The Quantum Dialectic

Thesis by

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Contents

Chapter 1

Introduction

I have grown tired of answering the question, “What do you study?” I have grown tired because I can never explain my answer; that answer being philosophy and physics. The polite reaction is one that appreciates academics as a whole and from all angles. The confused reaction is one that sees a fundamental clash. And I must admit, I more clearly see a fundamental clash than an appreciation of academics. But that is the last of my pessimism. I *do* see a correlation between the two, and many others do as well. And the clash within me will pass with time, as did my belief in correlation.

Quantum theory posits a description of physics that is as humbling as it is modest. When we represent quantum theory with its most general mantra, “Everything is one,” we move towards holist deisms and further from a genuinely physical account of the world. Quantum mechanics, though, is rooted in a physical description of the world. In describing the world, we bring sense to some spiritual claims while infecting physics with paradox. Quantum mechanics builds its philosophy from a contradiction embedded in ourselves. This paradox will prove to be more useful than confusing.

The best part: Quantum mechanics was the most atomic of surprises. Classical physics was operating so terribly well for centuries. Until, that is, physics started asking questions on the smallest and biggest of scales. There is debate whether a distinction can be made between classical physics and modern physics. This thesis, in the spirit of quantum physics, will prove both answers are possible. One thing is for certain: A hundred years ago, the mathematical physics was proving to be as successful as it was proud.

For the 1898-99 University of Chicago catalog, the physics section opened with:

> While it is never safe to affirm that the future of the Physical Sciences has no marvels in store even more astonishing than those of the past, it seems probable that most of the grand underlying principles have been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles to all the phenomena which come under our notice. . . . An eminent physicist has remarked that the future truths of Physical Sciences are to be looked for in the sixth place of decimals. (Treiman 1999, p. 3)

The excerpt was almost certainly written by famous experimental physicist Albert Michelson. (1999, p. 3) The state of the physics departments seemed ripe for a contradiction. Within two decades, the discovery of high-energy light, radioactive decay, free subatomic particles, special relativity, and the bedrocks of quantum mechanics splashed into physical community. (1999, p. 4)

Put bluntly, the grand underlying principles of physics had not been firmly established. While there had been great advances in electromagnetism, thermodynamics, and other fields, further implications of these theories had yet to be investigated, and this investigation required ingenuity not just in the sixth decimal place. Still, it was assumed that the intuitive and classical Newtonian description could be applied to any physical system. Such a description implied fundamental suppositions, such as the absolute nature of space and time, the principle of sufficient reasoning that governs all physical systems, and the necessity for every conceivable bit of matter to exist in only one place at any given time. Granted, Newtonian mechanics and classical physics provide immense practical application. But with the modern discoveries, physics begins to offer an opinion regarding our intuition of reality, an opinion that seems to contradict everyday experience.

When introducing modern physical concepts, most physics texts juxtapose the classical predictions with the modern experimental observations. I feel this is a good way to grasp the difficulties that came with the beginnings of quantum physics.

Quantized Systems

Classically, a particle might be anywhere *a priori*; and similarly, it might have any mass, or any velocity, or any angular momentum (defined by position, velocity, and mass), etc. Following, the particle's total energy, kinetic plus potential, might take on any value. However, quantum mechanics necessitates these characteristics take on discrete values, usually in some multiple of Planck's famous constant, h (also written $\hbar = h/2\pi$). We say the values are *quantized*. Classical values require nice, continuous, differentiable equations; in other words, they disallow such discretization.

Probability

As mentioned before, classical physics concludes that any bit of matter exists in a single place at any given time. Practically speaking, of course, the measurement apparatus will always have some limit to the level of specification available. But in principle, there is no *a priori* limit to a level of accuracy in any given measurement. Thus, if one wants to determine the future state of affairs, they only need to rigorously apply the theories of mechanics. Classical physics is deterministic in the sense that the future states of the system are set in stone given some initial state. In quantum mechanics, "state" refers to simply "all that can possibly be known about the system at any instant." (Treiman 1999,

p. 6) Quantum mechanics admits some level of determinism, but the difference lies in the description of the state. Quantum physics does not conclude on the specific position, momentum, etc. of any given particle; rather, quantum mechanics specifies a probability of these values. So rather than quantum theory determining the future, it states a probability regarding the future. So for some situations, the outcome is almost definite; for others, the probability function is extremely broad; and further, there lies an infinite number of possibilities between these two extremes. It is always important to remember this is an intrinsic state of the system, and not a limit of the experimental apparatus. For instance, if we were to set up some series of detectors to measure the position of a quantum mechanical particle (an electron, for example) at some given instant, then when one of the detectors clicks, we will know the exact position of the particle at that exact instant. But, if we were to repeat this experiment, we would find this particle to travel in all sorts of directions at all sorts of velocities, and the outcome can only be described probabilistically. These experimental descriptions will come in Part I.

Indistinguishable Particles

In our everyday life, it is impossible to call any two entities identical. They will differ in some physical way, in addition to their differences in spatial-temporal location. Classically speaking, one could in principle label the particles and track their behavior thus posing no conceptual problem. In quantum mechanics, the concept of identity must be approached probabilistically. Keeping track of any given particle is not only physically impossible, but is also meaningless: Switching two indistinguishable particles has no affect on the state of the system and thus carries no probabilistic ramifications. Considering that these probabilistic descriptions are all we can possibly know, a system of identical particles must be understood as truly identical, rather than the classical analogy of seemingly identical while distinguishable in principle.

Radioactivity

Some particles emit smaller, high-energy particles. This process is entirely spontaneous. Given a sample of radioactive material, we can predict a half-life based on experimental observation, when half of the high-energy particles have left the sample. But predicting when any given atom will emit its single, high-energy particle can only be done in terms of probability. Where these emitted particles come from was a question not answered until Rutherford's description of the atom, as discussed in Chapter 2. But when does the atom decide to decay? The answer to this question would have to await quantum interpretations. Classical models would predict that, if there is some mechanical mechanism that causes an atom to undergo decay, why don't all of the atoms in a given sample undergo radioactive decay at the same instant? Quantum mechanics claims that only a probabilistic explanation is possible. We now know that decay comes in many flavors, including decay of subatomic particles as well as atomic particles, and lifetime of radioactive elements varies from 10^{-24} seconds to billions of years. (Tipler and Llewellyn 2007, p. 49)

Tunneling

The probabilistic nature of the quantum world allows particles to exist where they would be otherwise classically forbidden. For example, we would not imagine a car to spontaneously lift itself from the gravitational "energy well" of our planet and hover above the ground. Quantum mechanics does not imply miracles of quite this magnitude, but it does suggest (and observe) some similar classically impossible scenarios. There can, for instance, be an energy barrier that separates two regions of space, such that a particle must have some threshold amount of energy to travel from one region to the next. Quantum physics states that there is a finite probability that a particle below this threshold energy could penetrate through the barrier. This mechanism is coined *tunneling* through forbidden regions.

Creation and Destruction

Even without a stable model of the atom, classical theory predicted that all matter was an arrangement of some fundamental building block. Naturally, the way to test this theory involves taking things apart. When we reach a subatomic level, we have to recreate some rather uncommon situations such as shooting high-energy projectiles at elementary particles. This is the research conducted in particle accelerators. This miniscule impact causes a small particle to burst into pieces, allowing physicists to trace the motion of the tinier particles of debris. Some of these reactions are considerably normal in that two things come together to make a third, or vice versa in some way. Other kinds of reactions, however, make very little intuitive sense. For instance, take the following reaction: $p + p \to p + p + \pi^0$. (Tipler and Llewellyn 2007, p. 234) Here, we have two free protons colliding to yield two protons and a third particle, the puon. No degree of rearrangment can hope to explain how it is that the final system contains the same ingredients as the initial system, *plus* some new element. There is simply no way around it: Particles can be (somewhat spontaneously) created or destroyed; there is no special, innate "conservation of matter law" on the microscopic scale.

The preceding paragraphs are meant to give a rough overview of some of the difficulties in combining a classical model with a quantum model. The first three examples will be referred to a considerable degree, while the last three serve as only a primer for our physics talks to come. There are some thinkers who wish to say that what makes physics *physics* is something more fundamental than the difference between these two models, and thus so-called "modern" physics is really no different than "classical" physics. As said earlier, either position here is possible, and the merits of each will come out in this thesis. Further, it is worth mentioning that while this philosophic claim carries weight, any practicing physicist will recognize a divide between classical and quantum models. Once I overheard a prospective-student tour-guide ask Harvey Mudd Professor John Townsend why it is that they teach quantum mechanics before any other form of physics in their curriculum. His response: "Because the classical model is simply wrong."

This thesis is divided into two parts. Part I is primarily an investigation into the odd world of quantum physics. Our entry point in Chapter 2 will be the principle of uncertainty, one of the founding theories of quantum mechanics. The uncertainty principle will fall out of some ordinary physical questions and will turn out to be incompatible with a "complete" classical theory. In Chapter 3, the uncertainty principle will prove to be only the tip of the iceberg. Some very practical experiments will show us that much more than "knowledge" is at stake here. Chapter 4 will begin to open up quantum mechanics so as to envelop the observer into the observed. We will see our actions have far-reaching consequences through mechanisms we cannot fully explain. In Chapter 5, the paradox will become apparent as we describe the classical response to the theories of quantum mechanics. In analyzing the rebuttal, we will begin to understand just how deep quantum mechanics goes.

Part II is dedicated to understanding the philosophic implications of quantum theory. In the first chapter of Part II, we will describe the locus of quantum philosophy, the Copenhagen interpretation. The philosophy will be presented as stemming from a paradox. Understanding the answers to the paradoxes will again allow us to run further with quantum theory and ask more fundamental questions. Chapter 7 will be our strongest link to primary sources of philosophy, specifically Kant's *Critique of Pure Reason*. We will see that Kantian dialectics are a good analogy for quantum mechanics, but stops short at recognizing the true significance of what we are discussing. The Copenhagen interpretation will prove to tear open some holes in the Kantian doctrine – Chapter 8 will hopefully fill these holes by juxtaposing the hard-hitting, anti-materialist philosophy of Martin Heidegger with the profound, well reasoned insight of Werner Heisenberg. We will see that quantum theory makes poignant claims regarding the world and our place in it. The conclusion will be a short summary followed by a reflection on what has been discussed. I hope to show you that marrying philosophy to physics is not only possible, but enlightening to us as humans.

Part I

Mirrors

Chapter 2

The Quantum Uncertainty Principle

To the common experimental scientist, the word uncertainty is analogous to error. For the entire history of natural science, uncertainty has been the asterisk presented alongside data. Uncertainty is used to assess the truth of a given claim. The question is often, does the theoretical prediction fall within the range of uncertainty? Theory becomes knowledge when justified by experimental observation. When an experiment is consistent with theory and has reasonably low uncertainty, an idea is actualized as knowledge. Uncertainty, then, is a gateway to knowledge: High uncertainty disallows succinct and well-founded explanations, while low uncertainty can conclude definitively on the validity of a given hypothesis.

In most natural science experiments, uncertainty takes two forms: statistical uncertainty and systematic uncertainty. Statistical uncertainties arise from random fluctuations in a measurement. These random fluctuations can occur in measuring devices. For example, air currents or electronic noise lead to small fluctuation in motion detector readings. These fluctuations occur even when the motion detector is measuring the distance to a stationary object. So, we might expect differing measurements for a given distance even though no change in the system occurred. Random fluctuations can also be a characteristic of the quantity being measured, in addition to the experimental apparatus. For example, if we use a meter stick to measure the landing positions of a series of projectiles, we see significant random variations which clearly do not arise from the limitations of the meter stick. Instead, we suspect the launch angle or velocity of the projectiles is subject to small random variations in the launching equipment.

The standard method of eliminating statistical uncertainty involves taking lots of data. The defining feature of statistical uncertainty is that the uncertainties average to zero. For instance, returning to our projectiles: Suppose we perform our experiment twice, measuring the distance from launch to landing. The first launch shot the projectile five feet; the second, six feet. Can we conclude on the forces at work in the launcher? Apparently not. Suppose, then, we repeat the procedure one hundred times. We find that the average launch distance is five and a half feet. Yet clearly this does not mean that every time the launcher shoots a projectile, that projectile will travel five and half feet. In fact, it is quite the opposite. The chances of traveling exactly five and a half feet are very small. Further, there might have never been a situation out of the one hundred and two launches where the projectile traveled within a tenth of an inch to five and a half feet. Nevertheless, the scientific method concludes that the most accurate piece of knowledge we have arises from the average distance of five and a half feet, and thus the scientist concludes that the launcher exerts a force x at and angle of ε. Statistical uncertainty is a part of *every* experimental conclusion.

Systematic uncertainties are due to defects in the equipment or methods used to make measurements. For example, if a motion sensor is poorly calibrated, it could consistently produce readings that are only ninety percent of the true value. It has a systematic uncertainty that is much greater in magnitude than the statistical uncertainty in its readings; while small fluctuations could cause small errors in data, systematic errors tend to produce large, sustaining uncertainties. Systematic errors are often difficult to detect because they do not show up as fluctuations in the results of repeated measurements. Instead, the scientist must deduce a reoccurring tendency of the experiment. Usually, this tendency can be isolated because the observations deviate from the theory in a consistent way. Other times, the systematic uncertainty is not noticed until some time after the experiment. Sometimes, the uncertainty is noticed within minutes or days after the observation; sometimes, it takes decades to isolate the problem with the apparatus and thus observe a system that is consistent with theory. And still others times, a systematic uncertainty goes unnoticed, a conclusion is reached, a theory becomes knowledge, and then much later theory takes a ground-shattering turn and suggests systematic error has been part of a whole body of experiments.

The standard method of eliminating systematic uncertainty, on the other hand, involves being a really good scientist. Edwin Hubble was just such a scientist. (Tipler and Llewellyn 2007, p. 341) Hubble was the first to prove that our surrounding celestial neighborhood is a type of island universe, one galaxy among billions of differing scale, shape, age, and morphology. How did he infer such a conclusion? In astrophysics, a common method of measuring the distance to source of interest is by using nearby stars, or in Hubble's case, a star inside the galaxy he was observing. These special standard-ruler stars are called variable stars. They come in many forms, but the unifying trait is their variability in luminosity, size, and temperature. Of course, Hubble could only detect one of these variations: luminosity (brightness). It had been known for quite some time (though considering the age of precise astrophysics it was quite a short time) that these stars follow rather strict variation patterns. Specifically, the magnitude of the change in luminosity is directly proportional to the time scale on which it varies. In other words, the bigger the variation in luminosity, the longer the period of variation will be. Similarly, the bigger the variation in luminosity, the more massive the star. Hubble noticed long variations of sources within a nebulous astronomical object, known today as the Andromeda Galaxy, our closest galactic neighbor. The luminosity variations, though, were surprisingly faint. Hubble thought that if these stars were within any contemporary estimate of the size of the universe, then the star would exhibit much brighter changes in luminosity. So, because the amount of light that reaches an observer drops off with distance from the source, Hubble concluded that these variable stars were in fact *much* further than the estimates for the size of the universe. In turn, it was clear that "the universe" was in fact an island amongst a vast sea of others.

Hubble's conclusion was by no means immediate. As an innovator and developer of highly sensitive photographic plates, Hubble examined the likelihood of systematic uncertainty carefully. Hubble spent years experimenting with different types of photographic plates, hoping that he could invent an accurate and reliable light-absorbing surface. Yet after countless runs of confirming the data of his peers and then turning his plates towards Andromeda, Hubble was forced to conclude that there exists no systematic error; the universe was, in fact, enormous. Most times, systematic uncertainty is a conclusion to an experiment that did not observe the predicted data. The scientist attaches systematic uncertainty to a fruitless trial. There are other times, though, when systematic uncertainty is a result of the theory. As a rubric for what is and what is not knowledge, theory can yield startling reactions to certain experiments. Uncertainty can be an uncanny gateway to knowledge, posing new questions and deconstructing the inconsistencies in theory.

Modern physics has added a new category of uncertainty: Quantum uncertainty. Oddly, it has almost no similarity to statistical or systematic uncertainty. While statistical and systematic uncertainty are characteristics of any experiment, quantum uncertainty is characteristic of any*thing*. Formally, the quantum principle of uncertainty is stated:

$$\frac{h}{2} \leq \Delta x \Delta p.$$

In words, the product of the uncertainties of position and momentum for any given particle can be no less than half the value of Planck's constant. In essence, when you try to measure both the position (in space) and the momentum (the product of the particles mass and its velocity), you will be met with an uncertainty that is neither statistical nor systematic. (Tipler and Llewellyn 2007, p. 113) The uncertainty is not a result of poorly designed experimental equipment. Rather, the system cannot be defined to have simultaneous, finite values for two variables. (The uncertainty principle is often stated another way: $\frac{h}{2} \leq \Delta E \Delta t$. In words, the product of the uncertainties of energy [of a given particle] and time [of observed energy] can be no less than half the value of Planck's constant. This formulation falls directly from the previous statement using first principles. Yet this way of stating the uncertainty principle has its own sorts of implications, and will become part of our broader analysis later.)

