CHAPTER 24

CAN WE KNOW WHAT IS REAL?

(Wherein we explore the implications of quantum physics for our understanding of reality)

One of the shocking consequences of quantum physics is that the act of measuring affects what is being measured. In fact, it defines what is being measured, giving it physical reality. This creates a link between observer and observed that is hard to sever. Perhaps no one put it more pointedly than Pascual Jordan, who worked with Heisenberg and Born in the formulation of matrix mechanics: "Observations not only disturb what has to be measured, they produce it. . . . We compel [the electron] to assume a definite position. . . . We ourselves produce the results of measurements."[1]

Once the link exists, the separation between you as observer and the rest of the world, what we usually call objectivity, is lost. How can you know where you end and what you measure begins? If we are entangled with what is "out there," there is no "out there" any more; there is only the whole of it, undifferentiated. Detachment is gone. You and everything else in the Universe make up a single unit. Even more problematic: If you are connected to everything else, to what extent are you free? Is our autonomy as individuals an illusion? Does the sum total of the influences out there dictate our behavior? Are we the spider that can't exist without the web?

"Surely," someone with a cool head may object, "that's not how things are in real life. Just look around, and you can see that we are apart from what's out there, that we exist independently of it. I'm not the chair I'm sitting on. The chair has its own existence, independent of my own. It is an autonomous object with nothing quantum about it. Furthermore, you don't detect the particle; a machine does, the detector. And the detector is also a large, classical object. So the extrapolation that the act of measurement connects observer and observed is a bit of a stretch. What happens is that a particle interacts with the materials that make up the detector, and this interaction, after being sufficiently amplified, is recorded electronically in a counting or tracking device. There is no 'you' or consciousness or mind behind the particle's existence; there are just clicks in detectors. The business of quantum mechanics is to make sense of these clicks, and it does so beautifully using probability. Microscopic objects don't exist in the same way you and I exist; they are just constructions of our minds, descriptive devices we create to make sense of what we measure. Why go all metaphysical with it?"

The above paragraph reflects what sometimes is called the "orthodox" position, based on the Copenhagen Interpretation of quantum mechanics that Bohr and Heisenberg originally developed to assuage confusion and despair. When we teach quantum mechanics, we tend to remain within the confines of the Copenhagen Interpretation and its pragmatic approach to reality. This is an acceptable position as long as you don't want to go deeper into the nature of things. But as soon as we start to think a bit more about it, an unsettling feeling creeps in. And the feeling only grows as our thoughts deepen.

It is certainly true that it is a detector that signals the existence of the particle, not a person directly. But the scientist and his intentionality, that is, his specific design for the experimental setup, comes before the detector. A detector doesn't exist without the scientist and won't work without someone turning it on or programming it to turn on at a certain time. The data the detector collects

won't make sense without a conscious observer who knows the science behind it. An electron doesn't really exist without a conscious mind to interpret it. Put it another way: existence, be it of a quantum or of a "classical" object, is contingent on minds to acknowledge it. In a mindless Universe nothing exists, since there are no conscious entities aware of what existence even means. The very concept of existence presupposes a mind capable of higher reasoning: "existence" as a concept is something we invented to make sense of how we fit in the cosmos.

Of course, this doesn't mean that the Universe only came into existence once there were conscious observers to notice it. Unless you agree with Bishop Berkeley and his *Esse est percipi*, the Universe existed long before any conscious observers came about. Humans and any other intelligence out there capable of thinking about existence are the result of countless physical and chemical interactions that engendered, in ways that remain unclear, complex biological entities. This all takes time, no less than a few billion years, enough for several generations of stars to come into being and perish, cooking up the heavier chemical elements of the periodic table that are crucial for life. Given that there were no minds at the beginning of time, we must conclude that consciousness is not a precondition for the Universe to be.[2] Indeed, if the multiverse makes sense, countless universes may exist out there without any trace of life in them. The opposite is obviously not true: life unfolds within a universe. Unless you believe in some sort of universal disembodied Mind, life presupposes a complex web of physical, chemical, and astronomical conditions operating within space and time. Many eons of cosmic history passed before life could start having a history of its own.

The key question then is not whether consciousness engenders the Universe—a very difficult position to defend scientifically—but rather what happens to the Universe once consciousness emerges. You may dismiss this with a Copernican flourish, arguing that we are negligible in the big scheme of things, that we came from stardust and to stardust will revert. In response, I'd argue that the Copernican position hinges on the wrong axis: what matters isn't whether the Universe cares about us, for it clearly doesn't. What matters is how *we* fit into the Universe once we understand our uniqueness as conscious beings. I called this position "humancentrism" in *A Tear at the Edge of Creation*. In a nutshell, we matter because we are rare. Even if there are other "minds" in the cosmos, we are a one-of-a-kind experiment in evolution.

