One purpose of a scientific theory is to accurately predict the results of experiments. A *different* purpose of a scientific theory is to describe the nature of reality.

These two goals are so closely linked that we usually don't consider them separately. Copernicus's model of the solar system correctly predicts the images in our telescopes; therefore we believe its underlying claim about planets orbiting the sun. Experiments by Lavoisier and others were incompatible with the phlogiston theory of combustion; therefore we believe that there is no such thing as phlogiston, and that oxygen is required for burning. These and many other theories reveal truths that are often invisible or counter-intuitive. We accept those truths as descriptions of reality (second goal) *because* they successfully match experimental results (first goal).

For the first goal—predicting the results of experiments—quantum mechanics is undoubtedly one of the most successful theories in science. Consider our favorite example, the double-slit experiment. We discuss that experiment in some detail in Sections 3.2 and 3.3, but here's the very short version: photons are fired one at a time through a double slit, and each time one reaches the far wall a spot appears. As far as we know, no theory can predict where the next spot on the wall will appear. But as many photons are fired, and an interference pattern builds up, the probability distribution beautifully follows the prediction made by Schrödinger's equation. The math works.

But this section is about the second goal. If astronomical and chemical results lead us to believe in the reality of planetary orbits and oxidation, what is the underlying reality described by Schrödinger's equation? Answers to that question are generally referred to as "interpretations of quantum mechanics." (Some authors prefer the word "theories," but "interpretations" is more common because these various formulations all predict the same experimental results.) The most common interpretation, sometimes referred to as the "orthodox interpretation," is the model we have generally used in this book. This model explains the double-slit experiment as follows.

- A wavefunction propagates according to the deterministic time evolution described by Schrödinger's equation, passing through both slits and then constructively and destructively interfering at different points in space. During this process, the question "where is the photon?" doesn't have an exact answer; the only reality is the wavefunction.
- When the wavefunction reaches the back wall, the position of the photon is *measured.* This causes a change not predicted by Schrödinger's equation: the wavefunction collapses from a spread-out wave to a highly localized spike. The photon therefore now has a definite position.

As a predictive tool, the two-step sequence described above works flawlessly. But as a description of reality, it raises troubling questions. In classical physics, "measuring" a system just means obtaining information about that system. But if measuring a wavefunction radically alters the behavior of that wavefunction, as the orthodox interpretation holds, then some interactions must constitute "measurements" and other interactions must not. For instance, the wavefunction clearly does not collapse as soon as it encounters its first air molecule. (If it did, then there would be no interference pattern.) What property of the back wall triggers the wavefunction's collapse?

The fact that measurement plays a pivotal role in the orthodox story, but no clear definition of measurement has been found, is referred to as the "measurement problem." In this section we will discuss the measurement problem—first in general, and then in context of the orthodox interpretation. We will then present two alternative interpretations that address the measurement problem in different ways.

For a much more in-depth discussion of the issues discussed in this section, we recommend the book *Foundations of Quantum Mechanics: An Exploration of the Physical Meaning of Quantum Theory* by Travis Norsen.

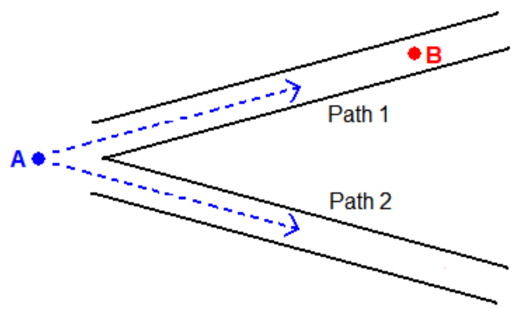
Measurement and Entanglement

Related to the measurement problem is the idea of "entanglement," which refers to different particles having properties that are correlated with each other.

To introduce entanglement, let's consider a different scenario from the double slit experiment. Particle A is in a superposition of being in two different paths: Path 1 and Path 2.

$$\psi_A = \frac{1}{\sqrt{2}}\,\psi_{\text{Path 1}} + \frac{1}{\sqrt{2}}\,\psi_{\text{Path 2}}$$

Particle B, meanwhile, is at rest in Path 1.



A moment later, the two-particle system is in a superposition of two states:

- First state: Particle A is in Path 1, and Particle B has been knocked away from where we left it.
- Second state: Particle A is in Path 2, and Particle B is undisturbed.

Particles A and B are "entangled," meaning the state of one is connected to the state of the other. For instance, the wavefunction for this system does not include a state in which Particle A is in Path 2 and Particle B has been knocked away.