Werner Heisenberg derived the uncertainty principle in 1926 along with significant contribution from his mentor and friend, Niels Bohr. There were challenges to Heisenberg's principle of uncertainty, including much criticism from Albert Einstein. Such criticisms took the form of thought experiments as well as competing mathematical descriptions of the world. While we will give a conceptual derivation of the uncertainty principle soon, delving deep into the philosophical implications of the quantum principle of uncertainty is the objective of Part II. For now, though, we can explain some of the physical implications of quantum uncertainty.

As stated before, quantum uncertainty has nothing to do with experimental apparatus; it is a condition of the system. To understand what this means, we must consider the particle that Heisenberg had in mind when deriving the principle: the electron. The uncertainty principle is by no means limited to only describe the electron; instead, this was the particle under highest scrutiny during the time of early quantum mechanics. The picture of the atom taught in most introductory physics courses describes a Newtonian mechanical system: Much like the planets orbit around the sun due to gravity, negatively charged electrons orbit around the positively charged nucleus due to electromagnetic force. This is quite intuitive, especially given that the equation for electromagnetic force is analogous to the equation for the force of gravity:

$$F_G = G\frac{m_1 m_2}{r^2}; \quad F_E = k\frac{q_1 q_2}{r^2}.$$

F_G represents the force of gravity, while F_E represents the electromagnetic force. G is the Newtonian gravitational constant and k is the Coulomb electromagnetic constant. Each equation considers two "particles." The first equation represents these as m_1 and m_2, the mass of each object, while the subject equation represents them as q_1 and q_2, the charge of each object. The distance from object one to object two is represented by r in the denominator. So, with these descriptions of two fundamentally different forces, the layman is lead to believe that the system of an atom is simple and similar to other, more tangible systems. The problem, however, arises when one tries to verify the orbit of the electron about the nucleus.

In 1909, Ernest Rutherford arrived at the familiar, orbiting-electron model of the atom. While the conclusion was reached experimentally, it did not observe any sort of electron motion. Rutherford shot α-particles (essentially helium atoms, two electrons surrounding a nucleus of two protons and two neutrons) at a sheet of gold foil. At the time, it was thought that the atom was a positively charged "solid" with negatively charged bits floating scattered throughout. Under this prevailing "plum pudding" model of the atom, Rutherford expected the homogeneous mixture of positive and negative charge within the atom would cause each α-particle to be deflected at a small angle as it passed through the gold foil. Specifically, the α-particles, which are small when compared to gold atoms, would push their way through the foil and be slightly nudged by electromagnetic forces as they exit the matrix of gold atoms. Rutherford believed that this scattering would give insight to the charge distribution of the plum pudding model of the atom.

The result was quite surprising. Rutherford's associates Geiger and Marsden surrounded the gold foil with a sheet of zinc sulfide; when the α-particles hit the zinc sulfide, the screen would darken in order to detect the angle of deflection. Geiger and Marsden observed α-particles scattered at angles greater than ninety degrees; basically, some α-particles were being reflected. Rutherford expressed his astonishment in a famous quote:

> It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you. On consideration, I realized that this scattering backward must be the result of a single collision, and when I made calculations I saw that it was impossible to get anything of that order of magnitude unless you took a system in which the greater part of the mass of the atom was concentrated in a minute nucleus. It was then that I had the idea of an atom with a minute massive center, carrying a charge. (Rutherford, 1902)

Rutherford concluded that the electromagnetic force required to reflect the α-particle could only result from a highly concentrated, positively charged nucleus of an atom. With this, the standard model of the atom was born: The race was on to observe the electron in orbit about its nucleus.

Not long after the birth of the standard model, it became obvious that observing the electron is no simple task. The size was estimated, using a classical non-quantum relativistic model of the electron, to be about $1/3000^{\text{th}}$ the size of the atom itself, which was estimated to be rather small: 10^{-15} meters. (Tipler and Llewellyn 2007, p. 120) The problem with observing such a small particle arises from the nature of light. Light travels in waves, and the size of the objects that light can interact with is proportional to the wavelength of that light. A wavelength is the distance from the crest of one wave to the crest of the next. For instance, radio wavelengths are many meters long, and thus pass right around most daily objects, including bodies. Ultraviolet light, on the other hand, has short wavelengths, short enough to collide with our skin cells and cause damage. Small fibers in our eyes are of just the right size to "catch" visible light and translate it into electrical signals. An analogy is a wave in the ocean: Waves with long wavelengths, perhaps miles long, pass right around a small island, while shorter waves smash against the shore and dissipate. So, the wavelength of light needed to image an electron must be equally as small as the electron itself. But short wavelength means highly energetic light, and light with *this* short of wavelength is *very* energetic. In fact, this light is so energetic that humans have yet to create, sustain, and direct such light.

But who cares? We can still *assume* that one day, we will be able to control such light and thus be able to image the electron, right? Okay, let us assume this technological feat. Also let us assume the electron is a "classical" particle, whose position can be described using more tangible Newtonian physics rather than probability wave equations.

Consider a microscope that emits γ-rays, light rays energetic enough to image the tiny electron. Most microscopes used to image small objects refract light to a point. This point could be a small bacterium or minerals in a piece of quartzite. (Keep in mind, though, the electron is *much* smaller.) Light is refracted by the microscope is done so the in same way light sunlight is refracted to a point with a magnifying glass. As such, the light forms a cone as it travels from the refracting lens to the electron. For simplicity, assume the particle is moving in one dimension along some x-axis. An image of the electron forms when the γ-rays strike the moving particle and bounce back to the observer. It is helpful here to draw a diagram (Figure 2.1).

Okay, so we have our microscope. It is necessary to talk briefly about two important observations from physics: The resolving power of an optical lens, and Compton scattering.

The resolving power of an optical lens can be written

$$\Delta x = \frac{\lambda}{\sin \varepsilon}.$$

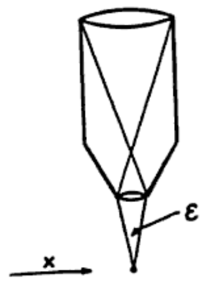

Figure 2.1: The Heisenberg Microscope. As an electron moves about the x-axis, we attempt to image it using a γ-ray. The γ-ray knocks the electron out of its path at an angle proportional to sinε. Heisenberg 1930, p. 21.

The goal is not to derive this equation from classical optics, but rather explain why the expression is important to understanding how a microscope works. The left side of the equation, Δx, is the "resolving power" of any microscope, camera, or optical device, more commonly referred to as resolution. While x represents the particle's exact position, Δx represents the *range* in which that instrument can detect an object. x is a position. Δx is a range of positions, or a distance. For example, the resolution, Δx, for the human eye is about 0.1 millimeters. In other words, things smaller than about a tenth of a millimeter are very difficult for people like me to see. To put it another way, I cannot detect the position of a particle smaller than Δx to any degree more accurate than 0.1 millimeters. On the other side of the equation, λ represents the wavelength of the light used to resolve an object, and sinε represents the angle at which the light is scattered following from Pythagorean geometry.

Why does light scatter, or bend, in this way? Sometimes it is more useful to describe light as a particle; here, it is more useful to describe light as a wave. Imagine ocean waves traveling perpendicular to a long jetty. Now, imagine there is a hole in this jetty. We know that as the waves pass through the hole, they will be refracted in radially out from the jetty opening. On one side of the hole, the waves will coming in will look like straight lines when viewed from above, while the waves on the other side of the hole will look like a semicircle. Now, imagine this jetty has seen one too many waves, and it has been reduced to a small wall sticking out of the water some short distance from the coast. The waves will pass by the jetty in a similar way, bending around the end walls.

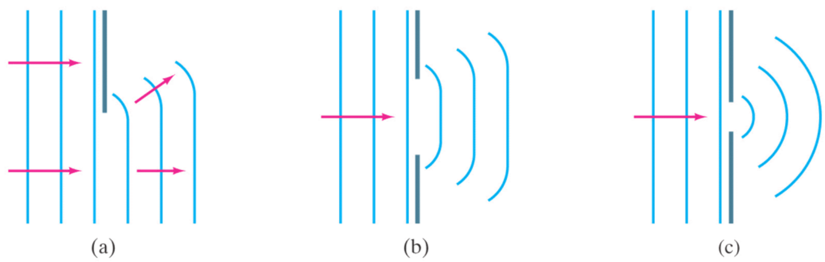

Figure 2.2: Waves around objects. In (a) we see how waves bend around a stationary object. In (b) see see waves propagate through a large slit; specifically, a slit larger than the wavelength. In (c) we see waves propagate through a slit with a width smaller than the wavelength.

So, we have a picture of light rays bending around the tiny electron. It so happens that the degree of this bending is proportional to the wavelength of the light itself. This makes sense: Short wavelength, high frequency light shoots around the particle at a greater angle than long wavelength, low frequency light. Now, recalling the equation for the resolving power, we see that the wavelength of light, λ, must be greater than or equal to the resolution, Δx. This follows from the fact that $\sin\varepsilon$ can only take on values from 0 to 1. Thus, to image the position of the electron, we can do so only to some range determined by the wavelength of light which the microscope emits.

Compton scattering is a bit easier to understand. Like the optics discussed above, it is entirely an observational conclusion. This time, imagine light as streams of tiny particles, call them photons, moving at the speed of light. These photons are extremely small; but something moving so fast will surely have great momentum. In 1927, Arthur Compton was awarded the Nobel Prize in physics for demonstrating that high-energy light (such as our γ-rays) scatters when it collides with an electron. Just as one billiard ball strikes another at an angle, the photon carries some bit momentum large enough to knock the near-weightless electron from the orbit of its atom. We can describe the electron and the photon bouncing off each other at some angle, ε.

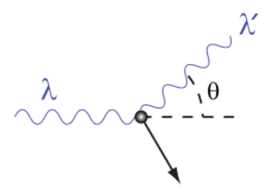

Figure 2.3: The Compton Effect. An incoming light of wavelength λ hits an object and is scattered at an angle θ. For our purposes, $\theta = \varepsilon$. The resultant wavelength, λ' will be of lesser energy and therefore $\lambda > \lambda'$. AP Physics 2011, WordPress.

When this photon hits the electron, the latter is deflected at a momentum directly proportional to the wavelength of incoming light. Recall the shorter the wavelength, the more energetic the light. We describe the energy of the wavelength simply: $E = hc/\lambda$, where h is Planck's constant and c is the velocity of the photon. So again, following form this equation, the smaller the wavelength, the more energetic the light. The momentum of the scattered electron p is then

$$p = \frac{h}{\lambda}.$$

We have our tools. Let us return to the Heisenberg microscope, along with the assumptions that we can control highly energetic γ-rays and the electron is a simple ball of matter zooming around the nucleus of an atom. This angle of scattering is determined by the position of the electron and the wavelength of our imaging light, the γ-rays. So, the γ-rays hit the electron and bounce back to the observer charting out some cone of light with an angle ε. The electron is knocked out of place by the incoming γ-rays due to Compton scattering. Conclusion: It is impossible to measure the position of electron about the atom without *disturbing* the system to some degree. (Heisenberg 1930, p. 22)

We can now finish this conceptual derivation of the Heisenberg uncertainty principle. Recalling the introduction, we know the energy carried by photons is quantized; it is always some multiple of Planck's constant h. If this energy is too big, it will nudge the electron and destroy the possibility of objectively measuring the electron's position, x. If this energy is too small, the wavelength of light will be longer than the electron itself and thus the microscope could not resolve the position to accuracy within this resolution limit. Thinking back to the angle ε Figure 2.1, we can know the momentum of the electron is only determined up to some range, Δp, proportional to the scattering angle and the wavelength of light:

$$\Delta p \approx \frac{h}{\lambda} \sin \varepsilon.$$

This equation is very similar to the momentum from Compton scattering. The difference, though, is that the angle of scattering introduces some uncertainty in momentum, Δp, rather than some exact momentum, p. Putting together our expressions for the range of possible values of position and momentum, Δx and Δp respectively, we have

$$\frac{h}{2} \leq \Delta x \Delta p.$$

The conclusion of the uncertainty principle is profound. If we call the range of possibilities for position and momentum *uncertainties*, then physics has stumbled upon a finite limit to the amount of knowledge available. Heisenberg's work was the first of its kind in the history of physics. Uncertainty suddenly moved from the realm of experimental error to the realm of physical truth. Perhaps more interesting though is the implication that the mere act of observing the electron can *only* disturb the electron itself, thus preventing any sort of objective knowledge. I say *only* here because: While our thought experiment involved a microscope, even if the human eye was able to see the tiny electron, any light wave illuminating the electron would shift the electron from "its" position. Thus, the bit of light I capture to see the electron, *I* and *I alone* capture. There is no doubt that this piece of information carries a subjective element. Further, this "subjective" claim digs deeper than it appears. *Every* piece of knowledge carries with it some amount of uncertainty. The uncertainty principle states there is no such thing as arbitrarily certain knowledge. Uncertainty is a *condition* of knowledge. (We must remember that we are referring to only physical knowledge. As it turns out, this is a good thing: Because we cannot refer to *all* knowledge with the uncertainty principle, we are forced to look elsewhere for sources of the paradox, *i.e.* sources outside epistemology. Instead, we will be forced to look at ourselves and our relation to the object. In this way, knowledge will be encompassed in our discussion. But the goal of these explanations of quantum mechanics is to dig deeper than knowledge of the physical world.)

It should be said that there are challenges to Heisenberg's microscope. For instance, to determine the magnitude of recoil that the electron receives after being illuminated by the γ-ray, we could make the microscope moveable and chart out this change in momentum along some kind of scale behind the electron. At the very least, then, we would need to observe two rays of light simultaneously: one bouncing from the electron and one illuminating our x-axis position scale. Because light travels at a finite speed, simultaneously observing the light from the scale and the light from the electron does not mean the events are simultaneous: Light from the scale will take longer to reach the observer than light from the electron. Thus the uncertainty in the recoil magnitude is again encountered.

We now know that for small systems such as the atom, the motion of a particle cannot be represented in the same way as the motion of a body under gravitational or electromagnetic forces. Given the historical perspective, it is clear that the uncertainty principle borders on what has been physical knowledge. The uncertainty principle is not so much a knowledge of something as it is a limit to the knowledge of something. Physics had its eye on certain knowledge since Newton and Galileo began to describe the motions of large bodies. As physics approaches a proof for monism, though, the face of knowledge takes a much different form.

Chapter 3

Uncertainty Expanded: The Decisive Electron

We now understand the difficulties in describing the state of a single electron. The overwhelming implication is the impossibility of "objective" knowledge. But, one can still make the argument that the quantum uncertainty principle is incomplete. One might argue that the probability distributions of quantum mechanics is a practical type of knowledge in that it allows the observer to make reasonable conclusions on the state of any given particle. Quantum uncertainty, though, does not allow any further development on the theory of small particles. A more complete theory would be one that describes, with certainty, the behavior of any given particle. Given a set of initial conditions, a complete theory would then *determine* the outcome of any given state of affairs, with certainty. This was the firm belief of Einstein and his associates, which will be described in full in Chapter 5. Before explaining this conjecture, I wish to make a greater case for the odd nature of quantum systems.

The result of the above thought experiment involving Heisenberg's microscope is not exactly *observed.* While the assumptions that play a role in the thought experiment are most definitely experimentally confirmed, Heisenberg's microscope is not an instrument that is experimentally practical for the reasons discussed. So, we turn to an experiment that *has* been conducted, numerous times in fact. (Tipler and Llewellyn 2007, p. 163) As Richard Feynman put it in his *Lectures in Physics*, the next experiment highlights

> the basic element of the mysterious behavior in its most strange form. We choose to examine a phenomenon which is impossible, *absolutely* impossible, to explain in any classical way, and which has in it the heart of quantum mechanics. In reality it contains the *only* mystery. We cannot make the mystery go away by 'explaining' how it works. We will just *tell* you how it works. In telling you how it works we will have told you about the basic peculiarities of all quantum mechanics. (Feynman 1965, p. 3)

We set up a similar apparatus as discussed earlier. Viewing our equipment from above, on our left we have a source of streaming particles. Moving to the right, we have a screen with two slits. Behind the screen we have a detector that lights up when an electron strikes its surface. Now consider three contrasting experiments. (Polkinghorne 1984)

In the first experiment, our source fires little bullets in a very inaccurate manner. The bullets may hit the screen and bounce off or travel through one of the two slits. If we close one of the slits, then the bullets will fly through and scatter across the detector behind the screen. There will be a probability distribution to the bullet scatter. Most of the bullets will hit directly behind the slit; some bullets will hit slightly to the left or right, depending on the angle at which the bullet was fired. If we were to graph this distribution versus position on the screen in a histogram, it would look like a hump or a Bell curve with the peak being the point directly behind the slit. Opening the second slit, we simply get two of these curves. If the slits are close enough, these humps overlap slightly. Graphing the total distribution of bullets emerging from the two slits, we might get a curve similar to the one-slit distribution. The humps of the two slits combine and build a total peak to the distribution. Classically, this is what is expected of any particle with mass (*i.e.* the electron) and is the obvious outcome of such an experiment.