How does this relate to the foundations of quantum physics and the nature of reality? For starters, everything that we can say about reality goes through our brain. When we design the experiment that determines whether the electron is a particle or a wave, "we" means the human brain and its ability to reason. Detectors are extensions of our senses designed to record events that we then decode through careful rational analysis. We have no direct contact with electrons, atoms, or other denizens of the realm where quantum effects prevail; all we get are flashes and pings and ticks and lines and reams of data that we rush to interpret. The world of the very small exposes in direct ways the limitations of our descriptions of reality. Yet these descriptions are all we've got. As such, they reflect in very deep ways our human essence, the ways we pursue knowledge and our limitations in doing so. We are meaning-seeking beings, and science is one offspring of our perennial urge to make sense of existence.

Even though I have used quantum mechanics in my research for decades, and have taught quantum mechanics and quantum field theory for as many years, as I began to survey the literature on the conflicting interpretations of quantum mechanics, a sense of loss took over my thoughts like a hungry vine. Could reality be this elusive? The hardest part is that there is no simple resolution, no agreed-on way out. Even though we all go through the same motions when calculating quantum probabilities, there is widespread disagreement as to how quantum mechanics relates to reality. There may not *be* a correct resolution—only different ways to

think about it. The difficulty, as we will see next, is that some quantum effects force us to confront their weirdness in ways that affect how we relate to the Universe. Could it be that there is no "us and the Universe" but a single wholeness? Unless you are intellectually numb, you can't escape the allure of the quantum, the tantalizing possibility that we are immersed in mystery, forever bound within the shores of the Island of Knowledge. Unless you are intellectually numb, you can't escape the awe-inspiring feeling that the essence of reality is unknowable.

In 1935, Einstein published a paper with Boris Podolsky and Nathan Rosen (referred to below as EPR) trying to expose the absurdities of quantum mechanics. The title says it all: "Can [the] Quantum-Mechanical Description of Physical Reality Be Considered Complete?"[3] The authors had no qualms with the correctness of the quantum theory: "The correctness of the theory is judged by the degree of agreement between the conclusions of the theory and human experience. This experience, which alone enables us to make inferences about reality, in physics takes the form of experiment and measurement." Their issue was with the completeness of the quantum description of the world. They thus proposed an operational criterion to determine the elements of our perceived physical reality: those physical quantities that could be predicted with certainty (a probability of one) without disturbing the system. That is, there should be a physical reality that is entirely independent of how we probe it. For example, your height and weight are elements of physical reality as they can be measured with certainty (within the precision of the measuring device). They also can be measured simultaneously, at least in principle, without any mutual interference: you don't gain or lose weight when your height is measured. When quantum effects dominate, this clean separation is not possible for certain very important pairs of quantities, as expressed in Heisenberg's Uncertainty Principle. EPR would have none of this.

We have seen that the uncertainty relation precludes knowledge of both position and velocity (momentum, really) of a particle. This is true for many different pairs of quantities said to be "incompatible." Energy and time are also incompatible, and they obey an uncertainty relation similar to that for position and momentum. Another example is the spin of a particle, a quantum property that we associate with some kind of intrinsic rotation and visualize, even if incorrectly, as the particle turning around like a top. Quantum particles with spin are like whirling dervishes who can never stop. Not only that, they always whirl with the same speed (angular velocity), although different particles may have different spins. Spins in different directions (say, aligned in the north-south or east-west directions) are incompatible: we can't measure them simultaneously. Classically this limitation usually doesn't exist, since most physical quantities are compatible.[4]

When quantities are compatible, you can obtain information about both without any a priori restriction. In quantum physics, whenever two quantities are incompatible, the uncertainty principle applies: the information we can obtain about both of them jointly is restricted. If we know the momentum of a particle and also want to know the position, a measurement of the position will "force" the particle into a specific spot, "collapsing" its wavefunction: in other words, the measurement will decisively disturb the particle and change its original state. More dramatically, we can't even speak of an "original position state": before the measurement, all that existed were potentialities of the particle being here or there.

Back to the EPR paper. We see that incompatible quantities violate their proposed criterion for a physical variable to belong to physical reality: since measuring the particle's property means disturbing it, the act of measurement compromises the notion of an observer-independent reality. The act of measurement *creates* the reality of a particle being in a given spot in space, which they found absurd. What is real must not depend on who or what is looking.

EPR considered a pair of identical particles moving with the same speed in opposite directions. Call them particles A and B. Their physical properties were fixed when they interacted for a certain time before flying off away from each other.[5] Say a detector measures the position of particle A. Since the particles have the same speeds, we also know where particle B is. But if a detector measures particle B's speed at that spot, we now know *both* its position and its speed. This seemed to clash with Heisenberg's Uncertainty Principle, since information was apparently obtained about a particle's position and velocity simultaneously. Furthermore, we know a property of a particle (position of B) without observing it. According to the EPR definition, this property is then part of physical reality even if quantum physics insists that we could not know it before we measure it. Clearly, argued EPR, that doesn't seem to be the case, and quantum mechanics must be an incomplete theory of physical reality. EPR closed the article hoping that a better (more complete) theory would restore realism to physics.