To appreciate the import of that idea, suppose we wait a few years, during which neither particle interacts with anything else. Then we make a measurement of the position of Particle A, and let's say we find it in Path 2. That means that Particle B was never knocked away; we now confidently know that a measurement of Particle B will find it in Path 1.

None of this is surprising in classical mechanics, which says that our measurement of Particle A simply revealed what the state of the system had been all along (even though we didn't know it until now). But according to orthodox quantum mechanics, the wavefunction of Particle A was in an indeterminate state until our measurement collapsed it. Because the two particles were entangled, the same event caused the state of Particle B to collapse. *Our measurement of the position of Particle A caused an instantaneous change in the state of Particle B, forcing it into the state of definitely being in Path 1.*

Here are a few implications of that idea.

- You will often hear the measurement problem (and also the uncertainty principle by the way) explained away as "When you measure something sufficiently small, no matter how passive you think your measuring device is, you are always pushing or prodding the observed particle." In our experiment here, your measurement may be pushing or prodding Particle A, but you are not physically touching Particle B. Nonetheless, Particle B changes state from "maybe here but maybe there" to "definitely here." In the orthodox interpretation, it is the *fact of measurement,* not a physical disturbance by the measuring device, that causes the change.

- Note also that your measuring device may be light-years away from Particle B when you do the measurement, but your effect on its state is instantaneous. We say that this interaction "violates locality." Such faster-than-light causal effects drew strong objections from Einstein and others, and Einstein referred to this aspect of quantum mechanics as "spooky action at a distance." But later work by J.S. Bell and Alain Aspect showed that this problem is not specific to the orthodox interpretation; the experimental results of quantum mechanics are fundamentally non-local. We discuss Bell's theorem at felderbooks.com/papers/bell.html.

- After Particle A hits Particle B (or doesn't), the system is still in an indeterminate state, and remains so until Particle A interacts with your measuring device. Once again we see that in the orthodox interpretation some interactions (e.g. A with your device) count as measurements that collapse the wavefunction, while others (A with B) don't.

It may appear that entanglement is a peculiar feature of the two-particle experiment we described above. But entanglement is central to any experiment, because *every measuring device works by correlating its own state with the state of the system being measured.*

To illustrate that point, let's return to the double-slit experiment. We begin at the moment before a photon strikes the back wall. According to the orthodox interpretation, the photon is in a state of "maybe here and maybe there." A particular spot on the wall is in the state "definitely dark."

Now the photon reaches the back wall. If the time evolution of the entire system is governed by Schrödinger's equation then the photon is still in a state of "maybe here and maybe there," but the back wall's state has been entangled with that of the photon, so our spot on the wall is in a state of "maybe light and maybe dark."

Now you, the scientist, take a look at the back wall. Continuing our entanglement story, the wavefunction for *you* is now in a state of "maybe I saw this particular spot light up, and maybe I didn't." The process seems to have no end. But we have to account for the undeniable fact that we never actually experience such an entangled state. After the photon reaches the back wall, you see a spot light up (with 100% certainty), or else you see that spot *not* light up (with 100% certainty).

You can think of all interpretations of quantum mechanics as different resolutions to that problem: how do we go from the world described by Schrödinger's equation (in which entanglement quickly transforms every wavefunction into an indeterminate state), to the world we see around us (in which every measurement yields only one answer)? In this section we will describe three of the most commonly discussed interpretations:

- The orthodox interpretation
- The many-worlds interpretation
- The pilot-wave interpretation

The Orthodox Interpretation

The orthodox interpretation is the one we primarily use throughout the book. We do so because it is the one most commonly used in physics, and because it is in some ways the most convenient interpretation to use when predicting experimental results.

You know by now how the orthodox interpretation explains the double-slit experiment. As the photon's wavefunction travels through both slits at the same time, its state may be entangled with the states of the many air particles it encounters. This part of the story is analogous to Particle A passing by Particle B in the experiment we described above; any given air molecule is in a state of "I have been disturbed if the photon traveled this way, and not if it didn't."

But when the wavefunction reaches the back wall, the entanglement works a different way. The photon does not put the back wall into an indeterminate state; rather, the back wall forces the photon into a state of definite position. The back wall, unlike the air molecules, constitutes a measurement.