For our second experiment, allow the source to produce waves; they can be acoustic compression waves or photon light waves. Our detector will then measure the loudness or brightness of the waves as more and more pass through the slits and impact. The result will be what is called an interference pattern.

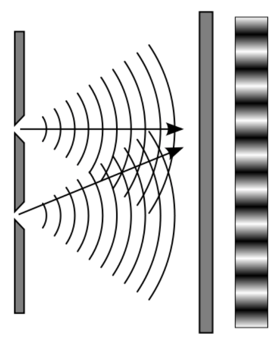

Figure 3.1: An Interference Pattern. When the crests of the waves meet in sync at the detector, we obtain a maximum; when troughs of a wave meet in sync at the detector, we obtain a minimum. The result is evidence for wave motion.

Again there is a peak distribution directly behind the middle-point of the two slits. In this case, though, the pattern to the right and left is a damping oscillation. This is due to the wave property of interference. At some points on the detector, the crest of a wave from slit one will coincide with the crest of a wave from slit two, thus resulting in constructive interference and causing a bright fringe. Similarly, if a valley from slit meets a crest from the other, they will destructively interfere and cause the total brightness to decrease on that section of the detector. The minimums on our distribution function correspond to a valley from one slit meeting with a valley from they other slit, and thus their total combined brightness is negligible. The combined geometry of the waves and our apparatus determine the spacing of the interference pattern. The presence of two slits is essential to the interference pattern, for if only one slit existed our result would be identical to that of the first part of experiment one.

For our third experiment we use quantum particles; for sake of consistency, we will use electrons. Let our detector be a Geiger counter, and every time an electron impacts the detector the counter responds with the stereotypical 'click.' We know the electron has a mass (Tipler and Llewellyn 2007, p. 54) and thus the classical physicist expects the particle to pass through one slit or the other. At first, this seems to be the case. The electrons arrive at the detector and the Geiger counter responds with discrete clicks just like the bullets from the first experiment. So we conclude the electron is a particle. However, after accumulating some data on our distribution plot, we notice the same type of interference pattern observed in experiment two. We conclude the electron is a wave. (Tipler and Llewellyn 2007, p. 165)

The question then of course is, if the electrons arrive at the detector one by one as the Geiger counter showed, then which of the two slits is the electron passing through? Suppose we say the electron passed through the first slit. Then, at that time, the second slit was irrelevant. We could have momentarily closed it without affecting the outcome of the experiment. However, if we perform a single slit experiment with electrons, we get the typical hump distribution observed in experiment one. We are back at the particle model. If we wish not to contradict ourselves, the only consistent conclusion at this point is that the electron passes through both slits. This classically forbidden result is inescapable in quantum mechanics. The problem of locality is beginning to take shape.

Such is our bewilderment if we passively allow the experiment to continue. Consider then taking active steps to determine through which slit the electron traversed. Feynman suggested putting a lamp that emits γ-rays to illuminate the particles as they pass through the slits. So, just before the Geiger counter clicks, we see the electron flash through one slit or the other, and thus we are able to conclude the locality of the electron. Quantum mechanics, though, necessitates that every form of measurement affects the result (the full explanation of this interpretation will be in Chapter 6). So, we check to see whether the result has be altered – quite counter to our intuition, the interference pattern is no longer observed. Instead, we have two humps that combine to form a single Bell curve of a distribution, no different than the result in the first experiment. (Feynman 1965, p. 18) Again, the conclusion is inescapable: The act of measurement changed the result of the experiment.

The physicist calls this process *collapsing the wavefunction*. The electron exists as a superposition of probability distributions, a collaboration of matter waves. (Tipler and Llewellyn 2007, p. 176) The illumination apparent at the first slit meant that the electron was no longer in a superposition of probabilities, but rather collapsed to a single, unique state corresponding to a position in the first slit. Without such superposition of acoustic or light waves, there is no interference pattern. We have effectively removed this superposition of states from the electron and determined its place in space all with a simple measurement. (Polkingthorne 1984, p. 38)

The double-slit experiment displays a fundamental feature of quantum mechanics, namely that we know where something is only if we look at it through measurement. Otherwise, the electron exists as probability, a distribution of possible states that manifests as wave phenomena similar to light or sound. Classically, particles have definite positions and trajectories. Thus we should be able to trace the motion of the electron through a slit. We must give up this assumption in the quantum world. There are no positions that coincide with a given trajectory. Given a stream of electrons, we are best to describe this body probabilistically, or in other words we are best to conclude merely that "some will go this way and some will go that way." Furthermore, considering a stream of only two electrons, it is still best to say, "one might go this way and the other might go that way, or they will both go this or that way." Notice we need not say, "one might go this way and the other might go that way, or one might go that way and the other might go this way, or they will both go this way or that way." Quantum mechanics assumes the electrons are identical in the sense that they are indistinguishable. Having one electron in slit one and the second in slit two is no different than having the second electron in slit one and the first in slit two. Here we find a basic assumption underlying the classical prediction: Identical particles are *in principle* distinguishable. (Jammer 1974, p. 26)

The philosophical problems inherent in quantum physics are becoming apparent. First, we have found that the possibility of objective knowledge seems at the very least conspiratorial. By objective knowledge we mean a knowledge that can determine the outcome of any given set of initial conditions with certainty. Second, we have uncovered a problem of locality. By this, we mean the seeming possibility that a single thing exists in two places at one time. We now find ourselves trying to defend, for the moment, our basic notion of locality, specifically our notion that things must have definite position regardless of our knowledge of them. To defend this notion, we are forced to explain our understanding of identity and distinguishability on the particle scale. Why? Again, if we are to claim that electron A exists in location x_a, then we must be able to distinguish electron A from the identical electron B. (We must *also* be able to distinguish position x_a from position x_b, but let's leave that question open. As it turns out, the theory of general relativity might have a better answer to this than quantum mechanics (Greene 2004, p. xv) even though the two are not easily compatible, if at all.) In our everyday lives, identical does not imply indistinguishable. In the quantum world, this is not the case, as we will show.

Step one: Dismantle the (classical) notion that identical does not imply indistinguishable.

Suppose, then, we have two electrons that are governed by wave equations; suppose these particles are identical but not indistinguishable, as per as conventional beliefs of singular locality. The most commonly adopted wave equations for quantum particles are called the Schrödinger equations, named after Austrian physicist Erwin Schrödinger. As done before, our approach will be to state the Schrödinger equation and then explain the parts. For our purposes, we need not express the equation as a function of time. In other words, to determine the implications of quantum mechanics on a theory of locality, we can assume the system of two electrons is in a steady state. We can picture this as the *instant* when two electrons "pass through" the first and second slits. The time-independent Schrödinger equation is (Tipler and Llewellyn 2007, p. 170):

$$-\frac{\hbar^2}{2m_e}\frac{\delta^2\psi(x)}{\delta x} + V(x)\psi(x) = E\psi(x).$$

(For clarification, the fact that the second term contains a derivative of ψ with respect to x implies that ψ is a function of x.) As normal, x refers to the electron's position in space, while m_e refers to the mass of the electron. Planck's constant divided by 2π is here as well written as $\hbar$. $V(x)$ is the potential energy of the wave; similar to a wave in the water, the potential energy will govern the height of the crests and so on. E refers to the total energy of the wave, which is shown as the sum of the potential energy, $V(x)\psi$, and what is called the Hamiltonian operator, the first term. To get a better idea of the energies, you can think of the potential energy V as the energy the wave would exert on you if it were to carry you from the bottom of its trough to the top of its crest, perhaps if you were floating in the ocean just off coast. The total energy, E, is the energy that would be dissipated into the sand when the wave crashes into the coast.

At a glance, it is obvious that each term in the equation includes some factor or function of $\psi(x)$. This is the quantum wavefunction. The wavefunction itself does not correspond to any physical reality. What does correspond to a physical reality, however, is the square of the wavefunction ψ^2, sometimes written $|\psi|^2$ or $|\psi(x)|^2$ to explicitly connote its nature as a function of position x and coordinate-system invariability. The wavefunction ψ^2 refers to the probability density. Recall the wavy probability distribution plots we drew along with experiment two in the beginning of this chapter. The y-axis measures the probability density, ψ^2. Physically, it is the probability that our electron will be at position x.

Before continuing, I should make two notes about the Schrödinger equation. First, it is analogous to other wave equations such as those for compressive sound waves or those for translational waves in water. Any wave equation will describe the *motion* and the *shape* of the wave; in describing these two characteristics, the energy of the wave is comes in handy. Second, the Schrödinger equation is entirely empirical. It does not fall out of any system of mathematics *a priori*; it is not *derived* in any sense. Schrödinger *wrote* the equation after observing countless experiments similar to the double-slit experiment described above. The equation gained popularity after its numerous set of solutions proved capable of explaining a countless variety of quantum experiments. (Jammer 1974, p. 21; Tipler and Llewellyn, p. 174)

So we have our wave equation, and we have an understanding of the elusive ψ. Now, return to our (classical) notion that identical does not imply indistinguishable.

Suppose I have a particle 'here' and an identical particle 'there.' Equivalently, suppose we have a wavefunction $\psi(x_a, x_b)$ corresponding to two identical particles with positions x_a and x_b. $\psi(x_b, x_a)$ must then be the same physical state because our electrons are identical. In other words, there is no physical difference between wavefunctions $\psi(x_a, x_b)$ and $\psi(x_b, x_a)$, *even if* we are able to label the electrons and keep them distinguished from one another. For any given set of vectors $\langle x_i \rangle$, the set forms a linear vector space if any linear combination of them,

$$\sum_i \lambda_i \langle x_i \rangle,$$

also belongs to that space. Likewise, any particle i described by the wavefunction $\lambda_i \psi(x_i)$ in a system of n particles can be described as a scalar factor of any other particle. (Polkinghorne 1984, p. 86) If we then interchange the positions of our two particles, this above sum means

$$\psi(x_a, x_b) = \lambda\psi(x_a, x_b).$$

In other words: We know the probability densities of two identical particles, ψ^2, are identical. This last equation takes this a step further, claiming that the wavefunctions differ by only a single factor, λ. To find λ, interchange our particles again: Applying the above equation twice yields

$$\lambda^2\psi(x_a, x_b)$$

for the wavefunction of our original particle at position x_a and x_b. (1984, p. 89) But two interchanges, regardless of the identity of the particles, must leave us in the exact same position we started, specifically back at $\psi(x_a, x_b)$. So,

$$\psi(x_a, x_b) = \lambda^2\psi(x_a, x_b),$$

and thus,

$$\lambda^2 = 1, \text{ or } \lambda = \pm 1.$$

Now we can write the relationship between the two original states, $\psi(x_a, x_b)$ and $\psi(x_b, x_a)$. It is

$$\psi(x_a, x_b) = \pm\psi(x_b, x_a).$$

(1984, p. 89) Particles that obey the positive relation, such as photons, are called bosons; particles that obey the negative relation, such as electrons, are called fermions. (1984, p. 39) Whether a particle is a boson or a fermion does not matter for our discussion. What matters is that if we interchange two identical particles, their probability density ψ^2 remains the same. So even if we assume the particles are distinguishable, their wave equations yield an indistinguishable description of their position in space. In other words, if the particles are identical, then the particles are indistinguishable.

Step two: Dismantle our (classical) notion of locality, that a particle must reside in a single position at any given moment, regardless of our knowledge of that particle.

Recall our observations of the detection screen in experiments one and two. In experiment one, we have two humps corresponding to a probability distribution of identical (albeit distinguishable) bullets passing through two slits. In experiment two (and three), we observed and interference pattern. While these two results appear very different, they are actually described in exactly the same way. This description relies on a mathematical truth that has been assimilated into the physics of wave motion, known formally as the *superposition principle*. The principle states that wavefunctions add linearly. (Tipler and Llewellyn 2007, p. 59) For the bullets, this is easy to see: Two, small humps corresponding to motion through each slit adds to form one, large hump corresponding to the bullets passing through both slits. The wavefunctions of these simple, non-quantum mechanical bullets are just straight lines, reflecting the trajectory of the bullet. For quantum mechanical particles such as electron and photons, this is slightly harder to see: The wavefunctions add to form a wavy distribution pattern. This is because the wavefunctions are not straight lines; they are sine waves. Squaring the wavefunction ψ gives the probability density ψ^2, as has been discussed.

For sake of honesty, we must allow the wavefunction to take on complex values. (The reason, put very simply, is because the sine wave that is the wavefunction dips below the x-axis into negative values, and superposition of these sine waves involves a Pythagorean-like argument that involves taking square roots of negative numbers.) A typical complex number z is the sum of a normal number with some multiple of i, the square root of negative one. As an equation,

$$z = x + iy,$$

where x and y are 'real' and i is 'imaginary' because the square root of a negative number does not exist. Mathematicians associate the complex number z with its *modulus*, $|z|$, expressed

$$|z| = +\sqrt{x^2 + y^2}.$$

Here, I wrote the plus symbol to denote that only the positive value be taken for the square root. (See Andreescu and Andrica 2005, Chapter 1)

In quantum mechanics, the probability that a particle exists at some position is always calculated in a two-step fashion. I have hinted at this process, but let us make it explicit. First, one calculates the wavefunction itself, a, which is always a complex number like z. Next, the probability itself is calculated by squaring the modulus, a^2, which naturally must be positive as indicated in the last equation. As said before, the wavefunction ψ in Schrödinger's wave mechanics is a particular example of the wavefunction, $\psi(x)$, in that it specifies the probability of finding a particle in a specific location x.

The single, large hump probability distribution in experiment one is given by the squares of the two, smaller hump wavefunctions. Let ψ_1 be the wavefunction of the particle passing through slit one, and P_1 be the corresponding probability as observed on the detector screen. Similarly, let ψ_2 and P_2 correspond to slit two. Thus we can write

$$P_1 = |\psi_1|^2 \text{ and } P_2 = |\psi_2|^2.$$

This corresponds to the probabilities when just one of the slits is open, as we suggested long ago when we believed that the particle passes through either slit one or slit two. But in the case we the particles are allowed to pass through both slits, the probability is given by

$$P_{12} = |\psi_1 + \psi_2|^2,$$

as per the rules discussed governing complex numbers. (Polkinghorne 1984, p. 41) This is the superposition principle at work, correctly adding the wavefunctions as opposed to the probabilities. The quantities ψ_1 and ψ_2 correspond to the wavefunctions, and the squares are the actual probabilities of position x. The wavy probability distribution pattern given in experiment two and three are due to the constructive and destructive interference between ψ_1 and ψ_2.

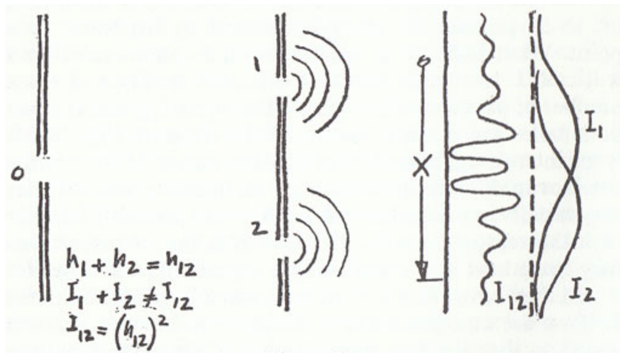

Figure 3.2: Adding Probability Amplitudes. Notice that with only slit 1 or 2 open, the intensity is a single-hump curve, I_1 and I_2. However, when both slits are opened, the wavefunctions can be added together to form I_{12}. Here, Feynman uses I for intensity; we have been using P for probability. The two are interchangeable in this context. Adaptation from his original lecture; Feynman 1965.

Earlier we claimed ψ^2 and $|\psi|^2$ are the same thing. What we *really* meant is that summing the wavefunctions just yields new probability, and that the last equation can *also* be written

$$P_x = |\psi_1 + \psi_2|^2 = |\psi_x^2| = \psi(x)^2.$$

But we just claimed that the only way to create a wavy probability distribution on the detection screen is to have interference, which must be between *at least two* particles! So if we assume identical particles are distinguishable *in principle*, we end up saying two things (or many!) are in fact one thing.

What is going on? In our third experiment, we observed that shooting *one* electron at a time through two slits over and over again produces an interference pattern identical to the pattern observed when light, sound, water, etc. waves pass through two slits. Now we have shown that this pattern can only be described as a superposition of (at least two) wavefunctions. Because the wavefunctions ψ in our case are specifically position wavefunctions $\psi(x)$, this superposition is analogous to a superposition of (at least two) positions corresponding to a single electron. We are forced to conclude: A single electron passed through *both* slits.

In the second chapter we explained the fact that every piece of knowledge (at the quantum level) carries some bit of uncertainty. But this proof was given using a famous thought experiment, Heisenberg's microscope. Now, using experimental observation and mathematical truth, we are claiming that one thing *is* for certain: Particles can exist in two places at a single time! The philosophical implications are far-reaching; but, we will put this discussion off for now. Part I is dedicated to laying the groundwork for the problems in quantum physics that demand response from philosophy. The philosophic literature on these topics is vast and often embedded in the physical arguments themselves. Part II is dedicated to unearthing these topics and exposing them to a philosophic deconstruction in order to illicit a philosophic response. For now, we turn to yet another mystery of quantum physics involving what knowledge we can have regarding photons, the traveling wave-packets of energy. Following the next chapter, we will discuss a famous rebuttal to these quantum mysteries first proposed by Einstein, Podolsky, and Rosen and the equally as famous response to this argument, Bell's Theorem.

