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Core Principles of Quantum Mechanics Explained Simply

A New Way of Looking at the World or, What is Reality?

> *We have become accustomed to asking questions and getting definite answers: What color is it? How heavy? How fast? Forgetting the almost ludicrous amount about everyday objects of which we remain ignorant, we figured we could go on forever asking and being answered, at ever finer scales. When we discovered that we cannot, we felt short-changed by nature and pronounced it "weird." That won't do any more. Nature does its best, and we need to adjust our expectations. It is time to go beyond weird. -Philip Ball*[1]

We expect reality to behave based on what happens in our everyday experience, and we build our view of the world on what we see, hear, taste, smell, and touch. From the 1600's onward, physicists have explained how the world works at this human-size scale. Then, in the early 20th century, when physicists were first confirming the existence of atoms (tiny pieces of matter) and subatomic (smaller than an atom) particles, they expected the same rules would apply to the world of the very small and the very fast. But they were wrong.

In the early 1900s, the world was introduced to a reality that defied all expectations of how things—in particular, matter and energy—behaved. An entire new field of physics, *quantum physics,* emerged that explained the behavior of objects at very small scales. The ideas of quantum physics (also referred to as quantum science, quantum theory, or quantum mechanics) were first explained using mathematics when physicists such as Niels Bohr, Werner Heisenberg, Erwin Schrödinger, and others described the behavior of these very small objects, which they called quantum objects. The scientists were able to describe what happens with mathematical equations and in experiments, even though at these atomic and subatomic scales, one cannot perceive what is happening with their senses: one cannot touch, see, smell, hear, or taste.

One thing the scientists wondered about was why the behavior of small objects was not seen in everyday reality. It turned out that it was only possible to observe this when an object was isolated —that is, when it did not interact with the environment around it. An object in isolation

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[1] Ball, Philip. "Beyond weird: Why everything you thought you knew about quantum physics is different." In *Beyond Weird*. University of Chicago Press, 2018.

from its environment behaves quite differently; it does not matter if it is a photon (a tiny piece of light), an atom, or a larger thing made of atoms, like a cat, a car or person. This difference persists as long as the object does not subsequently interact with anything else. Because a cat or a person invariably interacts with its environment, we can never isolate them enough to see this quantum behavior. In principle, everything can be a quantum object. But as of now, the only way that scientists have succeeded in creating a place with no interaction is at a subatomic level, where photons and single atoms are cooled to very low temperatures and/or are placed in very clean environments, so that they cannot be disturbed by any environmental effects.

Quantum physics seems to bring up questions about what we call reality, because it questions our intuition and ideas of the world we experience in our everyday lives. Since this quantum reality is vastly different from the reality we experience and take for granted (see below), it forces us to rethink our ideas of what we know about our world. What do we mean by a physical object? What do we know about that object? How did it get to be the way that it is? Why does it stay that way? How can it be used? It is questions like these that make quantum physics so exciting to work on.

Quantum reality is both and

Tiny objects that demonstrate quantum behavior are called quantum objects, and quantum objects display unusual behavior in that they can behave as either waves or particles. A quantum object sometimes behaves like a tiny particle, like a small pebble, and sometimes it behaves like a wave, like the ripples the pebble creates when it hits the surface of the water.[2] Quantum objects behave *both* like waves *and* like particles. To be more accurate, it is not that the quantum objects are precisely particles or waves, but comparing them to these helps explain how they behave in experiments in the lab.

Scientists understand these sometimes-particle, sometimes-wave behaviors as “wave-particle duality.” Figuring out this aspect of quantum behavior is the central idea of what Bohr and his colleagues developed in the 1920s. Tested through decades of rigorous experimentation, this dual quality of quantum behavior is one of science’s most successful interpretations of how nature works at its tiniest scale.

Quantum reality changes when we try to understand it

In order to obtain information and gain an understanding of any object, we take measurements. We measure someone’s foot to find the right size shoe. We take a child’s temperature to see if they have a fever. When we perform such a measurement, we do not expect the measurement

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[2] Feynman, Richard P., Robert B. Leighton, Matthew Sands, and Everett M. Hafner. "The Feynman lectures on physics; vol. i." *American Journal of Physics* 33, no. 9 (1965): 750-752.

process to distort the outcome. A foot does not change in size when we put a ruler next to it. A child's temperature does not drop when we put a thermometer under their tongue. But with quantum objects, this is not true!

