scientists believe that their understanding of the world is based on their own personal experience. Why should I insist that *my* interpretation of science, which *I* use to make sense of the world that *I* experience, should never make any mention of *me*? The existence of a quantum measurement problem, either unsolved or with many incompatible solutions, is powerful evidence that the experience of the scientist does indeed play as important a role in understanding quantum theory as the experience of the statistician plays in understanding ordinary probability theory.

Niels Bohr never mentioned a quantum measurement problem. I conclude with a statement of his that concisely expresses the view that there is no such problem, *provided* both occurrences of "our" are read not as all of us collectively but as each of us individually. I believe that this unacknowledged ambiguity of the first person plural lies behind much of the misunderstanding that still afflicts the interpretation of quantum mechanics.

"In our description of nature the purpose is not to disclose the real essence of the phenomena but only to track down, so far as it is possible, relations between the manifold aspects of our experience."

Additional resources

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QUICK STUDY

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Addressing the quantum measurement problem

Sean M. Carroll

Attempts to solve the problem have led to a number of well-defined competing theories. Choosing between them might be crucial for progress in fundamental physics.

What precisely happens when a quantum measurement is performed? That's the quantum measurement problem, in broad strokes. There are optimistic folks, like David Mermin (see Physics Today, June 2022, page 62), who believe there is no measurement problem, but that's because they think they know the answer to it. Unfortunately, despite almost a century of effort, no one solution has been completely accepted by a majority of physicists. The fairest thing is to admit that the measurement problem is still with us.

The awkwardness of the measurement problem is only enhanced by the undeniable empirical success of textbook quantum theory. According to that treatment, quantum systems are described using wavefunctions. Wavefunctions evolve according to the Schrödinger equation, at least when the system is not being observed. Upon measurement, the wavefunction collapses to an eigenstate of the measured observable.

That textbook version of quantum mechanics fits a wide variety of data, but it clearly isn't the final answer. It is too vague and ill-defined to qualify as a rigorous physical theory. What exactly is a "measurement"? What kind of system is allowed to make a measurement, and when precisely does it happen? Are measuring apparatuses and observers themselves quantum systems? Do measurements reveal a pre-existing reality, or bring the world into existence?

Any plausible approach to the foundations of quantum mechanics would have to provide definite answers to those questions.

Lines of attack

The issue is not that no plausible solutions to the measurement problem exist, but that several reasonable lines of attack are available, all of which come with obvious drawbacks. In particular, each seems to demand a significant leap away from our traditional intuitive view of the world. Perhaps that is to be expected—quantum mechanics differs profoundly from classical mechanics—but opinions vary about which leaps are worth taking and which are just too wild to countenance.

One strategy, descending from Niels Bohr and Werner Heisenberg, is to take the notion of measurement as central, rather than as an annoying technicality. The basic focus of analysis is not the physical world itself, but rather a set of agents within it, and the experiences and knowledge that those agents accrue. That approach is known as epistemic, because the wavefunction doesn't represent physical reality but is simply a device for tracking what agents know about it. The Copenhagen interpretation falls into this category, as does the QBism approach favored by Mermin and others (see the Commentary by Mermin, Physics Today, July 2012, page 8).

The idea that physics isn't about objective reality, but about the experiences of agents, would certainly be a dramatic shift. It seems counter to the general progression of science, which has acted to remove human beings from a central role in the workings of the universe. More substantively, one would still presumably like a rigorous mathematical definition of what the physical world really is, and for that matter what agents are. But perhaps the radicalness of that change in perspective is simply what quantum mechanics demands of us.

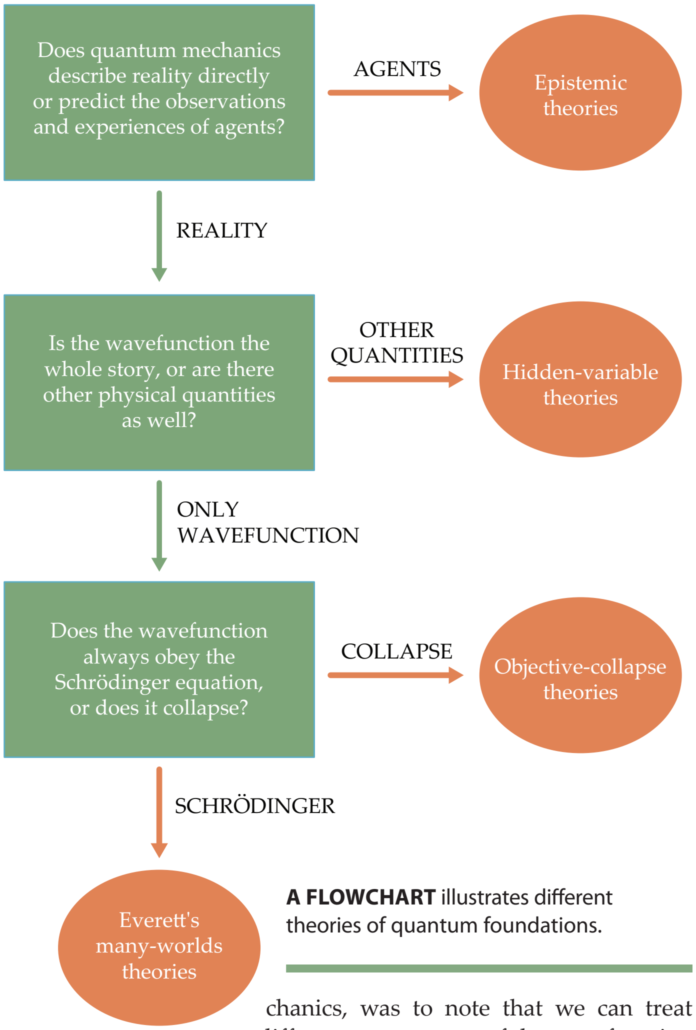
It's not the only option, however. A second strategy is to posit that the wavefunction represents reality, entirely and exactly—an ontic rather than epistemic role. The wavefunction of an electron interferes with itself when it passes through a double-slit experiment; that kind of behavior seems characteristic of physical stuff, not of a knowledge representation. For that matter, things like the solidity of materials are explained in terms of the energies of wavefunctions of atoms; again, a very stuff-like property for something to have.