Chapter 4

Observations of "Polarization"

We now switch our focus from one quantum mechanical particle, the electron, to another, the photon. The nature of the photon allows some interesting observations that further the quantum mechanical penetration into basic assumptions. We will see that our investigations into the behavior of the photon pose further problems for our understanding of reality and locality, specifically what we mean by the term "action." By reality, I refer (with foresight) to the type of reality that Einstein had in mind when arguing against quantum mechanics and claiming every measured quantity has some corresponding physical reality. Einstein stated the principle of locality to argue that dynamically separated particles cannot interact without some information passing between them (here, information could be a photon traveling at the speed of light). These concerns of Einstein will be discussed in the following chapter. Now, we describe experimental observations of the photon.

The photon, as it turns out, is not an easy thing to describe. Before explaining the experimental setups that will reveal quantum behavior and uncertainty, we need to understand the two complimentary pictures of the photon.

On the one hand, the photon can be described as a small particle traveling at light speed c and carrying with it some amount of energy proportional to its frequency f. As mentioned earlier, this amount of energy is quantized, and so comes in a multiple of Planck's constant. Thus, we say the energy of the photon $E = hf = hc/\lambda$. (Tipler and Llewellyn 2007, p. 204) The final expression here is in terms of c and the photon's wavelength λ. An experiment that describes both the quantization of light energy and the particle nature of the photon is the photoelectric effect. (Tipler and Llewellyn 2004, p. 128) In such an experiment, light is shined on a piece of metal, and at some length in front of the metal is a positively charged plated. Light hits the metal, excites electrons, and the positively charged plate attracts the electrons across the distance. The rate at which electrons are ejected from the metal plate can be determined by measuring the current through the charged plate if we establish a simple closed circuit. Classical mechanics predicted that the photons would hit the metal plate, and after some time, the atoms would have received enough energy from the light and would then eject their electrons. The process of energizing atoms and inducing the electron ejection is called ionization. Furthermore, the classical prediction said that the rate of ionization would be proportional to the intensity of light. The brighter, more powerful the light, the more electrons would be ejected. It was found, however, that the rate of ionization was not proportional to the intensity at all. Instead, electrons were being ejected even with the faintest light. However, once the frequency of light was turned down below some threshold (*i.e.* making the light redder), ionization stopped completely. The conclusion is that photons are discrete packets of energy, particles with energy proportional to their frequency.

On the other hand, photons can be described as light waves that act similar to other forms of waves such as compression (sound) or translation (water) waves, as discussed in the previous chapter. The simple experiment here involves

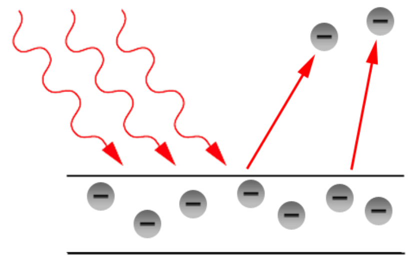

Figure 4.1: The Photoelectric Effect. When a photon with energy equal to the ionization energy of the atom strikes a metal surface, the electrons are freed from the atom and jump off the plate. If there is a positively charged conductor present, the electrons will float towards it.

shining a light upon two slits and observing the pattern that forms on a wall behind the slits. If photons were merely particles, we could predict that the pattern on the wall would essentially be two vertical strips: The photons would pass through one slit or the other and hit the wall like hurling thousands of small rocks through two slits and watching two impact strips form behind. However, light creates an interference pattern. The area on the wall between the two slits is brightest, followed outward by strips of dimming light separated by darkness. The reason is because the light waves constructively and destructively interfere with one another. The light waves pass through a slit and propagate radially from the slit, as shown in in previous figures. If you put two of these patterns next to each other, you create corresponding areas of minima and maxima: Light propagating from one slit interferes with light propagating from the other slit. Constructive interference creates bright strips on the wall, and destructive interference creates dark strips. This process is exactly the same for a wave in water approaching a wall with two slits, passing through the two slits, forming two radial patterns, and interfering on a distant wall. Recall Figure 3.1.

With this particle-wave model, we proceed to explain the polarization experiment. First, what is polarization? Most waves require a medium through which to propagate, such as sound waves or waves in water. Light, however, is self-propagating. This is because there are two components to a light wave, an oscillating electric field and an oscillating magnetic field. According to Maxwell's equations, a changing electric field induces a magnetic field, and similarly a changing magnetic field induces an electric field. If both fields are changing at a periodic rate, *i.e.* if both fields are oscillating like a wave, then they induce a periodic oscillation in each other. The result is a light wave composed of an oscillatin g electric field perpendicular to an oscillating magnetic field with both fields perpendicular to their direction of propagation. A photon is built by superimposing many oscillating electromagnetic waves. After many waves are put on top of one another, the result is a single "point" in space where all the added waves constructively interfere to form a packet of electromagnetic energy. We call this packet a photon.

So, if you were able to see a photon "head-on," it would look like an cross. Each line of the cross would correspond to an oscillating field; the length of the line would correspond to the amplitude of oscillation. One can imagine that this cross can be oriented in an infinite number of directions. Focusing on only the electric field, the line could be pointed vertically, horizontally, and at any angled value in between. Such is the case with sunlight: The sun releases an infinite stream of photons with an infinite number of orientations. *Polarized* light refers to a light wave that has a specific angle of polarization. There are many ways to polarize light. Some *polaroids* absorb all light except the light that is enters at some specific angle as determined by the orientation of the polaroid, and thus all emerging light is polarized at that angle. We say that the polaroid allows through the component of the light which is polarized in the direction of the polaroid axis. An electric field pointing in any direction, let's say line OA, can be through of as two perpendicular components, OX and OY. If the polaroid axis points in the OX direction, the light will be "divided" and only the component corresponding to that direction will emerge. The same is true if the polaroid axis is pointed in the OY direction. In the special cases when the electric field is entirely in the direction OX or OY, a polaroid oriented in the x-direction transmits all and none of the light, respectively.

Another device used to polarize light is a calcite crystal. Instead of absorbing the component of the light that is perpendicular to the polaroid axis, the calcite crystal allows all the incident light through but forces the two components of the light to emerge out different paths. The intensity of the two emerging beams, E_x^2 and E_y^2, equals the intensity of the incident light, E^2, by the Pythagorean Theorem. The inner workings of such a calcite crystal polaroid is not important to our discussion, and we shall simply refer to these polaroids by drawing boxes. The label HV will refer to a calcite crystal oriented in such a way that the emergent light is polarized along a horizontal and vertical path; similarly, $\pm 45°$ will refer to calcite crystal polaroids oriented such that the emergent light is polarized along $+45°$ and $-45°$ path. (Rae 1986, p. 19)

At this point, it probably seems that polarization is a phenomenon that supports only the wave picture of light and might not be applicable to individual photons. However, as our 'energy-packet' description predicts, this is not the case. Consider a very faint beam of light entering a calcite crystal such that only a single photon passes through at a time. The photon must emerge in one of the two channels, for at the very least the photon must go somewhere. We can set up a detector behind the H path and behind the V path; the detector will click each time a single photon passes through the crystal. We can confirm the validity of this experiment by including two additional HV polaroids, one behind the H path of the initial crystal and one behind the V path. The photons will emerge from one of the two paths and then enter the second HV crystal. If the photon follows the H path out the first crystal, then it will follow the H path out polaroid in the second set; if it follows the V path out the first, it will follow the V path out the polaroid in the second set.

Things start to get strange when we manipulate the setup further. Suppose the incident light on the first HV crystal is polarized in the $+45°$ direction using a traditional light-absorbing polaroid. Now replace the second set of polaroids with $\pm45°$ polaroids. (Remember from previously that if a beam of light is polarized in the H direction, say, a $\pm45°$ polaroid will divide the light into two equal components.) As expected, half of the photons emerge from the HV crystal polarized in the H direction and half emerge polarized in the V direction. Each beam is then sent through a separate $\pm45°$ crystal. We now find that the intensity of the light emerging from the $+45°$ and $-45°$ paths of each of the second polaroids equals exactly one quarter of the initial $+45°$ polarized light; the second set of polaroids divides the H and the V beam into equally intense components. In other words, the photons seem to have forgotten their original polarization of $+45°$. The original polarization of $+45°$ has been destroyed by the HV measurement. We reach a similar conclusion to that achieved in the second chapter: A measurement necessarily affects the state of the system being observed. Furthermore, we cannot know the state of a system unless we measure it. When the photons passed through the first HV crystal, we *thought* we knew the polarization; namely, we thought it was $+45°$. As the second set of polaroids proves, though, we did not in fact know anything about the $\pm45°$ polarization of the photons emerging from the HV crystal. The *only* way to know such a fact is through measurement; but conversely, such a measurement affects the very thing we are after.

These explanations might not seem all that surprising. We know that a calcite crystal splits a beam of light into two components, either H or V polarized. No matter what the initial polarization of the beam was, the H or V polarization says nothing about the $\pm45°$ polarization. It should not be too surprising that it is impossible to attribute two polarization directions to a single photon – our conclusions followed directly from the wave-packet model of light extended to a beam of faint light. However, we have already observed some insight into the question of determinism and certainty. When a $+45°$ photon enters an HV polaroid, the channel through which the photon will emerge is completely unpredictable. We know that after many photons, the number emerging from each will be roughly equal. If we focus on a single photon, however, the outcome is entirely random (though we should be careful with such language). It is important to note that this uncertainty arises from the fact that the photon should be treated as a particle just as much as it should be treated as a wave. If the light were merely a wave, then both the H beam and the V beam emerging from the initial polaroid would emerge from the second set of crystals polarized in the $+45°$ direction. The indeterminacy arises because the photon must go through *either* the H path *or* the V path, and thus the HV measurement destroys the initial $+45°$ polarization.

So far, no new conclusions regarding uncertainty, locality, or objective knowledge have been reached.

Another interesting fact about calcite crystals is that we can reverse our polarization measurement. When a beam of light enters a calcite crystal, it is split into two components. These component beams emerge parallel to one another. We can set up another HV polaroid oriented in exactly the opposite direction behind the initial; call this second polaroid HV′. (Rae 1986, p. 24) If we set the distance between HV and HV′ very carefully, we can make it so the two component beams converge perfectly 'in-step' with one another in HV′ thus allowing the final beam to have the same intensity as the initial beam. Now suppose we send a beam polarized in the $+45°$ direction through this same setup. Suppose further that we want to measure the polarization of the final beam with a $\pm 45°$ polaroid, just to make sure the photon original $+45°$ polarization actually *was* destroyed by the HV and/or HV′ measurement. From the preceding experiment, we expect an equal number of photons to emerge from the $+45°$ and $-45°$ paths of the third calcite crystal. But instead, the photons emerge from only the $+45°$ path of the third polaroid. When the intensity is turned down such that only one photon passes through at a time, the same result is observed: It is as if the single photon was split by the first polaroid, followed both H and V paths, and was reunited in the second crystal. Yet if we had instead placed a detector behind the first HV polaroid instead of the HV′ polaroid, we would be able to conclude with confidence that the photon was polarized in either the H or the V direction but not in both. This fact is quite difficult to reconcile with the previous conclusion that the measurement of the photon changes the polarization state.

One might rebut that the effect of the second polaroid might be different from what we thought and that in actuality each photon passing through is somehow turned into a $+45°$ polarization. We could test this possibility by blocking the H or V path emerging from the original HV polaroid so that we know for certain that the photon is either H or V polarized, respectively. But when we do this, we observe that the original $+45°$ polarization has indeed been destroyed because the photons emerge at random through the third $\pm 45°$ polaroid. We are then forced to conclude that, either the photon passes through both HV channels at once, or if it does pass through only one path then it somehow *knew* what it would have done had it passed through the other. At this point, it is unclear which disjunct we should accept!

In the start of this chapter, I claimed we would stumble upon a quite unorthodox conclusion regarding locality. With foresight, I will call this conclusion 'action at a distance,' or entanglement. The problem is coming: We must continue with the polarizing apparatus. It is important to note, though, that all the experiments discussed in this chapter up to now and following are reproducible and perfectly practical. These are not thought experiments, but rather observations we must accept. (Rae 1987, p. 47; Albert 1992, p. 2)

The next set of experiments involve an atom that transitions from an excited state to a ground state and releases two photons in quick succession. These photons will have different wavelengths corresponding to different colors, say red and blue. What is important for our discussion, though, is that these photons will always be polarized perpendicular to one another; for instance, the red photon might be polarized in the $+45°$ direction and the blue photon might be polarized in the $-45°$ direction. Naturally, not all atomic transitions undergo this type of photon emission, but some in fact do and such systems are perfectly practical in the experimental context. (1987, p. 28)

How is it that we know the photons are perpendicularly polarized? One answer is that quantum mechanics requires it. For our purposes, though, it is easier to point out that this property can be directly observed using HV polaroids. Suppose we have an atomic gas light source that emits these special pairs of photons. Because the gas is constantly emitting photons, we might mix up the blue photons with the red photons and vice versa. To avoid this confusion, we can set up color filters on either side of the source so that photons going to the left pass through a red filter, allowing all red light through, and the photons going to the right pass through a blue filter, allowing all blue light through. Behind these filters we set up HV polaroids. Now, we are ready to observe which photon (blue or red) is H polarized and which is V polarized.

So, in our apparatus, whenever a photon emerges from the left polaroid in the H direction we expect another photon to emerge from the right polaroid in the V direction. We adjust the intensity of the light such that detectors behind the polaroids can operate sufficiently fast to record individual pairs of photons. Of course, there is nothing special about the HV polarizes: The could just as well be $\pm 45°$ polaroids or any other pair of perpendicular polaroids.

Let us remove the right-hand polaroid and detector. After all, if we know that the right-hand photon must be polarized in the perpendicular direction as the left-hand photon, then a measurement of the left-hand photon constitutes a measurement of the right-hand photon. (1987, p. 29) Up to this point, we have spoken as if the polarization of each photon is exactly H or V. While we know the photons are polarized perpendicular to one another, it is *very* improbable that the photons are polarized in *exactly* the H and V directions. But if we are dealing with single photon pairs, we know that there is only one photon passing through the polaroid, and thus there cannot be some component of intensity that is subtracted. Such a subtraction only makes sense in the context of many photons where the wave model can be applied with total confidence. Still, the photon passes through one channel of the left-hand HV polaroid, let's say the H channel. We thus know the polarization of the right-hand photon is V. But wait! We have learned numerous times now that the measurement of the system affects the state of the system. So while the left-hand photon could not have *possibly* been *exactly* polarized in the H direction, measurement of this polarization implies the right-hand photon *is* polarized *exactly* in the V direction. We can prove this by setting up the right-hand polaroid at a much greater distance from the light source than the left-hand polaroid: It does in fact turn out to be polarized in the V direction. It seems that measurement of the left-hand photon has in essence polarized the right-hand photon. (1987, p. 30) It seems that the photons have instantaneously communicated with one another post-measurement. This is quantum entanglement.

Here lies a potential problem. We just stated that the photons are never polarized in *exactly* the H or V directions. Instead, the HV polaroid 'averages' the polarization of the photon: If the photon is in fact polarized $+44°$ to the horizontal, it will emerge through the H channel; if the photon is in fact polarized $+46°$ to the horizontal, it will emerge through the V channel. So, we might conclude that the result of the above paragraph comes as no surprise. Perhaps the photon emerges from the left-hand crystal in the H direction, but because this is merely an 'average' polarization, the photons do not need to communicate for the right-hand photon to be measured as polarized in the V direction because it too is just an averaging. By arguing this, we have implicitly rejected the quantum principle that the act of measuring is a random and indeterministic process. (1987, p. 31) Instead, we conclude that the polarization measurement of each photon was determined from the beginning.

But one thing is for certain: Once the left-hand photon emerges from the H channel, it is in fact polarized in the H direction. Perhaps the crystal 'averaged' the polarization of the incoming photon, this we concede. Yet upon exit, the photon *must* be polarized in the H direction as per the physics behind the structure of the calcite crystal. Because the photons must always be polarized in the perpendicular direction, measurement of the left-hand photon implies the right-hand photon must now be polarized in exactly the V direction. Wherever the right-hand photon is at the time of left-hand H polarization, *its* polarization *becomes* polarized in the V direction. There is thus no room for randomness associated with this measurement. (1987, p. 34) The obvious response is: "This cannot be possible. The two photons are distinct entities separated by some distance. Thus, when one photon is polarized, the other photon remains unchanged."