The measurement of a quantum object both gives us information about the quantum object and affects the quantum object being measured. The quantum object stops being quantum when measured; the act of measuring destroys its quantum reality. So if the quantum object stops being quantum when measured, *how do we know if it was a quantum object in the first place*? We cannot know with certainty what the quantum object's reality is before we measure it: whether it is a particle or a wave, whether it is at a specific location or moving, whether it is pointing one way or another, etc.

This raises an important question: Do quantum objects even have definite qualities before we measure them? It is not clear that they do. As Ball suggests, we need to let go of the idea of an objective, pre-existing reality and accept that measurement and observation bring specific realities into being.[3]

Quantum reality is simultaneously every possibility

In our everyday experience, if we look at an object we know exactly where it is and in which direction it faces. When we observe and measure a quantum object, will we find it here, or will we find it there? Will it be facing up or will it be facing down? Here, there, up, and down are all options. A quantum object has a palette of possibilities that it can exist in before we measure it. If the quantum object will only "decide/reveal" this upon observation/measurement, then *before* it is observed and measured, we can say it is here, there, up, and down all *at the same time*.

A quick use of some simple scientific lingo: in the palette of possibilities, each possibility is referred to as a "state." Here, there, up, and down are each a state of the quantum object. As we said earlier, a quantum object can be both here and there, up and down, fast and slow, all at the same time. That is, a quantum object exists in multiple states simultaneously. And being in more than one state at the same time is called being in "superposition."

Superposition, or being in *many states at the same time*, is a way of being that is entirely foreign to anything we have or will ever encounter in life. Saying that the object is all of these at once and not just one of these is the closest way to describe very weird quantum behavior with language. Superposition contains a deep uncertainty that cannot be observed directly but defines the identity of a quantum object.

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[3] Ball, *Beyond Weird*, 82-83.

As mentioned above, a quantum object decides/reveals what state it is in when it is measured. This means it is no longer in superposition and, therefore, it is no longer a quantum object.[4]

In quantum reality things do not necessarily happen for a reason

In the quantum world, observing and measuring bring specific realities into being from a "palette of possibilit[ies]."[5] So, if there is no definite reality before we observe and measure, but instead only an array of potentialities, then when we *do* observe and measure, which one of those options will we find? We cannot know in advance, and as far as we currently know, the quantum object itself does not know in advance which possibility it will "choose." The outcome of a measurement is completely random.

But this randomness is different from the randomness we encounter in our everyday world. This concept has been described using a roulette wheel, in which the pockets on the roulette wheel are thought of as the palette of possible random outcomes. There are many possible outcomes for where the ball might land. We do not have information about the exact pocket in which the ball will land on the wheel. We cannot anticipate which one it will be. Where the ball lands is completely random. Actually, when we say that where the ball lands is random in a "regular" roulette wheel, what we really mean is that we are ignorant of the conditions that would help us determine where the ball would land. If we did know how fast the wheel was spinning, the force with which the croupier set the wheel in motion, what the wheel is made of and how much it weighs, the force of the air coming from the room's ventilation system, and all the other relevant facts, we could determine where the ball would land. But a quantum roulette wheel would behave differently. Even if we meticulously recorded every relevant fact, we would not be able to determine where the ball would land. Quantum reality is fundamentally random. This might not seem like a big deal at first glance, and it is a rather subtle difference. In the case of the "regular" roulette wheel, the information is available, but we do not have access to it. In the case of the quantum roulette wheel, we do not have access to the information because it is unknowable. Even Albert Einstein, who explained the world through a lens of definite cause and effect, could not come to terms with the uncertainties associated with a quantum object. Quantum behaviors do not have explanations in which specific causes lead to specific effects. They have only a random outcome from a palette of likely outcomes, i.e., the palette of possibilities. What most disturbed Einstein about quantum physics was the replacement of cause and effect with randomness.

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[4] There are many interpretations of quantum physics, and this interpretation of measurement is referred to as the "Copenhagen Interpretation," named after Bohr's hometown of Copenhagen, where Bohr and Heisenberg did their foundational work. The Copenhagen interpretation is the most popular interpretation of what is going on in quantum physics.