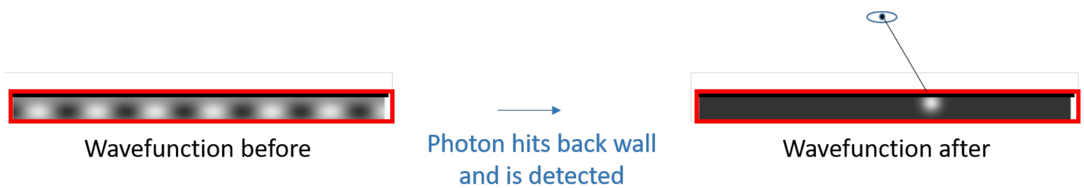


Figure 1: In the orthodox interpretation, a photon hits the back wall and its wavefunction collapses, instantly changing from spread-out to localized. The observer sees a spot on the back wall at the location the photon collapsed to.

What makes the back wall cause such a different effect from the air molecules? The orthodox interpretation offers no answer. Anything that gives a clear reading that scientists could read as a measurement (the position of a dial, the digits on a readout, a mark on a photographic plate, . . .) is a measurement. Clearly some microscopic interactions don't count as measurements (e.g. a photon passing by some air molecules in a double-slit experiment). And we shouldn't worry about exactly what constitutes the difference.

In a hand-waving way, many physicists who subscribe to the orthodox interpretation think of *size* as the fundamental difference. Somewhere between single particles and macroscopic objects is a mysterious line where something becomes a measuring device.

Some authors have proposed alternatives to the orthodox interpretation that preserve its basic feature of wavefunction collapse, but attempt to give precise definitions for what causes that collapse. One such model is "spontaneous collapse," which posits that a wavefunction will from time to time randomly collapse into a state with well-defined position. The probability per unit time for that collapse scales with the number of particles entangled. For a single particle, you would have to wait hundreds of millions of years to see such an event, and thus we never observe single particles spontaneously collapsing. But for a macroscopic object the time scale is virtually instant, so we never observe macroscopic objects in superpositions of different positions.

Other authors, including John von Neumann and Eugene Wigner, have suggested that the collapse of the wavefunction occurs when a system is measured by a conscious observer.

Many adherents of the orthodox interpretation describe the measurement problem as a semantic question: a concern for philosophers, not for scientists. But in our view, the orthodox interpretation remains a fundamentally incoherent view of reality unless a satisfactory answer to this question can be found.

The Many-Worlds Interpretation

The "many-worlds interpretation" of Hugh Everett III starts from the same premise as the orthodox interpretation: particles *are* wavefunctions. But Everett breaks from the orthodox interpretation by saying that the wavefunction never collapses.

We have already outlined a many-worlds description of the double-slit experiment. When the photon reaches the back wall, a patch of molecules on the back wall goes into a superposition of "maybe lit up, maybe not." When you observe that spot on the back wall, you yourself go into a superposition of "maybe I saw a light spot, maybe I saw a dark spot." Every possible outcome of every quantum event happens, in an infinitely branching superposition.

This branching is often described by saying reality continually splits into parallel universes: hence the name "many-worlds interpretation." But that picture doesn't have to be taken too literally. In Everett's view there is one universe, described by one wavefunction, and that wavefunction is in a superposition of all the sequences of events that might have occurred up to this moment.

For all its strangeness, the many-worlds interpretation is in some ways the most natural interpretation of quantum

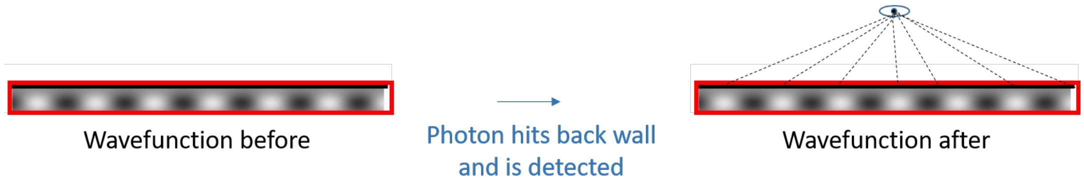


Figure 2: In the many-worlds interpretation, a photon hits the back wall and its wavefunction continues to be spread out. The observer goes into a superposition of seeing spots at many different locations on the back wall.

mechanics. Since we know wavefunctions evolve according to the deterministic Schrödinger equation, why not simply say that there is nothing else happening? Measurement problem solved!

But a new difficulty arises in explaining probabilities. Suppose you put a particle in the following state.

$$\psi = \sqrt{\frac{1}{3}}\,\psi_{\text{Location 1}} + \sqrt{\frac{2}{3}}\,\psi_{\text{Location 2}}$$

If you measure the state of that particle, you will either find it in Location 1, or in Location 2. If you repeat this experiment millions of times, you will find almost exactly 1/3 of your particles in Location 1, and 2/3 of them in Location 2.