However, the above set-up can be further complicated to show that after the left-hand photon has been measured, say in the H direction, the right-hand photon is polarized *exactly* in the V direction. There is no averaging going on; instead, the H measurement on the left implies a polarization of precisely V on the right. To explain this experiment in detail and how the results are consistent with a quantum mechanical description requires more mathematical formalisms and further changes to our original polarization apparatus. These experiments use statistical arguments that consider a large number of photons. It is not necessary to go into detail on these experiments. Rather we can state with experimental confidence that when the left-hand photon emerges H polarized, the right-hand photon is V polarized, regardless of its initial polarization. (Rae 1987, p. 36; Polkinghorne 1984, p. 70; Albert 1992, p. 45; Jammer 1974, p. 58)

We seem to have some strong evidence for a deterministic hidden-variable theorem. In other words, the result of polarization measurement appears to be determined with certainty in advance by some property of the photon: The photons seem to 'know what they are going to do' before they enter their respective polaroids. There must exist some hidden variable that determines the action of the photons, a variable of which we are not yet aware. This was the conclusion of Albert Einstein and his coworkers, Boris Podolsky and Nathan Rosen. Explaining this argument in full and the quantum response is the subject of the next chapter.

Before setting the out the argument for hidden variables and Einstein's determinism, I would like to end this chapter by explaining a much simpler *observation* of the indistinguishability. In a textbook of statistical mechanics, Daniel Schroeder explains the curious behavior of a Bose-Einstein condensate, a collections of bosons (particles mentioned briefly in Chapter 3). A boson gas undergoes Bose-Einstein condensation when the temperature drops to a *very* low value (the standard BE condensation temperature is less than 1 Kelvin, or colder that $-272°$C). The temperature is distributed throughout the bosons as kinetic energy. When the temperature reaches this very cold threshold, the boson particles condense in the "ground state." The ground state of a particle is the lowest possible energy state. No temperature, no energy, no excitation. We can actually watch this condensation take place in the laboratory setting. How can we explain this behavior? Schroeder ends the section:

> So the explanation of Bose-Einstein condensation lies in the combinatorics of counting arrangements of identical [indistinguishable] particles: Since the number of distinct ways of arranging identical particles among the excited states is relatively small, the ground state becomes much more favored than if the particles were distinguishable. You may still be wondering, through, how we *know* that bosons of a given species are truly identical and must therefore be counted in this way? ...the answers are not completely airtight–there is still the possibility that *some* undiscovered type of interaction may be able to distinguish supposedly identical bosons from each other, causing a Bose-Einstein condensate to spontaneously evaporate [upon observation]. ...as David Griffiths has said, even God cannot tell them apart. (Schroeder 2000, p. 322-323)

Here, Schroeder is quoting the introduction of Griffith's textbook *Introduction to Quantum Mechanics*. It is true that quantum physics makes the assumption that identical particles are not distinguishable *in principle.* This assumption allows countless problems to be understood in a new light. However, some might say this assumption is not true, and there must exist some hidden variable that allows us to distinguish. Perhaps this alternative is even stranger. If, while watching a gas of bosons condense, we were suddenly able to distinguish the particles, they would "spontaneously evaporate." The behavior of the particles themselves would change because we suddenly gained the ability to distinguish bosons. So, if we assume the classical argument that all particles are distinguishable *in principle*, then we (again) run into the quantum argument that observation changes the state of a system. We thus invoke Occam's razor and cut out the classical assumption of identical yet distinguishable particles. Still, we will dive deeper into the defense of hidden variables clarify our understanding of what is at stake with quantum mechanics.

Chapter 5

Einstein's Conjecture and Bell's Response

In their essay *Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?*, Einstein, Podolsky, and Rosen argue that the quantum-mechanical description of such phenomena as the one described above *cannot* be considered complete; the argument is commonly referred to as EPR. Fortunately, we can apply their argument directly to where we left off in the previous chapter. However, there are some definitions underlying the EPR argument that must be highlighted before we continue.

First, as the title of their paper begs, what does it mean for a description of physical reality to be complete? EPR ask this question explicitly in the first few paragraphs.

> In attempting to judge the success of a physical theory, we may ask ourselves two questions: (1) "Is the theory correct?" and (2) "Is the description given by the theory complete?" . . . The correctness of the theory is judged by the degree of agreement between 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. (Einstein et al. 1935, p. 777)

Perhaps it is obvious that before even reaching their question of interest, namely question (2), EPR have already adopted a certain theory of knowledge. "Correct" knowledge, to EPR, is the consistency between theory and human experience. EPR are implicitly endorsing a type of empiricism, a type that analogy is discussed in Chapter 6. Putting this note aside for now, EPR continue:

> Whatever the meaning assigned to the term *complete*, the following requirement for a complete theory seems to be a necessary one: *every element of physical reality must have a counterpart in the physical theory.* We shall call this the condition of completeness. The second question is thus easily answered, as soon as we are able to decide what are the elements of the physical reality. (Einstein et al. 1935, p 777)

In other words, in order for a physical theory to be complete, it must be able to predict with certainty the measurements described at the end of the previous chapter. If the left-hand apparatus cannot affect the state of the right-hand photon, then the left-hand polaroid must measure some property of the right-hand photon without disturbing it. (Rae 1987, p. 31) While this property might not be the polarization, it must be related to some hidden variable which would predict with certainty the result of the right-hand polarization measurement. This hidden variable is what EPR consider the *reality* of the complete physical theory.

> The elements of physical reality cannot be determined by *a priori* philosophical considerations, but must be found by an appeal to results of experiments and measurements. A comprehensive definition of reality is, however, unnecessary for our purpose. We shall be satisfied with the following criterion, which we regard as reasonable. *If, without in any way disturbing the system, we can predict with certainty (*i.e.*, with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.* ... Regarded not as necessary, but merely as sufficient, condition of reality, this criterion is in agreement with classical as well as quantum-mechanical ideas of reality. (Einstein et al. 1935, p. 777)

(Let us point out right away that EPR calling their criterion for reality *sufficient* as opposed to necessary does not protect them in any way. They argue, “If we can find a hidden variable that describes an event, then we can *sufficiently* call this event real.” I believe they make distinction because they do not want to get wrapped up in a discussion on the formal criterion for reality. Nevertheless, even this sufficient condition will cause trouble.)

EPR refer to another important criterion for any given physical experiment. It is an extension of their criterion for reality, but it will prove problematic in its own way. Einstein proved that the speed of light is a sort of ‘speed limit’ for anything in the universe. (Greene 2004, p. iix) No piece of information (*i.e.* a photon or an electron) can travel faster than the speed of light, in any inertial references frame. (See Section 6.2 for further discussion.) This led EPR to assert a principle of locality:

> If two systems have been for a period of time in dynamical isolation from each other, then a measurement on the first system can produce no real chance in the second. (Polkinghorne 1984, p. 73)

This sounds perfectly reasonable, but we have shown in the last chapter that such a principle is conspiratorial at the very least. At the time of the development of quantum mechanics, this principle was rather undisputed. We shall see, however, it is the nub of the matter.

So, we have two paths to choose from: Either the quantum mechanical description can be extended so that the measurement of one photon instantaneously affects a photon a long ways away, or there is a hidden variable theory that determines the outcome with certainty underlying the quantum description. Put simply, we can either accept action at a distance, or we can accept determinism.

At the end of the previous chapter, we left off by claiming that it appears the measurement on one side of the room instantaneously affects the state of a photon on the other side of the room. This is the quantum conclusion. We also said that the polarization measurement is always a type of averaging of each individual photon. This mechanism presented a challenge to the quantum conclusion: There might exist a hidden variable within the photon that determines the perpendicular polarizations, *not* the measurement itself.

In order to avoid over-complicating our photon polarization experiment, we will switch to another pair of quantum particles: an electron and a positron. The behavior of this pair is very similar to our photon pair. Through a process called pion decay, an electron and a positron are sent in opposite directions. Instead of having perpendicular polarization, the electron and positron have perpendicular spins. The spin of a particle is derived from its angular momentum vector, and has two values in any given axis: up or down. This pair (as well as the photon pair, for that matter) has another similarity to what has been discussed above: uncertainty in the product of observables. In the second chapter, we used the observables of position and momentum. We showed that the product of these two observables must yield some amount of uncertainty. In other words, we cannot know with certainty the value of *both* observables to an arbitrarily high degree. The observables are *incompatible*. In our discussion of photons, this did not matter: We were only discussing one observable, namely polarization. Here, though, we want to discuss two observables, namely the spins along two different axes.

Say that I am on one side of the laboratory ready to measure the spin of the electron; you are on the other side of the laboratory ready to measure the spin of the positron. We know that if I measure an x-spin of up, then you must then measure a x-spin of down. We repeat this experiment many times, differing our distances from the source, changing to y-axis and z-axis spin measurements, hiding our answers from each other, etc. Yet our measurements always result in anti-parallel spins. Thus is the behavior of pion decay. So, like our photons, we can conclude that one of our measurements is unnecessary, because one measurement will always imply the other. Let us say that when I measure spin-up in the x-direction, we have state Ix; similarly spin-up in the y- and z-directions are Iy and Iz respectively. Alternatively, when you measure spin-down, we call those states IIx, IIy, and IIz. We also know when I measure a spin-up in any given direction, you should measure spin-down in that same direction. So when I measure Ix, you measure IIx, likewise with Iy and IIy, and so on.

For our purposes, it is also important to know that the spin of a particle is a vector quantity. (Tipler and Llewellyn 2007, p. 126) Because it is derived from the angular momentum of a particle, the spin axis is always pointing in one direction. The spin of the particle is always pointed in one and only one direction. The spin is the result of the summation of angular momentum vectors. Also it should be noted that, like polarization, spin is practically *never* exactly parallel to a given axis. This makes sense, of course: Whatever coordinate system we impose upon the particle will be entirely arbitrary, and we should not expect the motion of the particle to perfectly comply. So, when we say spin-up and spin-down, we are averaging the angular momentum vector; if the spin points to the top half of the coordinate hemisphere we say spin-up, and if it points to the bottom half of the hemisphere we say spin-down. Why does it have this summative property? Simply, spin can be considered up or down, but in actuality the vector that points up or down precesses like the handle of a top. So we can imagine the spin vector as twirling around in a hemisphere of a sphere. This second note, however, does not impact our conclusions; it is a point of conceptual clarification. The first point, however, is crucial: A particle cannot have two spins, because the spin is a summative property that considers the entire system within the particle.

Now, suppose I intend to measure the x-spin of the electron, as before, but you intend to measure the y-spin of the positron. Suppose you are a step further back from the pion decay source than I am, so that I measure the x-spin of the electron before you measure the y-spin of the positron. Because the spins in perpendicular axes are incompatible observables, quantum mechanics necessitates that knowledge of the electron's x-spin destroys knowledge of the positron's y-spin. (Recall that the uncertainty principle argues that the products of the uncertainties of two observables equals a discrete value. Thus as one variable goes to zero, the other must go to infinity. In other words, as the we achieve certainty of one variable, the other uncertainty of the other variable explodes.) If I measure Ix, then there is a 50% chance you measure Iy and a 50% chance you measure IIy; similarly if you chose to measure the z-spin. It is impossible to predict the outcome of these two spins until a measurement is made.

To clarify, we can physically imagine this quite easily. Suppose I have a sphere, and at the center I have a vector. The vector must point to either the left half or the right half of the hemisphere, for it has nowhere else to point. Now, consider we have two spheres, A and B, each with a vector pointing in one direction, $\vec{a}$ and $\vec{b}$, respectively. Like the electron and the positron, the vectors point in opposite directions. Suppose $\vec{a}$ points to the left side of the hemisphere, in the $-x$ direction. Then, $\vec{b}$ must point to the right side, in the $+x$ direction. So we have in our minds, for A, the left hemisphere 'shaded,' and for B, the right hemisphere 'shaded.' What can we say about the other hemispheres of the circle? Suppose we want to know the direction of $\vec{a}$ or $\vec{b}$ relative to the y-axis of our sphere. Well, for A, we know that $\vec{a}$ can only point to the left; but this still leaves a 50% chance for $\vec{a}$ to point in the $+y$ hemisphere and a 50% chance for $\vec{a}$ to point in the $-y$ direction. The same is true of the direction of $\vec{a}$ relative to the z-axis. For ease, let's call the spin of the electron $\vec{a}$ and the spin of the positron $\vec{b}$

The EPR argument is thus: A measurement of $\vec{a}$ in state Ix enables us to predict with certainty the value of $\vec{b}$ to be in state IIx. The same is true if $\vec{a}$ is measured to be in Iy or Iz. On the basis of our the principles endoresed by EPR, namely the criterion for reality and the principle of locality, we can therefore say that IIx, IIy, and IIz are all real properties of $\vec{b}$ once we have determined the corresponding properties of $\vec{a}$. However, we know that either vector being in two states, for instance IIx and IIy, is not 100% probable: For if $\vec{a}$ is in Ix, then it must be the case that $\vec{b}$ hase a 50% chance of being in Iy and a 50% chance of being in IIy. As stated, EPR claimed this indicated an incompleteness of quantum theory. (Albert 1992, p. 42) The incompleteness, to be precise, is that measurement of the spin of $\vec{a}$ necessitates uncertainty in the state of $\vec{b}$. The EPR paper concludes:

> While we have thus shown that the wavefunction does not provide a complete description of physical reality, we have left open the question of whether or not such a description exists. We believe, however, that such a theory is possible. (Einstein et al. 1935, p. 780)

Thus the conclusion of EPR is that quantum mechanics is merely a practical way of describing systems, but there exist hidden variables governing the properties of the particles. A complete theory of physics would include such hidden variables. However, EPR had defined the rules so as to assure themselves victory. First, let us tell the story EPR set up in a different way. This is Bell's theorem, conjectured by John Bell in 1964.

To begin, let us assume it is possible to know the spin state of a particle relative to all three axes. To use our sphere model, this would localize the spin to a region of an eighth of the sphere. If $\vec{a}$ spin-up relative to all its axes, then we can say $\vec{a}$ is in state (x_+, y_+, z_+). So, there are eight possibilities in all: (x_+, y_+, z_+), (x_-, y_+, z_+), $\ldots$, (x_-, y_-, z_-). Suppose I measure $\vec{a}$ and find that it is in state Ix, or x_+. We know then $\vec{b}$ is in state IIx, or x_-. Now I measure $\vec{b}$ and find that it is in state IIy, or y_-. We know then $\vec{a}$ is in state Iy, or y_+. So $\vec{a}$ must be in one of two states, (x_+, y_+, z_+) or (x_+, y_+, z_-). Similarly with $\vec{b}$.

Now, instead of measuring just a single pion decay, let us measure many pion decays. Sometimes we measure spin along the x-axis for both, sometimes we measure spin along the x-axis for $\vec{a}$ and spin along he y-axis for $\vec{b}$, and so on until we have a sufficiently high number of measurements. For each measurement, we can nail down the spin relative to only two axes: As said just above, each measurement-couplet will yield two possibilities for spin along the third axis. So, we add up the numbers of each measurement. For example when either $\vec{a}$ or $\vec{b}$ has up-psin relative to the x- and y-axes, I mark one point for $n(x_+, y_+)$. I do the same for the numbers $n(x_+, y_-)$, $n(x_-, y_-)$, $n(x_+, z_+)$, and so on. Bell was able to show (using some combinatorics that are not entirely beyond the scope of this thesis but would indeed bog us down; for a great discussion using only counting [no vectors or spin], look to Rae 1987, p. 37) that the outcome of such an experiment, given EPR's criterion for reality and principle of locality, should be:

$$n(x_+, y_+, z_\pm) \leq n(x_+, y_\pm, z_+) + n(x_\pm . y_+, z_+).$$

This statement, known as Bell's inequality, is a testable prediction that is inline with the assumptions in EPR. The experiment (using *lots* of pion decays) has been performed many times. The results violate Bell's inequality about half the time; in other words, there are equally as many times where the conjunction in the inequality is $>$ rather than $\leq$. (Polkinghorne 1984, p. 75) In other words, there *must* be some kind of action at a distance that allows one particle to switch spins when we measure the spin of another. (1984, p. 76)

Bell's inequality and the combinatoric setup above are predicated only on the two assumptions of EPR. For one, if the property that determines spin is 'real' to EPR then it should result in a measurable quantity. Bell responded, "Fine, consider the system as normal and start adding things up." For two, no particle can undergo instantaneous change upon action some dynamical distance away. Again, Bell responded, "Fine, consider the system as normal and start adding things up." Bell's theorem works flawlessly in all normal cases. One example is if we are to shoot a ball from a cannon and give it some spin: Measuring the spin vector many times would leave us with Bell's inequality. Another example is if we are to make a table with the top variables as x, y, and z, and then start listing random triplets of +'s and −'s under the columns, like so:

x	y	z
+	−	+
−	−	+
+	+	−
+	−	−
−	−	+
+	+	+
−	+	−
...	...	...

Go ahead, do so yourself and see if you can find a set of n triplets that does not obey Bell's inequality. You will not succeed, because it is impossible.