Bohr's answer came after only six weeks, in a paper he provocatively titled the same as EPRs. (I don't think you could do this nowadays.) Bohr invoked his notion of "complementarity," which asserts that in the quantum world we cannot separate what is detected from the detector: the interaction of the particle with the detector induces an uncertainty in the particle but also in the detector, since the two are correlated in inseparable ways. Essentially, the act of measurement *establishes* the measured property of the particle in unpredictable ways. Before the measurement we can't say it had any property at all. This being the case, we also can't attribute physical reality to this property in the sense that EPR defined: "Indeed the *finite interaction between object and measuring agencies* . . . entails . . . the necessity of final renunciation of the classical ideal of causality and a radical revision of our attitude towards the problem of physical reality"[6] (italics in the original).

In his classic textbook, David Bohm elaborates: "[We assume that] the properties of a given system exist, in general, only in an imprecisely defined form, and that on a more accurate level they are not really well-defined properties at all, but instead only potentialities, which are more definitely realized in interaction with an appropriate classical system, such as a measuring apparatus."[7] Bohm then takes it home, dialing up the dramatic rhetoric: "We see then that the properties of position and momentum are not only incompletely defined and opposing potentialities, but also that in a very accurate description they cannot be regarded as belonging to the electron alone; for the realization of these potentialities depends as much on the systems with which it interacts as on the electron itself."[8]

According to Bohr and his followers, EPR implicitly built their arguments using the old classical assumption that there is such a thing as a reality independent of measurement. That expectation, they insisted, had to go. Reality was far stranger than Einstein would have liked it to be. All we could do was to probe it with our measuring devices the best way possible and make sense of the results using the probabilistic interpretation of quantum mechanics. What lies underneath, if anything, was *unknowable*. This is why Heisenberg wrote, "What we observe is not Nature itself but Nature exposed to our method of questioning."

In EPR we identify traces of Plato's idealism, the notion that there is an ultimate reality out there, the underlying stratum of all there is, and that it is accessible to reason. The key difference is that while for Plato this reality was in the abstract realm of Ideal Forms, for Einstein and the scientific realists it was very concrete, even if hard to get to. The clashes with the pragmatism of the Copenhagen Interpretation and with Bohr's complementarity was direct and unavoidable.

Were Einstein, Schrödinger, and the scientific realists being merely hopeful, echoing ancient dreams of a complete understanding of the world? How far *can* we go unveiling Nature's underlying structure, as opposed to seeing only shadows on the wall? Is the underlying stratum of physical reality truly unknowable?

Schrödinger would have none of this. In 1935, prompted by the EPR paper and Bohr's response, he composed his own critique of quantum physics in which he introduced his famous cat. Schrödinger's intent was to ridicule the very theory he helped to found when it is extrapolated to macroscopic objects. He had a point.

Consider a cat locked in a black box together with, as Schrödinger called it, a "hellish contraption": a Geiger counter attached to a sample of radioactive atoms and a bottle of cyanide. When an atom decays and emits a particle, the Geiger counter detects it, triggering a mechanism that releases cyanide from the bottle, killing the cat; if the atom doesn't decay, the cat stays alive. Clearly, an outside observer can't tell whether the cat is alive or dead until he opens the box. Schrödinger's point is that quantum mechanics would state that *before* the box is opened, the cat is *both* alive and dead. The wavefunction describing the whole system would contain equal parts of a living and a dead cat. (It would be in a "superposition" of both states.)[9]

According to the Copenhagen Interpretation, the act of looking has a 50 percent probability of killing the cat. Talk about looks that can kill! And that's not all: if the cat is either dead or alive when you open the box, its past history must reflect this—that is, it was or was not poisoned. Does this mean that the act of observing actually determines the past history, acting backwards in time? Can a look not just kill but recreate the past?

One response is that the measuring device is the Geiger counter and not the person opening the box: if the atom decays and the Geiger counter registers the decay, this constitutes the act of measurement. You may counter by arguing that since we don't know what goes on inside the box, what happens between the cat and the Geiger counter is irrelevant. Only looking has meaning, since it explicitly introduces the observer into the picture.