In the orthodox interpretation, each measurement you performed collapsed the wavefunction of the measured particle, and that collapse was probabilistic according to the (squared) amplitudes of the separate wavefunctions. But in Everett's theory, each measurement might be said to have produced two versions of you: one that found a particle in Location 1, and one that found a particle in Location 2. (More precisely, the universe went into a superposition of your having seen each of the two results.) How does all that lead to your eventual experience of finding 1/3 of the particles in Location 1?

In this particular example, you could say that each experiment in this scenario would produce, not two different branches, but three. One branch would represent you finding the particle in Location 1, and the other two in Location 2. But such an ad-hoc hypothesis seems to mar the elegance of the theory. More importantly, this scheme becomes untenable when the ratios are irrational, or when (as in a position measurement) there are an uncountably infinite number of possible outcomes. Everett himself referred to different branches having different "branch weights" that distinguish how likely you are to be the observer in each of them, but it's hard to make sense of that without introducing a back-door collapse postulate that somehow puts your awareness in only one branch.

Bohmian Mechanics (aka The Pilot-Wave Interpretation)

The last viewpoint we shall discuss was introduced by Louis de Broglie in the 1920s, but the idea was more fully fleshed out by David Bohm in the 1950s, and is thus often called "Bohmian mechanics."

Recall that in both the orthodox and many-worlds interpretations, there is no "particle" in the classical sense. There is only a wavefunction, although that wavefunction sometimes exhibits particle-like behavior in experiments. In the pilot-wave interpretation, there is an actual particle: a pointlike dot with a definite position and momentum. There is *also* a wave spread throughout space. These are not two different descriptions of the same object; they are two different objects that interact with each other.

We have seen how the double-slit experiment looks in both the orthodox and many-worlds interpretations. The Bohmian description of this experiment sounds almost entirely classical: a particle passes through one slit (and not the other one), and later hits one particular spot on the back wall (and no other spot). The measurement on the back wall doesn't change the particle's position; it just lets you know what particular spot was hit.

So how to account for the interference pattern? While the particle passes through one of the slits, the wavefunction passes through both slits simultaneously. The resulting wave generates an interference pattern in the usual way, giving it a high amplitude in some places and a low amplitude in others. And—here's the key point—*the motion* *of the particle is determined by its wavefunction.* Bohm wrote an equation for this motion in such a way that the particle would generally be pushed away from regions where the field had low amplitude, and toward regions where it had high amplitude. He was able to show that this equation of motion leads to the same experimental predictions as the orthodox interpretation.

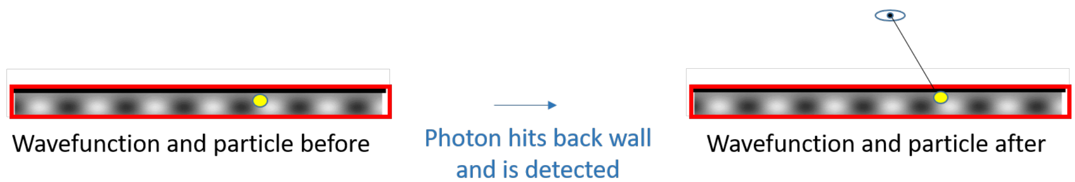


Figure 3: In Bohmian mechanics, a photon hits the back wall and its wavefunction continues to be spread out, but the particle itself is at one location before and after the measurement. The observer sees a spot on the back wall at the location that the photon hits.

In Bohmian mechanics, the wavefunction always evolves deterministically according to Schrödinger's equation. The particle also evolves deterministically, according to a law that includes effects of the wavefunction. When you measure a particle's position, you don't collapse the wavefunction or change anything else about the system. Rather, just as with a classical measurement, you passively find out the position that the particle already had. That puts *you* into a state of definitely having seen the particle at that position, just as it would in classical physics. The particle, the measuring device, and you all obey the same quantum mechanical rules.

Bohmian mechanics is a proof of possibility that the results of quantum mechanics are compatible with a completely deterministic theory.

The Bohmian model shares some important features with the many-worlds viewpoint. In both systems, the overall wavefunction of the universe evolves according to Schrödinger's equation, eternally sprouting branches corresponding to all possible events. When you measure a particle whose wavefunction is peaked in two places, the overall wavefunction of the universe has an amplitude for a version of you measuring the particle in Position 1, and an amplitude for a version of you measuring the particle in Position 2.