Bell's theorem operates like clockwork everywhere, expect of course in the quantum world. As such, the philosophical ramifications are now teaming at the gates of quantum theory. This last chapter of Part I was meant to articulate a zenith to the problems of quantum mechanics. EPR, and many others, did not disagree with Bell's theorem. Once experimental results began to flow in the 1970's that violated Bell's inequality (see Freedman 1972; Clauser 1974; Aspect 1981; Bell 1987), the strangest of interpretations became somewhat undeniable. But with this interpretation comes extremely urgent questions. To the false criterion of reality as per observation, we might ask the question, "What, then, makes an object real *in and of itself* rather than the reality of our observation?" To the false principle of locality, we might ask the question, "What, then, is the *cause* of such instantaneous communication?" Obviously, there can be many questions stated to the results of quantum experiments. The thread of commonality, however, is that they all seem to outright deny our intuitive grasp of space, time, and existence. What to make of our knowledge on these matters?

Part II is dedicated to unravelling the philosophic ramifications of quantum mechanics. Our first task will be to understand the interpretation of quantum mechanics as per the founders of the theory, such as Werner Heisenberg and Neils Bohr. I believe these people are just as much philosophers as they are theoretical physicists. We will begin to see many aspects of this Copenhagen interpretation that reflect trends in modern philosophy, specifically those that find their roots in Kant's critique of metaphysical knowledge. We will then use Kant to defend the Copenhagen interpretation against the classical philosophy of physics. This, however, will uncover holes that Kant could not possibly have foreseen. We will attempt to patch these holes in the final chapter where we will utilize postmodern understandings of quantum physics.

Part II

An Image of Ourselves

> “As far as the laws of mathematics refer to reality, they are not certain; as far as they are certain, they do no refer to reality.”
>
> –Albert Einstein

As our discussions have shown, measuring the location, or the momentum, or the polarization, or the spin, or any observable involves “breaking” or “collapsing” the wave function. By this, we mean: The particle can have any given value for any given observable until that observable is measured. Before measurement, the wavefunction describing any given observable yields an infinite number of possible values. Our experiments have attempted to limit the number of possibilities in order to predict the outcome of a given set of initial conditions. First, we tried a brute force method: In Chapter 2, we attempted to image the electron itself, and thus limit a single variable to a single possibility. This proved impossible, and gave us an understanding of how the uncertainty principle functions in our observations of the physical world. In the third chapter, we gave the electron two choices; the electron refused to cooperate and instead passed through both slits creating an interference pattern. Until, that is, when we measured the electron, its wavefunction collapsed, and it willingly went through a single slit, erasing any semblance of an interference pattern. In Chapter 4, we showed that again that measuring the system affects the system. We then proceeded to show that not only does measurement affect the system we are measuring, but measurement of a system instantaneously affects systems at great distances! In the fifth chapter, we presented an argument against these claims which proved to be supported only by more fundamental, essentially philosophical assumptions of cause, action, and reality. We were left without an answer to the rudimentary question, “How can we know *anything* about a system without directly observing?”

Our answer has been inescapably empirical. If we do not look, we cannot know the state of the system. Our conclusion, however, was further-reaching:

The system *exists* in a state of probability. It makes no sense to talk about the system in any other way until we collapse the wavefunction and measure the state of the system. What, then, *is* real?

Chapter 6

The Copenhagen Interpretation

6.1 A Paradox

The interpretation of these questions as adopted by the founders of quantum mechanics is known as the Copenhagen interpretation. The name comes from reference to the series of talks that were held in Copenhagen during the initial formulations of quantum theory. Headed by Neils Bohr, the Copenhagen school of quantum theory taught that our descriptions of reality are limited by our descriptive framework. How this conclusion is reached is the subject of this section. I will primarily draw this interpretation from one of its founders, Werner Heisenberg, and his book *Physics and Philosophy*, written in 1958. While quantum mechanics accurately describes the observations of the experiments in the previous chapters, we will see that it also poses challenges to some fundamental assumptions.

The Copenhagen interpretation begins with a paradox:

> Any experiments in physics, whether it refers to the phenomena of daily life or to atomic events, is to be described in the terms of

> classical physics. The concepts of classical physics form the language by which we describe the arrangement of our experiments and state the results. We cannot and should not replace these concepts by any others. Still the application of these concepts is limited by the relations of uncertainty. We must keep in mind this limited range of applicability of the classical concepts while using them, but we cannot and should not try to improve them. (Heisenberg 1958, p. 44-45)

Heisenberg is making explicit the claim that it is impossible to build, from the ground up, a new conceptual framework for describing the natural world. To get a better understanding of this paradox we can compare a classical approach to a quantum approach. In Newtonian mechanics, for instance, we can begin our inquiry by measuring, say, the position and velocity of some moving body. These results are translated into a mathematical schema by deriving values for the coordinates, rates of change, etc. These formulas are then used to derive the coordinates or rates of change at any given moment. We predict, with certainty in our mathematical consistency, the properties of the system at any later time. When describing the motion of planets, say, this approach works quite well and we can be confident in our conceptual schema. (1958, p. 45)

In quantum mechanics, the approach is quite different. We might be interested in the motion of an electron and determine some kind of initial position and velocity. But these descriptions will be subject to the uncertainty principle. Still, the uncertainty principle allows us to insert the observations into a mathematical schema that is essentially classical. Quantum mechanics does not *change* the mathematical schema. It uses the mathematical schema in precisely a classical way. In a classical way, I mean that quantum mechanics simply inserts an uncertainty, rather than a known variable, into classical physical descriptions. In doing this, it yields what we have called the wavefunction, a probability function. The wavefunction "represents a mixture of two things, partly a fact and partly our knowledge of a fact . . . [it] represents both a tendency for events and our knowledge of events." (1958, p. 45-46) We can calculate the probability of the electron being at some specific point later at some later time, but this probability does not represent a course of events through time. There is no *reality* to it *a priori*.

> The probability function can be connected to reality only if one essential condition is fulfilled: if a new measurement is made to determine a certain property of the system. Only then does the probability function allow us to calculate the probable result of the new measurement. The result of the measurement will again be stated in terms of classical physics. (1958, p. 46)

At the same time, it is tempting to say that while we cannot know what the electron does between measurement A and measurement B, it did in fact follow some kind of path between the two points of observation. This argument is valid in the classical framework. In quantum mechanics, we will see that such an approach is a misuse of the language which cannot be justified. For now, we can leave open the question whether this statement refers to our description of the event, epistemology, or the event itself, ontology. What matters for now is that all we have in the mathematical schema is a statement of possibility. We can therefore not describe what happens between two observations. We cannot pin down which slit the electron goes through; we cannot explain how it is that the photon suddenly switches its polarization from almost-V to precisely V. Further, simply *saying* the electron went through one slit or the other slit is problematic and leads to contradictions.

From Chapter 2 forward, it seems that observing a system introduces an element of subjectivity. This element contradicts the framework of classical physics: We describe not the universe as a whole, but instead some isolated system within the universe. There are many elements in the classical model that are *not* part of the description of the system, such as the experimental apparatus or the observer. We are forced to accept this framework when describing our observation of quantum events: We get a probability function post-measurement which allows us to follow the laws of quantum theory (such as the uncertainty principle). So, “the probability function combines objective and subjective elements.” (1958, p. 53) On the one hand, the wavefunction includes objective possibility or tendency; Heisenberg invokes the Aristotelian term, *potentia*, a potential for the particle to have some definite value. (1958, p. 53) On the other hand, the quantum description will contain our subjective experiential data on the matter, subjective insofar as it can differ from the experiential data of another observer.

The transition from possible to actual, objective to subjective, is inherent in the act of observation. Heisenberg calls this a discontinuous change in the probability function, referring to the impossibility of using mathematics to change a probability into a discrete value. The discontinuous change of our (observational) knowledge is the *image* of the discontinuous change in our (classical-mathematical) wavefunction. (1958, p. 55) The function collapses before our eyes, and our knowledge collapses as a result. The reason is because the function itself is the language with which we articulate knowledge. Knowledge is always bound to our language and our conceptual schema. As Heisenberg quotes Carl Friedrich von Weizsäcker: “Nature is earlier than man,” in that the ideal of objectivity in classical physics in justified; “but man is earlier than natural science,” in that we cannot escape the paradox of quantum mechanics. (1958, p. 56; *circa* 1949)

Classical physics began with the belief that the world could be described without any reference to ourselves, and for the most part, this belief has proved largely practical in describing the world. (Stapp 1993, p. 19) Objective knowledge is the first criterion for the value of any scientific result. Yet at the same time, we know that these objective means of describing the physical world do not yield a result consistent with our observations. This paradox, this tension, is where the statistical, probabilistic representational framework of quantum mechanics is born. If quantum mechanics were entirely objective, it would determine the outcome of events with certainty: Initial conditions would always obey a set of laws that do not reference the observer. If it were entirely subjective, the possibility of any given state would always be infinity: What we observe directly is all that can be known. Quantum mechanics combines these approaches to produce probability.

One could argue that we could break from the schema of classical description. We could build our conceptual approach from the ground up, and arrive back at some completely objective description of the physical world. For instance, we could build a model of reality that includes our existence and is predicated by our observational actions. Including ourselves in the system will then arrive at a determinist theory of everything. One that attempted such a theory was Leibniz, who argued that everything was composed of inner perceptions which could project themselves and the world upon observation of other perceptions. He claimed that there was no strict delineation between perception and reality, but instead "only a non-causal relationship of harmony, parallelism, or correspondence between mind and body." (Kulstad 2007, p. 1)

But such an argument rests on a misunderstanding. We said above that classical theory begins by dividing the world into, first, the object to be studied, and second, everything else (which includes ourselves, the observers). The determinist would argue that we can include ourselves and the measuring device into the classical division of the world. But it can be shown that such an alteration of the delineation of the system does not affect the measurement of the system. (Polkinghorne 1984, p. 66; Stapp 1993, p. 21) In other words, experimental observations yield similarly paradoxical results. The reason is because the principles of uncertainty apply to every object, inside and outside our isolated system. Complicating our measuring apparatus by broadening the boundary of our system cannot help to avoid the fundamental paradox of quantum mechanics. There is simply no method of delineating a system such that objective situation and subjective observation collide in a way to produce uncertainty.

Further, as Bohr has argued, we should not attempt to free ourselves from a classical schema. (Murdoch and Murdoch 1989, p. 12) We should *not* attempt to argue that the classical division of the world is arbitrary. When we want to understand the physical world, we want to understand how an event follows from the physical laws of nature. The observed stuff of matter is the object under consideration, while the experimental apparatus necessitates a subjective feature in the description of any event. "What we observe is not nature itself, but nature exposed to our method of questioning." (Heisenberg 1958, p. 58) The only method by which we can ask a question about nature exists in and of our language. As Bohr put it, "One must never forget that in the drama of existence we are ourselves both players and spectators." (Murdoch and Murdoch 1989, p. 9)

I will say, with some foresight, that the above resembles a Kantian perspective. Kant argues simply that we cannot understand our experience outside our schema of space and time. Similarly, the classical-mathematical schema is the language through which we understand our observations. Our questions are designed using classical concepts, and these classical concepts are bound to their (rather intuitive) description of space and time, cause and event, subjective and objective. So to summarize, the Copenhagen interpretation argues that the mode in which we understand the physical world is destined to paradox; there will always be a gap between what exists and how we describe it.

6.2 Counterproposals

The Copenhagen interpretation has lead physics far away from "the simple materialistic views that prevailed in the nineteenth century." (Heisenberg 1958, p. 128) As such, there are of course counterproposals that attempt to argue quantum physics can be inserted back into the materialist philosophy of classical physics. Heisenberg divides these counterproposals into two basic categories. The first group does not want to change the Copenhagen interpretation as far as the experimental inquiry goes, by rather tries to change the language of the interpretation so as to agree with classical physics. The second group argues that quantum mechanics offers no description of what happens independently of and between observations and thus is not a complete physical theory. I will argue that both of these groups attempt to return the quantum insights back to the reality concept of classical physics (first discussed in Chapter 5). In other words, all the groups attempt to return to a ontology of materialism, in which the smallest parts of the world exist objectively in the sense that they are not dependent on our observations of them. Before, we left open the question of whether quantum mechanics is an epistemological statement or an ontological statement. With discussion of the counterproposals, I now wish to show that the nature of the quantum phenomena discussed in the second chapter imply that such an objective ontology is impossible.

To the first group of counterproposals, Heisenberg maintains that they do not dispute quantum mechanics on the observations and their results. Rather they dispute the interpretations of these claims, specifically the language through which the paradoxes are discussed. These claims then attempt to reconstruct the body of experimental observations "with its exact repetition in a different language." (1958, p. 130)

The EPR conjecture is of this first group. From the classical perspective, we are inclined to think that hidden variables govern the apparent statistical behavior of quantum systems. The language through which the Copenhagen interpretation describes these observations 'misses' the hidden variables. If the reality of the observations were to be described completely, as EPR argues, the chain of events would unfold in a determinist way. The language, then, is one that includes the hidden variables and thus describes reality completely. Bohm also had such theory, where he claimed that our measurements are limited by our experimental apparatus, which are in turn limited by the questions quantum mechanics allows us to pose. In other words, if we could think in terms of these hidden variables, we could describe a system that reveals these variables and thus design an experiment to detect these variables

Bell responded that any attempt to create such a language results in the same paradoxes. Recall Bell's inequality – even if we admit there is a hidden variable that governs the actions of particles in our experiments, we should still be able to arrive at Bell's inequality through simply counting up all the spins. We argued that Bell's inequality takes only two assumptions into account. One, particles that are far away from each other cannot affect one another. Two, every piece of reality can be 'counted' and given a value. So even if we assume there are hidden variables governing the system (as intuitive a claim as it gets), the outcome of our pion decay experiment is so strange that it does not obey a simply combinatoric relation.

Heisenberg claims this type of classical defense "reveals itself as a kind of 'ideological superstructure' which has little to do with immediate physical reality; for the hidden parameters . . . are of such a kind that they never occur in the description of real processes, if quantum theory remains unchanged." (1958, p. 132) EPR and Bohm argue the classical claim; namely, that the particles (electrons, photons, etc.) are 'objectively real' structures in space and time. To the description of these particles as waves (as discussed when considering how electrons and photons act as both particles and waves), EPR and Bohm claim that they, too, are 'objectively real.' Returning to EPR's criterion for reality from Chapter 5, something that is real is something that can be assigned a physical value with certainty. Yet it seems that this is more so a criterion for *objectivity* rather than reality. Sure, the matter waves that govern the action of electrons can be assigned an objective value; but to say that these *waves* are 'real' seems very strange. While structures, like the electron (half the time) or a molecule or a stone, have definite reality in space, matter waves have definite reality on configuration space. A matter wave, like a photon or the electron (the other half of the time) is not so much a thing in space as it is a description of the behavior of a thing in space, namely a disturbance in space.

> What does it mean to call waves in configuration space 'real?' This space is a very abstract space. The word 'real' goes back to the Latin word 'res,' which means 'thing'; but things are in the ordinary three-dimensional space, not in an abstract configuration space. One may call the waves in configuration space 'objective' when one wants to say that these waves do not depend on any observer; but one can scarcely call them 'real' unless one is willing to change the meaning of the word. (1958, p. 130)

Heisenberg's argument is hardly clear here, but it seems to strike at the EPR's criterion of reality. He seems to be defining his criterion for reality *analytically.* Within our notion of real lies the notion of a thing. A wavefunction, for example, is not a thing in Heisenberg's mind. A wavefunction is necessarily a description. This description does not lie within space; it lies within our knowledge of phenomena. Because it does not lie in space, it does not lie in reality. Heisenberg claims that reality corresponds to things-in-space in the way that bachelors correspond to unmarried.

Meanwhile, to say that such a description of the wavefunction *does* lie inside of reality is a *synthetic* judgment. The two parts of the synthesis are, (1), reality, and (2), an analogue or value that is knowable with certainty. Claiming (2) is within (1) is claiming that every piece of certain knowledge we have has some correspondence to reality. Every bit of reality has 'potentia' for a direct, knowable value. To put it this bluntly seems strange and begs for justification. EPR and Bohm hold this claim to be self-evident, but this is essentially a synthetic, metaphysical statement concerning the nature of reality. Still, EPR and Bohm hold this statement to be *a priori* knowledge. The 'ideological superstructure' exists in the belief that we can define reality *a priori* without referencing our experience.

How do we know EPR and Bohm hold their criterion to be *a priori* knowledge? We can apply simple process of elimination: Our experience does not give us any evidence supporting this criterion, so we cannot call it *a posteri-*

ori. Rather, our experience gives us quite the opposite of such a criterion! Our experiments have shown us that there is no way to predict with certainty the motion of an electron or photon. The uncertainty principle demands that a probability in place of a value must describe the electron. Reality appears to be much more elusive than to guarantee us a pretty description. Any hidden parameter is merely hoping to know an unknowable. EPR and Bohm's criterion cannot possibly be *a posteriori* knowledge. The criterion asserts hidden variables govern the interactions, regardless of our observation or experience of those phenomena.