[5] Ball, *Beyond Weird*, 82-83.

In quantum reality, separated objects act as one

In addition to superposition, John Bell observed another interesting behavior in quantum objects, which is called "quantum entanglement."[6] This behavior is seen when two distant quantum objects that have met in the past maintain a sort of connection to one another, almost as if they were able to communicate. Like two lost lovers that sense the emotions of one another, they are, as we say, entangled, connected in a mysterious way.

Suppose that Joe and Mary are gamblers playing roulette. Joe is in Monte Carlo and Mary is in Las Vegas. When Joe's croupier spins the wheel, we expect the ball to land in any pocket. For Mary's spin, the outcome is equally unpredictable. But let us say Joe and Mary's roulette wheels are entangled quantum objects, tied with a special entanglement rule that the pockets black 6 and red 9 must occur together. Let us say Joe's ball in Monte Carlo lands into black 6. Nothing odd about that. But because of the entanglement, the ball on Mary's roulette wheel in Las Vegas lands into red 9. Alternatively, if Mary's wheel spins first and the ball lands into black 6, Joe's ball lands into red 9. The landing, or measurement, of the first ball is completely random, but the outcome of the 2nd ball depends entirely on the first ball's random landing. Their outcomes will always have a connection to each other because they are entangled. You might understandably say, "That's absurd." Absurd it may be. And brainstraining it may be. But it is true in quantum reality.

No matter how far entangled quantum objects move apart—even if the whole world lies between them—if one is tweaked, measured, or observed, the other seems to instantly know its own outcome.

The part of the description of entanglement that is often missed is the funny way in which these two objects are correlated. For a moment, think of each of the entangled objects by itself. On its own, its behavior is completely random. When it is measured or observed by itself, it does not seem to have any preference for doing one thing or another. But at the same time, while this object by itself is random, and the other object by itself is random, their randomness is completely linked. Once one of them gets measured and its outcome gets determined, we can know the outcome of the other with complete certainty. The idea of both being completely random by themselves, yet at the same time being completely correlated, is a very strange concept around which to wrap one's mind.

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[6] Bell, John S. "On the Einstein Podolsky Rosen paradox." *Physics Physique Fizika* 1, no. 3 (1964): 195.

Einstein did not believe in entanglement and called it “spooky action at a distance.”[7] To this day, no one knows how two entangled particles can instantly “decide” at the same time, without making a “deal” beforehand or sending each other signals, to act in the same way. But they do.

This conclusion flies in the face of all our commonsense notions of reality because communication in our world can only occur through cause and effect. No information can be transferred between two objects unless some physical cause to the first object creates a physical effect that is felt by the second object. In regular communication, a time lag (proven to be no faster than the speed of light) always exists between a message being sent and its reception. Quantum physics seems to break this fundamental rule. It is not that any information is actually “traveling” faster than light; it just seems like it is because quantum entanglement is a whole new way that information is shared over distances, and we do not quite understand its mechanism yet. But we can still prove that it is happening in quantum experiments.

The field of quantum physics is at a stage similar to the first computer, which was the size of a huge room with power lines seemingly everywhere. At that time, no one imagined we would hold a computer in one hand that could run on rechargeable batteries. Aspects of quantum physics are already in use in smart phones and MRI machines, and they fuel the frontier of what is coming, e.g., quantum computers and sensors.

Quantum physics challenges our fundamental understanding of nature. What is truly remarkable is that, although scientists are still studying exactly how or why quantum superposition, measurement, and entanglement work, they are able to harness the power of these behaviors to create new technologies. This field of science holds the promise of revolutionizing present day technologies and solving problems in various disciplines such as biology, chemistry, and astrophysics. No one yet knows all the things quantum physics can do or all the problems it might solve. That is what makes quantum physics so thrilling: the mysteries it holds are invitations to discover, invent, and explore like never before.

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[7] Einstein, Albert, Max Born, and Hedwig Born. "The Born-Einstein Letters: Correspondence Between Albert Einstein and Max and Hedwig Born from 1916-1955, with Commentaries by Max Born." *(No Title)* (1971).