At the heart of the puzzle lies a paradox that was inexistent in classical physics. In quantum physics, the trio consisting of the observer, the measuring device, and what is being measured form a new entity, which is described by a single wavefunction. As Schrödinger explained, their individual wavefunctions are "entangled."[10] In principle, the whole Universe should be part of the description, given that all sorts of remote effects act on all of us: Jupiter's gravity, the Sun's radiation, the pull from the giant black hole at the center of the Milky Way and the one at the center of the Andromeda galaxy, the bird fluttering its wings outside the window and the clouds drifting across the sky, the waves crashing at Ipanema beach, and so forth. How can we reconcile this entangled universal wholeness with the fact that the act of observation necessitates that what is being observed is *distinct* from who (or what) is observing? Otherwise, if observer and observed can't be separated, how do we know where one ends and the other begins? Isn't this separation the essence of measurement?

Fortunately, the vast majority of measurements are such that the small quantum effects coming from the interactions between the observer and his apparatus or between the observer and the rest of the Universe are perfectly negligible. Their net statistical impact is much smaller than the typical experimental errors arising from limitations of the measuring devices. We are thus justified in treating the observer and her measuring device as two distinct entities interacting strictly along the laws of classical physics. Also, since the states of the measuring device are the same for different human observers (clicks on a Geiger counter, deflections of a measuring gauge, tracks on a cloud chamber etc.), we are justified in considering these states as independent from the act of observation or of the particulars of the observer. The quantum theory of measurement conveniently reduces to analyzing data collected from a classical device designed to capture and amplify signals from an observed system. This description should be effective as long as there is a clear separation of scales so that the measuring device behaves classically.

This sharp distinction between what is observed and the measuring device, which is at the very core of Bohr's complementarity idea, made sense sixty years ago, when the difference in scales was indeed huge. However, experiments today probe the "mesoscopic" realm, the mysterious boundary between an acceptable classical description and quantum physics, roughly below one-millionth of a meter, the size of a bacterium. Atoms can be visualized and manipulated individually, as in the famous 1989 IBM experiment in which Don Eigler used a scanning tunneling microscope to manipulate thirty-five argon individually and construct the company's initials. Nanotechnology explores the fabrication of devices at the mesoscopic scale, taking advantage of quantum effects. Certain contraptions are sensitive enough to capture oscillations coming from the "zero-point energy" of quantum harmonic oscillators, effectively detecting the energy of the vacuum. Far from being a shortcoming, the elusiveness of the quantum realm is being put to work in the development of revolutionary new technologies, from highly secure bank wirings to ultrasensitive detectors and, potentially, new types of computers.

The net result is that the boundary between the quantum and the classical is no longer well defined. In many applications physicists can't hide behind Bohr's conveniently pragmatic separation between a quantum system and its classical measuring device. The weirdness must be faced head-on. This explains why so many more physicists work today on the foundations of quantum mechanics than, say, even twenty years ago.[11] The question, though, remains: Is quantum weirdness an unavoidable aspect of Nature, or can we somehow make sense of it? The answer is essential to our argument, since, if the weirdness of quantum mechanics can be explained, it would simply imply a further growth of the Island of Knowledge, while if it can't, we would have to accept that large portions of physical reality are not just unknown but unknowable to us.

Critics of the Schrödinger cat puzzle would claim that a cat is just too big to isolate from the rest of the world and be placed in a superposition of two states, dead and alive. The whole thing is impractical and thus nonsense. At first glance it may be. But where do we draw the line? Austrian physicist Anton Zeilinger and his group have performed amazing experimental feats, making increasingly large objects go through double-slit obstacles to test whether they create interference patterns like electrons and photons.[12] In 1999, they succeeded in interfering buckyballs—a large spherical molecule with sixty carbon atoms and shaped like a soccer ball. More recently, they have extended their reach to include large biomolecules and intend to test if viruses can be put in a superposition of quantum states and interfere. As the object's size increases and its associated de Broglie wavelength decreases, it becomes much harder (and more expensive) to isolate objects from external influences and place them in a superposition of two or more quantum states. If a single photon emitted from the box wall bounced off the cat, it could, if it escaped and were detected, tell us whether the cat was standing or lying down. The single photon could collapse the cat's wavefunction. Still, the day will come when quantum interference experiments will attempt to pass a bacterium through double slits. How would life respond to quantum superposition? Is life a classical state of matter?

Schrödinger was well aware of these difficulties. His challenge was not experimental but conceptual. Was there a boundary between the quantum weirdness and our supposedly more reasonable conception of reality? Surely the world doesn't seem to be made of superimposed quantum states. Taking the three seminal papers from 1935—the EPR paper, Bohr's response to it, and Schrödinger's own take on the matter—we can see why most physicists opt to ignore all of this and go on with their work, happily computing transition rates and quantum superpositions as if there were nothing to worry about. But if we take a careful look at what the EPR paper was really saying, and how current experiments actually confirm

the bizarre reality that it tried to deny, including faster-than-light action-at-a-distance, how can we just dismiss the whole thing as a mere philosophical debate? Einstein and Schrödinger were convinced that Nature was trying to tell us something. Perhaps we should listen more carefully—which is what we do next.