But we don't see wavefunctions when we measure properties of quantum systems. We see specific values of the quantity being measured. That's what inspired quantum pioneers to think differently. How can we explain that feature if the world is nothing but wavefunction?

Life in a superposition

One bold version of the ontic strategy is to simply erase all of the textbook rules pertaining to observation. Remove measurements from the formalism entirely, accept that the wavefunction describes reality fully, and insist that all it ever does is obey the Schrödinger equation. From those postulates we find that a measuring apparatus does not collapse the state of a measured system; rather, it becomes entangled with it. When an electron's spin is measured, one component of the universal wavefunction describes the electron as spin-up and the observer as having measured it as such, while another component does the same for spin-down. Both components continue to exist if we simply take the Schrödinger equation at face value.

The problem with that perspective is that we never *feel* like we're in a superposition; empirically, we report definite measurement outcomes. The solution proposed by Hugh Everett, founder of the many-worlds interpretation of quantum me-



A FLOWCHART illustrates different theories of quantum foundations.

chanics, was to note that we can treat different components of the wavefunction as distinct, noninteracting worlds. Modern decoherence theory puts meat on those bones, explaining how worlds are chosen and why they never interact.

Problems, no doubt, remain. How do you recover the Born rule—the probability that an outcome is given by its amplitude squared—if every outcome comes true in some branch? At a more philosophical level, are we really prepared to accept the existence of countless copies of ourselves, living in slightly different worlds? That approach is arguably as metaphysically dramatic as putting agents at the center of our theories of physics.

Yet another tactic is possible—still accepting that a wavefunction exactly represents reality, but denying that it always obeys the Schrödinger equation, and instead introducing genuine collapses into the dynamics. Rather than invoking measurements, however, we can allow such collapses to be spontaneous (every particle has a probability per unit time of suddenly localizing) or triggered (collapse happens when branches of the wavefunction become sufficiently distinct). In either case the collapse is imagined to be genuinely stochastic, with frequencies that recover the Born rule.

In effect, those objective collapses prune off the extra worlds implied by Everett's approach. At the same time, doing stochastic violence to the deterministic beauty of the Schrödinger equation might seem *ad hoc*, as is the choice of what the wavefunction collapses to. The good news is that such modifications are generally experimentally testable, though the experiments generally involve keeping large numbers of particles in a coherent superposition.

Hidden variables

The last strategy could be thought of as a middle ground: Accept that the wavefunction is part of reality, but not the whole thing, and not the part we see when we perform a measurement. We see particles, in this view, because particles exist as distinct entities, in addition to the wavefunction. Those extra degrees of freedom are known as hidden variables, even though they are what we observe. The wavefunction acts as a "pilot wave," guiding particles into the right positions to be measured. That guidance is a nonlocal effect, which allows such theories to be compatible with Bell's theorem. Louis de Broglie pioneered the approach, and it has been championed by David Bohm and John Bell.

Pilot-wave theories, like objective-collapse theories, seem a bit contrived. The wavefunction guides the particles, but the particles exert no influence on the wavefunction whatsoever. Perhaps more worryingly, it is hard to generalize that strategy from theories of particles to more modern quantum field theories, and much harder still to imagine how quantum gravity might ultimately be incorporated. Needless to say, proponents of the approach have ideas about addressing those problems, as do partisans of the above theories for the problems of their own.

So there are a number of different approaches to the quantum measurement problem, all of which are legitimately distinct and well-defined physical theories. (And there are others we don't have space to mention.) But at the end of the day their experimental predictions are seemingly identical, or pretty close to it. Should we care?

Yes, we *should* care, because physics isn't finished. As Richard Feynman noted, theories can be formally equivalent but psychologically different. As we try to construct more comprehensive theories of grand unification, quantum gravity, and emergent spacetime, the ideas we come up with might be strongly influenced by our attitude toward quantum foundations. Questions that seem hardly worth addressing in one approach might merit intense concern in another.

Besides, are we sure that those approaches are experimentally equivalent? My own view is that the theories are not quite developed enough, and we haven't yet put sufficient effort into understanding them, to say for sure. Only by knowing exactly what the options are and how they fit in with the rest of physics can we be certain. There might be new experiments that we haven't thought of, which could distinguish between them. And that is what physics is all about.

Additional resources

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