But in Bohmian mechanics, one of those positions is *where the particle actually ends up* in any given experiment, and the other position is not. The wavefunction peaking at both positions is important, not because it collapses probabilistically into one location or another (orthodox), or because it represents different co-equal branches of the universe (many-worlds), but because it pushes the particle into the location where you eventually find it. The probability problem in many-worlds is resolved because we only ever experience the branch of the wavefunction with the actual particle in it, and that branch is more often found in high amplitude regions than low amplitude ones.

The uncertainty principle still holds, and must hold in any interpretation because it arises from the math of quantum mechanics. In the orthodox view, the uncertainty principle says that a particle cannot *have* a definite position and momentum at the same time. In the Bohmian formulation, the particle (like a classical particle) has a definite position and momentum at all times; the uncertainty principle limits what we can *know* about those properties.

Conclusions

We began this section with the measurement problem: interference implies a wave that exists in multiple places at once, but measurements finds a particle in a single place. We can sum up the three interpretations we have discussed by listing how each one addresses that problem.

- The orthodox interpretation says that the particle is a wave that exists in multiple places at once until you measure it. At that moment it discontinuously changes into a sharply peaked wave, effectively existing in only one place.
- The many-worlds interpretation says that the particle is always a wave that exists in many places, and the act

of measurement turns the observer's wavefunction into a superposition of versions of that observer who have measured each possible outcome.

- Bohmian mechanics posits two separate entities, a wave that exists throughout space *and* a particle at one location. The wave exerts a force on the particle, and the act of measurement simply reveals the true location of the particle.

At present there is no experimental test that distinguishes these viewpoints, but some physicists continue to work out their consequences in hopes of finding ways to ultimately figure out what's really going on.

To conclude, we should note one other viewpoint somewhat different from any of these.

What we are calling the "orthodox interpretation" is often called the "Copenhagen interpretation" because of its connection to the Danish physicist Niels Bohr. However, the orthodox interpretation does not necessarily match the view Bohr promoted, which could perhaps be better termed "principled agnosticism." Bohr argued that a scientific theory can only predict the results of experiments, and any attempt to discuss the reality behind the mathematics of the theory is meaningless. As Bohr put it: "The entire formalism is to be considered as a tool for deriving predictions, of definite or statistical character . . . These symbols themselves are not susceptible to pictorial interpretation."[1]

Bohr's viewpoint is shared by many physicists today. N. David Mermin summarized this common philosophy in a 1989 essay: "If I were forced to sum up in one sentence what the Copenhagen interpretation says to me, it would be 'Shut up and calculate.' "[2]

Mermin's four-word summary has become a catchphrase among many physicists who view all questions of interpretation as empty philosophical chatter. We have talked to a number of physicists about these issues, and we can summarize the most common discussions in three steps.

1. They begin by describing themselves as proponents of the orthodox (or Copenhagen) interpretation: the wavefunction collapses when measured. They have given little or no thought to exactly what constitutes a measurement, and don't consider it a particularly interesting question.

2. When pressed, many of them suggest that the measuring device itself goes into a superposition of states. At this point their descriptions start to sound a lot like the many-worlds interpretation, but if asked point blank, they describe that idea as absurd.

3. Ultimately, they fall back on the Bohr/Mermin position, sometimes directly using the phrase "shut up and calculate."

Bohr's position is not in any way self-contradictory. But if you take it to its logical extreme, we should not say "there are actual planets in orbit around the sun"; we should confine our conclusion to "when we point our telescope at this angle at this time, it will reveal an image like that." Einstein vehemently opposed such a denial of objective reality, and argued the point extensively with Bohr. Most physicists today believe that Bohr won the debate.

As should be clear by now, we do not subscribe to this viewpoint.

The laws of the universe are counter-intuitive. Our hard-wired Newtonian assumptions about time, space, and motion are fundamentally incompatible with experimental results, in ways that make the study of modern physics both fascinating and frustrating. But there is a difference between *unintuitive* and *incoherent*. When a scientific theory is logically self-contradictory—as we believe the orthodox interpretation is, without a clear definition of measurement—then the theory is wrong, or at least incomplete, and we should try to find a better one. Predicting the results of experiments is a vital tool for testing and refining our scientific understanding of the world. But experimental predictions are not, and never have been, the only goal of science.

Nonetheless, a survey of the strange features of all the current attempts to understand those foundations, coupled with an acknowledgment that we currently have no experimental way to distinguish these viewpoints, is enough to give us at least some sympathy for those who share Bohr's attitude.

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[1] N. Bohr, "On the Notion of Causality and Complementarity," Dialectica **2**, 312-319.
[2] N. D. Mermin, "What's Wrong With This Pillow?", Phys. Today (1989).