Heisenberg argues that this formulation is embedded in the ontology of materialism. We want to associate some objective, materialist reality to every event observed. We want a 'complete' theory of reality would describe all these pieces, but instead,

> It is the 'factual' character of an event describable in terms of the concepts of daily life which is not without further comment contained in the mathematical formalism of quantum theory, and which appears in the Copenhagen interpretation by *introduction of the observer.* (1958, p. 137)

In other words, the factuality or materiality of an event only comes into being through the introduction of the observer. Sure, there exists a reality outside the observer, but this reality has statistically infinite possibility if there exists no the observer to collapse the wavefunction.

> The observer has only the function of registering decisions, *i.e.* processes in space and time, and it does no matter whether the observer is an apparatus or a human being; but the registration, *i.e.*, the transition from the 'possible' to the 'actual,' is absolutely necessary here and cannot be omitted from the interpretation of quantum theory. (1958, p. 137)

When Heisenberg says here that such an observational 'registration' cannot be omitted from the theory, he means that the introduction of any hidden variable that eliminates the action of the observer is bound to reach the same contradiction. That contradiction, he argues, stems from the irreversibility of our measurement. Once measurement is made, the infinite possibility collapses to a single value. This is "a consequence of the observer's incomplete knowledge of the system and in so far not completely 'objective.'" (1958, p. 138) Put simply: The act of measurement is fundamentally an entirely nonobjective process. (We are careful here to not say the process is entirely subjective, either. Quantum mechanics claims these observations are *more* than subjective in the sense that there is no other way to experience the workings and phenomena of quantum mechanics.)

As we see now, the two categories of counterproposals are closely liked. The second group claims that statements regarding the probability of atomic events because they deny any event between points of observation. Regardless of the method of description, "The physicist must postulate in his science that he is studying a world which he himself has not made and which would be present, essentially unchanged, if he were not there. Therefore, the Copenhagen interpretation offers no real understanding of atomic phenomena." (1958, p. 144) This is the second counterproposal.

This conjecture without a doubt attempts to return to the classical materialist ontology that drives our inquiry into the rationality of the physical world. The Copenhagen response is that physics will always aim to offer a description and understanding of nature. These descriptions and understandings must be formulated and communicated within the scope of language. This is why the Copenhagen interpretation begins with a paradox: The only language we have available (namely the classical schema) is at the same time problematic to our description of nature. We are bound to our intuitive modes of experience, and our language is built from this experience. We cannot say anything on the subject of possibility until that possibility is actuality: Our language simply does not allow us to ask those questions.

If therefore the atomic physicist is asked to give a description of

> what really happens in his experiments, the words 'description' and 'really' and 'happens' can only refer to the concepts of daily life or of classical physics. ... Therefore, any statement about what has 'actually happened' is a statement in terms of the classical concepts and – because of thermodynamics and of the uncertainty relations – by its very nature incomplete with respect to the details of the atomic events involved. (1958, p. 144-145)

Ontological materialism rests on the illusion that the "direct actuality" of the world can be extended to describe atomic events. The illusion is that ontological materialism can be *a priori* metaphysical knowledge. The classical criterion for reality is a synthetic assumption that forces counterproposals to the Copenhagen interpretation to hope for a better, more complete description of reality. This description of reality must necessarily be in classical language, and is thus by its very nature incomplete knowledge. "The statistical nature of the laws of microscopic physics cannot be avoided." (Murdoch and Murdoch 1989, p. 32)

The conclusion is that if we accept the uncertainty relations and statistical descriptions of quantum mechanics, we must accept the Copenhagen interpretation. There exists no alternative method with which to articulate our descriptions that escapes the fundamental claims. Here ends our discussion of the Copenhagen interpretation. As has been pointed out at numerous points, Heisenberg's philosophy seems to reflect many elements of Kant. The next chapter is meant to tie links between the Copenhagen interpretation to Kantian doctrines. We will see that while there exists many similarities, there are some holes when importing quantum mechanics into philosophy. These holes will hopefully be filled in Chapter 8, and thus move us closer towards a philosophic understanding of quantum mechanics.

Chapter 7

The Kantian Analogy

This chapter will be divided into three parts, each highlighting a specific way the Copenhagen aligns with Kantian philosophy. Kantian philosophy is, of course, very broad to say the least. I wish to primarily focus Kant's conception of causality, knowledge of things-in-themselves, and his arguments regarding metaphysical *a priori* claims. These topics are the three sections, and each will present difficulty which will be responded to in Chapter 8.

7.1 Causality

At the end of the fifth chapter, in response to the violation of locality, we asked the question, "What is the cause of instantaneous communication?" This section is meant to shed light on this question. We will find that the way the question is posed is in itself a problem. The Copenhagen interpretation argues that the statistical nature of quantum particles does not obey the kinds of cause-necessity relations with which we are familiar. As an entry point, I want to consider the Kantian concept of causality. We will see similarities both between Kant and the Copenhagen interpretation as well as between Kant and the counterproposals to Copenhagen.

It has been said that Kant's impetus for describing the concept of causality comes from Hume. Immanuel Kant, with the Critique of Pure Reason, claimed that Hume had awaken him from a slumber of dedication to the principles of absolute rationalism. Many take this to signal Kant's distaste for Hume's skeptical empiricism. In actuality, Kant admits that Hume isolated a fundamental problem with pure rational discourse; Kant's departure is his answer to Hume's problem. We attempt to show that the Copenhagen answer to classical interpretations of quantum theory is analogous to this pure rationalist position. As we have shown, the fundamental criterion for reality is essentially a rationalist claim. What, then, is Hume's concern with pure reason?

The problem is found in Hume's position regarding causality. To Hume, the notion of causality was a particularly nebulous concept in philosophy. The standard approach was that in order for one event to cause another, the second must necessarily follow the first. Hume coined this link a necessary connection. His primary concern was that there was no empirical evidence of such a necessity. In order to understand how Hume came to this conclusion, we must first understand Hume's place in early modern philosophy as an empiricist.

Hume was primarily a content or concept empiricist, claiming that the only things we can know are those things that are directly derived from experience. Further, the only concepts of which we can actually make sense and utilize for the pursuit of knowledge are those concepts that directly come from experience. To use an extreme example, Hume claimed that there cannot possibly be rational justification for the existence of God. On the one hand, there is no empirical evidence derived directly from experience that indicates the existence of an omnipotent, omniscient being. On the other hand, the rational concept of God itself has no justification grounded in experience. So for two reasons the existence of God cannot be known. Hume did not claim whether a God existed, even though he was an atheist. Rather, Hume was arguing against the rationalists that attempted to *prove* the existence of God such that it is certain and undeniable knowledge.

So for Hume, the notion of causality must have direct correlation in experience. Further, to know that such a concept as causality exists, we must be able to prove that this concept is found in our experiences. Hume claims that we cannot directly experience a necessary connection. For instance, consider three events A, B, and C. A is when I have an object in my hand. B is when I release this object from my grasp. C is the object falling, or the object's motion towards the ground. To most, it is common knowledge that C follows B which follows A. Hume argues that there are in fact three distinct experiences of an observer when such an object falls to the ground, namely experiences A, B, and C. Hume's argument is that while the object falls to the ground, and will always fall to the ground, there is no experience of causality; there is no experience of a necessary connection between events A, B, and C. In other words, we can experience each of these events individually, but we cannot experience something like ($A \rightarrow B \rightarrow C$). We merely see effect following cause, but never the causality itself. To Hume, there is contiguity in space and time albeit, but no notion to suggest a necessary connection between events. This belief is argued in sections six and seven of the *Enquiry Concerning Humen Understanding* published in 1748.

What exists, then, to give the illusion of a necessary connection between these events? Hume argues that the mind mistakes constant conjunction for necessary connection. After a repetition of similar events, the mind uses judgment and is carried by habit to expect a certain effect once the complementary cause appears. Constant conjunction, then, is a link made through habitual imagination. This link forms what Hume calls an impression. This impression then acts as a stand-in for the concept of necessary connection. For Hume, all concepts must derive from an impression, and this impression is precisely a mental mark remnant of direct experience.

When we look at external objects, and consider the operation of

> causes, we are never able, in a single instance, to discover a necessary connection; any quality which binds the effect to the cause, and renders one a necessary consequence of the other. We find only that the effect does, in fact, follow the cause. The impact of one billiard ball upon another is followed by the motion of the second. There is here contiguity in space and time, but nothing to suggest necessary connection. (Hume 1748, p. 559)

Kant agrees with Hume in that there is no purely rational basis for the notion of causality. Kant, though, believes that Hume's knife has cut too deep and has either cast out important developments in natural sciences and metaphysics, or trivialized important developments in mathematics and logic. Kant wants to lay the grounds for a true metaphysics, a science of things that are not physical. The criterion of reality put forth by EPR is the type of metaphysical claim that has problems in classical metaphysics. In order to lay the appropriate grounds, though, he needs to be able to dodge Hume's criticisms of causality and necessary connection which apply to the sciences as well as avoid the argument that metaphysics is wholly trivial.

To do this, Kant first delineates between two types of knowledge: analytic and synthetic. (Kant 2007, p. 48) Analytic knowledge is the type of knowledge that is contained in the concept itself. For instance, if I were to recall my notion of a dog, I would necessarily recall my notion of a hairy four-legged animal. This, to Kant, is analytic knowledge. Within the definition of a dog lies the characteristics of hairy and four-legged. We are saying nothing new when we say a dog is hairy of four-legged, because, of course, all dogs are hairy and four-legged. Further, hairy and four-legged are necessary characteristics of dog, and therefore anything that is not hairy or four-legged cannot be a dog. Therefore, if I know that a certain dog is hairy and has four legs, this is analytic knowledge. EPR and other proponents of a classical interpretation to quantum mechanics suggest that the predictable, determined values (such as the hidden variable) are the legs of the dog of reality.

Perhaps the dog I am thinking of is blue. Surely the color blue is not in any generous definition of a dog. Kant calls this synthetic knowledge. Synthetic knowledge is that which puts two concepts together. These two concepts cannot be analytically tied together, and therefore their relation is not trivial. While the dog I am thinking of might be blue, it is certainly not the case that all dogs are blue, or in other words, it is certainly not the case that the dog is necessarily blue. This, then, is a synthetic piece of knowledge because it puts two concepts together that do not necessarily exist as one.

Kant makes another distinction important to saving the scientific studies and nontrivializing other disciplines, again regarding the nature of knowledge. Kant asks the question whether there exists knowledge that is entirely separated from sense perception. He admits that there does exist such a type of knowledge, proven in the existence of such disciplines like mathematics and pure logic. This type of knowledge Kant labels *a priori*. *A priori* knowledge is specifically knowledge that does not rest in experience. *A posteriori*, on the other hand, is knowledge that sources in experience.

How do these distinctions help Kant answer Hume's problem with the notion of causality? Kant agrees that it is impossible to directly experience something like a necessary connection. Where Kant departs from Hume, however, is in the distinction between the types of knowledge that are available to the human. Kant does not agree that the only kinds of knowledge we can have are those that are directly derived from experience. He argues this specifically in his defense of synthetic *a priori* knowledge.

To understand Kant's defense of causality and relate it to the Copenhagen interpretation, we must first understand what Kant means by experience. For Kant, experience itself is a kind of thinking, judging, or cognizing using the conceptual vocabulary that is available to us. "Thoughts without content are empty, intuitions without concepts are blind. . . . Only from their unification can cognition arise." (B75/A51) "Experience itself is a kind of cognition requiring the understanding." (B77/A53) For Heisenberg, our classical physical language is the cognition that allows us to understand the natural world. Meanwhile, this cognition is fundamentally limiting because it stops short of any determinist description of the world. Yet this determinist description of the world is impossible given, one, our classical mode of experience, and two, a description that actualizes only through our experience of the world. Still, for Kant,

> . . . the concept of cause . . . would be false if it rested only a subjective necessity, arbitrarily implanted in us . . . I would not be able to say that the effect is connected with the cause in the object . . . but only that I am so constituted that I cannot think of this representation otherwise than as thus connected; which is precisely what the skeptic wishes most, for then all of our insight through the supposed objective validity of our judgments is nothing but sheer illusion. . . (A464/B492)

EPR and others claim that the Copenhagen interpretation is exactly this type of objective judgment that is an illusion. The wavefunction and the uncertainty principle are objective in the sense that they are descriptions that do not rely on any subjective feature. The experiments are as objective as we can get: There *is* no objective description outside the ideality of classical physics. Classical physics is the language built to reflect the utmost objectivity when describing the world. As such, we cannot describe the world in any other way. To say that these classical descriptions of quantum phenomenon are subjective illusions is to say that *everything we say* is a subjective illusion because, of course, all explanation is and only is through classical language.

So, what is the link of causality between Kant and Copenhagen? The link exists in that any reference to causality must also reference our interpretive, experiential schema. To Heisenberg, this schema consists in the classical-mathematical formalisms that have made up our language of physical phenomena. He argues that any other formulation of causality or ‘happening’ between two events is fruitless in that it will always reach a gap of uncertainty. There must always exist a fundamental uncertainty in any description of the world. This uncertainty takes the form of statistical and probabilistic representations in the classical schema. It would be a mistake, however, to claim that we can dodge this uncertainty with a new language of description. Again, any language will be an experiential language, and that language will always lead to the paradox of the Copenhagen interpretation.

> [T]he physcists have gradually become accustomed to considering the electronic orbits, etc., not as reality but rather as a kind of 'potentia.' The language has already adjusted itself, at least to some extent, to this true situations. But is it not a precise language in which one could use the normal logical patterns; it is a language that produces pictures in our mind, but together with them the notion that the pictures have only a vague connection with reality, that they represent only a tendency toward reality. (Heisenberg 1958, p. 181)

To Heisenberg, any unmeasured event always exists as possibility or 'potentia.' To explain the cause of a possibility, we must be equally ambiguous. If we are to stand by the classical criterion for reality, our concept of causality breaks down in the quantum world: Any attempt to validate a complete theory will necessarily include a measurement, and this measurement *will be* the 'cause,' in the classical sense, of the result. To rescue such a concept, we must admit the language of probability is the best we can do.

Another way to envision the link is through Kant's argument regarding the infinite regression of cause. For Kant, the cause is no different than the effect. Every cause must be an effect of another cause. Attempting to know a cause only poses further questions of causality. Every cause in and of itself must also be an event or a happening to Kant. But in the same way that describing an object is limited to our understanding of it through time, so too is our conception of the cause itself. Here we are beginning to brush up against Kant's conception of things-in-themselves: The primary cause is that type of thing that cannot be nailed down. Why? Just like anything else, the object of cause is bound to our experiential mode:

> The accepted view is that only through the perception and comparison of events repeatedly following in a uniform manner upon preced-

> ing appearances are we enabled to discover a rule according to which certain events always follow upon certain appearances, and that this is the way in which we are first led to construct for ourselves the concept of cause. . . . Since the universality and necessity of the rule would not be grounded *a priori*, but only on induction, they would be merely fictitious and without genuinely universal validity. It is the same with these *a priori* representations – for instance, space and time. We can extract clear concepts of them from experience, only because we have put them into experience, and because experience is thus itself brought about only by their means. (B241/A196)

For Kant, all conception is driven by experience. On the one hand, objects like physical things or causes are experienced in space and time, and our knowledge of these objects is driven by this framework for experience. On the other hand, there exists space and time, which are not objects. Still, we have an intuition of these concepts only given the necessity that our experience must take place within and through space and time.

But is this really Heisenberg's view of causality? There is an agreement between the two in that the concept of cause cannot exist outside a certain experiential framework. For Kant, it is our intuitive *a priori* notion of space and time; for Heisenberg, it is the classical schema from which we "cannot and should not" escape. Kant assumes a constant object, such as a physical thing or an event. The object, though constant, remains outside the knowledge of our experiential framework. Alternatively, Heisenberg believes the object, such as an electron or the polarization event, becomes constant only *during* the act of experience. His argument is that we are *not* ignorant spectators of the object. Instead, we play an intimate role in the 'reality' of the object. In this way, experience *becomes* the object through the act of observation. There is no such thing as a constant object without the act of measurement. Instead, the object is precisely *uncertain* in that it exists merely probabilistically. We can attach this probability to the object as a physical thing: The electron is *both* here and there, until we try to measure, in which case it appears *only* here or there. We can also attach this probability to the object as a cause: The detector will register an interference pattern if we just look at the distribution of electrons, or the detector will register discrete particles if we try to view the electrons themselves. Furthermore, the instantaneous change in polarization direction of the right-hand photon is *caused* by my measurement of the polarization of the left-hand photon. Heisenberg wants to make it very clear that experience is an object just as much as any other object, and this is proven by the object of our experience colliding with objects of the world.

Here is the first disconnect between Kant and Heisenberg. Kant has helped us immensely, and will continue to help, in supporting the Copenhagen interpretation against counterproposals. However, we run into problems with Kant's outdated notion of experience as non-objective. Remember, Heisenberg will always claim experience is *both* objective and subjective. It is subjective in the sense that it is ours and we can control it (this side is the easy part), and it is objective in the sense that it has measurable, irreversible effects on a physical system. The Copenhagen interpretation is thus an attempt to breakdown this binary. Some have tried to claim everything is objective, others have tried to claim everything is subjective; Copenhagen claims *everything is both.*

7.2 Unknowables and Things-in-Themselves

At the end of the fifth chapter, in response to the violation of EPR's criterion for reality, we asked the question, "What makes an object real in and of itself?" Surely the experiments and conclusion in Part I make us question what it means for a particle to be real. EPR held that real objects must have a direct link to variables that can be predicted and known with certainty. Heisenberg's uncertainty principle, as well as our observations of the motion of an electron, show us that such a variable *must* be precisely *uncertain.* So after the failure of an intuitive and classical description of a real object, we ask the question whether such a description is possible. We will see that the classical criterion for reality is an assumption regarding the possibility of this description. Kant will help us to see that knowledge of things-in-themselves is both conspiratorial and the desire towards which our mode of understanding tends.

Here I want to show that Heisenberg, like Kant, argues we cannot know things-in-themselves. We know that Kant rules out knowledge of what is most fundamental. At the same time, the theoretical job of our faculty of reason is to point us toward a fundamental description of nature. The classical interpretation seeks an unconditioned set of conditions: There is a determinist theory underlying all outcomes in the natural world. This would be the classical 'complete' description.

> [R]eason in its logical use seeks the universal condition of its judgment (its conclusion). . . . Now since this rule is once again exposed to this same attempt of reason, and the condition of its condition thereby has to be sought. . . . we see very well that the proper principle of reason in general (in its logical use) is to find the unconditioned for conditioned cognitions of the understanding, with which its unity will be completed. (A307/B364)

The hidden variable approach is such an unconditioned condition. But does such a thing exist? We have found that any attempt to detect such a condition results in a necessary conditionality, namely the observation. Kant argues, however, that such a desire to search for the universal condition is built into our rational schema. Something that exists in space and time, available to our sensibility, never appears unconditioned. "In sensibility, *i.e.* in space and time, every condition to which we can attain in the exposition of given appearances is in turn conditioned." (A796/B824) Our very framework of interpretation necessitates that we attribute all events to some larger, more fundamental reason. We necessarily and rationally have interest in something unknowable, namely this universal condition or this hidden variable. Kant argues that we have no choice but to recognize this tendency in our mode of thinking:

> For to what cause should the unquenchable desire to find a firm footing beyond all bounds of experience otherwise be ascribed? Pure rea-

> son has a presentiment of objects of great interest to it. (A796/B824)

And it is this very desire that provides indispensable guidance or regulation to the classical interpretation:

> Accordingly, I assert: the transcendental ideas are never of constitutive use, so that the concepts of certain objects would thereby be given, and in case one so understands them, they are merely sophistical (dialectical) concepts. On the contrary, however, they have an excellent and indispensably necessary regulative use, namely that of directing the understanding to a certain goal. (A644/B672)

The classical counterproposal is a rationalist metaphysical argument, and we are tempted to accept. Reason guides us by projecting an image of the unconditioned. The particle, though, is statistical by nature. It behaves according only to statistical predictions, and probability vanishes to a discrete value only upon observation. We could say the event is random, and in this way unconditioned (though again we must be careful with such language). The classical metaphysical criterion for reality is an illusion which tricks us into thinking there must exist an unconditioned ground for everything condition.

For both Heisenberg and Kant, the problem lies within the way in which we understand the thing. When we refer to Kant's phrase of things-in-themselves, we are using shorthand for the longer phrase "things considered in themselves" (*Dinge an sich selbest betrachten*). The correlative difference is one of human sensibility and understanding. So 'in-itself' and 'how it appears' are two different ways of talking about the thing. I argued that Heisenberg and EPR seem to differ in their understanding of the thing, the latter using a synthetic description. The synthetic description is problematic, however, because it utilizes an appearance. This appearance is the determinist outplay of most physical systems, namely the physical systems a classical model was best at describing. However, assuming every physical system is determinist in-itself is doubly wrong. For one, it claims that this synthetic metaphysical claim is *a priori* knowledge. For two, it assumes our web of interpretation and language can describe the thing-in-itself:

> Now a thing in itself cannot be known through mere relations; and we may therefore conclude that since outer sense gives us nothing but mere relations, this sense can contain in its representation only the relation of an object to the subject, and not the inner properties of the object in itself. (A49/B67)

It is important to note that the difficulty with knowledge of things-in-themselves comes from the appearance of things to us. For Kant, appearance is always through the lens of space and time. We cannot perceive space and time directly; rather space and time are the structures which support our mode of perception. The structure itself appears to operate by laws of causality, so we are inclined to extend these laws to the things themselves. However, we must remember that the things-in-themselves are within a larger structure that we cannot perceive directly and distorts any direct knowledge we may have of things-themselves.

> *In appearance* every effect is an event, or something that happens in time; the effect must, according to the universal law of nature, be preceded by a determination of the causality of its cause (a state of the cause) on which the effect follows according to a constant law. (343)

I italicized the first words here because they are the clinch-pin of this argument: Cause itself is an appearance, and not a characteristic of the thing-in-itself. Or rather, we cannot possibly know whether it really is a trait of the thing-in-itself because we are forced to understand and perceive the thing in this way. When Kant speaks of space and time as the blinders which limit us to a knowledge of only appearance, Heisenberg similarly refers to classical physics as a mode of perception we are forced to adopt. Quantum mechanics is novel in that it suggests a discrete limit to our knowledge, a limit that exists because of the thing's appearance in classical language. We must always remember that for Heisenberg, even quantum mechanics is bound to this schema: There *is* no language to describe phenomena outside this schema.

The Copenhagen interpretation states that quantum mechanics does not represent particles, but rather our knowledge, our observations or our consciousness, of particles. (Popper 1967, p. 8) To recall, difficulty in calling quantum mechanics knowledge of the thing-in-itself comes from the spontaneous collapse of the wavefunction, a discontinuous change in the existence of a particle that must not be viewed apart from our observation. No such change occurs outside our observation. An objective, thing-in-itself description is impossible and not fruitful: Any attempt to rework the observations will result in more uncertainty; any attempt to find a hidden variable that gives new insight into the thing-in-itself will result in similar paradoxes. Accordingly, Heisenberg suggests that "it is now profitable to review the fundamental discussion, so important for epistemology, of the difficulty of separating the subjective and the objective aspects of the world." (Popper 1967, p. 11)

K.R. Popper suggests looking at quantum mechanics without the observer. While he does not say this himself, I submit that conceiving of a quantum mechanics with and without and observer is analogous to perceiving a thing through appearance and in-itself. (1967, p. 20) Popper argues that without the observer, there would not be a significantly different state of affairs. Sure, if we shoot a γ-ray at an electron and bounce it off in one direction, the world is in a slightly different state of affairs. But Popper's argument is that the universe would maintain a statistical arrangement on the particle scale. At the instant of measurement, the observer sees only one of an infinite number of properties.

> It is this *relativity* of the propensities that makes them [quantum descriptions] sometimes look 'unreal': it is the fact that they refer both to single cases *and* to their virtual repetitions, and that any single case has so many properties that we cannot say, just by inspection, which of them are to be included among the specifications defining what should be taken as 'our' experiment and 'its' representation. (1967, p. 38)

It is easiest to understand these properties as various positions in space. At any given instant, a particle can have the property (or properties?) of existing anywhere in space (here, space refers to a relatively tiny sphere of possible particle-space). But to say that the particle exists in such and such a place only be*cause* of the observation is a misguided formulation. Yes, it seems we are the authors of the electron bumping out of our Heisenberg microscope; but this is always appearance, always our representation of the event. Defining more and more variables of the experiment *ad infinitum* will not change the only available representation. In other words, we *cannot* think of the quantum world without using our observer intellect; similarly, we cannot know the thing-in-itself without referencing how it appears to us.

There remains one critical difference in the philosophy of Heisenberg and Kant. It seems that Kant's view of space and time is analogous to Heisenberg's conception of the classical schema of physical description. I have argued that they are similar because we cannot perceive the natural world without looking through these lenses. Heisenberg argues that Kant was the first to draw our attention to "the fact that the concepts of space and time belong to our relation of nature, not nature itself; that we could not describe nature without using these concepts." (Heisenberg 1958, p. 27) He claims this Kantian interpretation of space and time closed those concepts to new experience and elevated them to *a priori* knowledge, in some sense. However, in tipping his hat to Einstein, Heisenberg points out that the theory of relativity *did* fundamentally change our concepts of space and time. Kant assumed *a priori* that our understandings of space and time were fixed. Here I do not mean 'fixed' in the sense that they could not change (even though Kant was wrong here, too). I mean Kant assumed space and time were fixed relative to every object *within* space and time. This, though, is simply not the case.

Einstein's famous thought experiment was, If one were to travel the speed of light, at what speed would an adjacent beam of light travel? Under the Kantian doctrine, the answer is obvious: the same speed! We could wave at the photon as if we were waving to passengers on an adjacent subway. Einstein instead stated the apparent speed of light, *i.e.* how light appears to be traveling to us, as the real velocity of light, *i.e.* how the light travels in-itself. I like to think of this as Einstein imposing the Kantian doctrine upon the things Kant himself held to be constant and *a priori*.

> Speed is a measure of distance traveled divided by duration of the journey, and so is intimately bound up with the concepts of space and time. And, Einstein claimed, space and time – in contrast to Newton's [and Kant's!] intuitively sensible description – are *not* fixed and unchanging. Instead, they are fluid and malleable. Space and time, he argued, adjust themselves to keep something else – the speed of light – fixed and eternal, regardless of the motion executed by the light's source or someone observing it. (Greene 1994, p. ix)

In Einstein's eyes, there *was* an *a priori* piece of knowledge: the speed of light. The speed of light is constant in any inertial reference frame. If we are to travel at the speed of light, space and time travel with us per se. As we drag spacetime along with us, it contorts, yielding very peculiar appearances and phenomena indeed.

One major problem in the classical theory of gravity was explaining how it 'instantaneously' traveled through infinite distances. It appeared to be a problem of action-at-a-distance as discussed in Chapter 4. The suggestion was to give gravity a definite speed and fill space with an ether through which these gravity waves (and light waves!) travel. Newton, in *Principia*, left this problem to the reader. (Greene 1994, p. xv) Einstein's answer was that the very fabric of spacetime was the medium that transmits the force of gravity, such as the classic example of relativity which includes a bowling ball stretching the fabric of spacetime.

> The cosmic scaffolding could not be dismantled into rigid, universally agreed upon struts of space and time. . . . the shape of the cosmic scaffolding *responds* to the presence of matter or energy – and, in turn, the shape of spacetime affects how other objects move. Space and time . . . are participants in the evolution of the universe. (Greene 1994, p. xi)

Heisenberg, as a true founder of modern physics, cannot deny the magnitude of this shift in thinking.

> Since all systems of reference that are in uniform translation motion with respect to each other are equivalent for the descriptions of nature, there is no meaning in the statement that there is a substance, the ether, which is at rest in only one of the systems. . . . it is much simpler to say that light waves are propagated through empty space, and that this space itself is subject to magnification and rarefaction on the largest of scales. (Heisenberg 1958, p. 114)

While of course Kant never suggested such an ether or eternal substance, we can correlate Kant's space and time to such a concept. If we accept space and time are constant, then we run into two immediate fallacies. First, as already indicated, there seems to be instantaneous communication between objects at great distance. While we have argued that such a phenomenon might be possible in the quantum realm, Einstein did not take this to be a possibility. Second, light can propagate without a medium; but physicists did not want to say that light was a reality on its own. This ether would constitute the struts that hold together the cosmos; the ether would be what fills space and time but has no influence on the events that take place within that arena. This was primarily born from our understanding of a wave – something that needs a medium. Yet it was *also* born from an assumption about the universe – that space and time are static dimensions such that matter and energy do not affect the fundamental structure of the cosmos.

Returning to the discontinuity between Kant and Heisenberg: Kant claims that the lens through which we experience the world (namely space and time) is *a priori* in the sense that it cannot be affected by any experience. Heisenberg argues that the lens through which we experience the world (namely the classical schema) is precisely *a posteriori* in the sense that it is built from our experiences and is always added to by our experiences. There is no *a priori* truth to the existence of the classical schema, as our Weizsäcker quote eloquently put. Kant thought space and time were exactly those types of things-in-themselves that we cannot know and thus cannot conceptualize in any other way. To Kant, we had no choice but to accept our intuitions of space and time.

As the opening quote of Part II stated, mathematical concepts do not refer to reality with certainty. The violation of Bell's inequality confirms this statement. Quantum mechanics proves that is is a mistake to consider our mode of experience as "how it is" *a priori.* The Copenhagen interpretation argues that the classical-mathematical mode of experience is at root uncertain *a posteriori* knowledge. Hesienberg himself says that this mode of experience *is* open to change and will do its best to adapt to new observations like quantum mechanics. Nonetheless, the language binds us to a certain body of expressive tools such that the articulation of knowledge will always be subject to uncertainty. The thing-in-itself, then, can never be know; this is the primary similarity between Kant and Copenhagen. The paths separate at how it is we *know* we cannot know the thing-in-itself. Kant attributes this to a larger argument, that we cannot make metaphysical *a priori* claims. This topic is the next field on which Kant and Copenhagen play out their dual.

7.3 *A Priori* Synthetic Metaphysics

After this discussion of Kant combined with the Copenhagen interpretation, we may be thinking, "Why should we even ask, then, *really* what constitutes an electron, or a photon, or pion decay?" Surely such a pessimistic stance is unpleasantly skeptic. The stance also resembles a Berkeleyan strategy: You *want* to know whether perception corresponds to the way things are independent of perception, but the very idea of a way-things-are independent of all perception is incoherent. Our perception can be our imbedded conceptions of space and time, for Kant, or our classical-mathematical mode of analysis, for Heisenberg.

We are stumbling upon a metaphysical question. The question can be stated: Can the properties of objects of reality, *i.e. real* objects, be determined with certainty? To answer this question either way is to make a metaphysical claim. I have argued that the EPR criterion for reality is just such a claim. I have also argued that EPR and others hold this claim to be *a priori* knowledge. Further, with the help of Heisenberg, I claimed the criterion for reality is a synthetic judgment, because it combines to distinct concepts, namely reality and our ability to determine with certainty. Following our discussion of quantum physics, our goal is to break down this *a priori* synthetic judgment.

Such a claim regarding the nature of reality falls into the cosmological metaphysics. These arguments refer to our summative set of experiential data, *i.e.* all appearances through the mode of space and time. (A420/B448) In the *Critique of Pure Reason*, Kant responds to such cosmological metaphysics using the famous antinomy approach. To Kant, all cosmological arguments give rise to a set of competing arguments, the *thesis* and the *antithesis*. The world and our interpretations of it are pseudo-empirical, which makes all cosmological claims inherently dialectical. On the one hand we have to refer to sensible objects in space and time, thus using our empirical faculties, and on the other hand we must refer to the totality of space and time, thus abandoning empirical intuition. In such a dialectic, Kant sees two approaches: We can either take an dogmatic route or a empiricist route. (Grier 2007, p. 1) The problem is that each of these strategies is unsatisfying.

To satisfy the rationalist is to posit an idea that can never be grasped empirically. The demand of the rationalist is an ultimate unconditioned condition upon which the world is built. The theses in Kant's antinomies can offer such a first-mover, but does so by retreating to the realm of the unintelligible by providing explanations that have no have no grounding in our spatio-temporal existence. (Grier 2007, p. 4) Likewise, the empiricist approach can never live up to the fundamental demands of reason. Any argument derived from experience will necessarily limit the scope of the intellect until we arrive at a Humean strategy, which is to deny everything we do not perceive with absolute certainty and clarity. The empiricist ends up being just as dogmatic for assuming that whatever arguments hold in our spatio-temporal existence hold generally. And we have already proved for ourselves that it is dangerous to extend our subjective conclusions to universal ontological claims. Kant claims that if we are to avoid dismissing particular parts of our reason and thus a "euthanasia of reason," we must accept the distinction between appearance and thing-in-itself. (A407/B434)

In the *Critique*, Kant cites four such antinomies. The first regards the question of finite versus infinite space and time, second is the divisibility of objects in space and time, the third regards the conflict between determinism and freedom, and the fourth is the conflict over necessity and contingency. Clearly, the criterion for reality which we want to examine does not fall nicely into one of these categories. Still, we can call it a cosmological dilemma because it regards the *a priori* nature of physical things in space and time. Up until now, we have put the criterion for reality in this way: If an object is real, it has a value that can be predicted and known with certainty. Posing the question this way, however, is inherently classical. It states a necessity, observable empirically, on rationalist grounds. Let us pose the criterion as thesis/antithesis:

> **Thesis:** Every object in reality has, in principle, a corresponding value in any complete description of the world.
>
> **Antithesis:** Every object in reality has a value insofar as we ascribe to it a value via our mode of description.

In the tradition of Kant, we claim the thesis as the dogmatic argument. As asserted in Chapter 5, EPR and others defined the game in order to assure victory. Using this thesis as their criterion for reality, they proposed a method to find the hidden variable that corresponds to the odd nature of quantum systems. They supposed the quantum theory was in fact complete, and upon making this supposition, they arrived at the conclusion that particles communicate instantaneously over great distances (nonlocality). Because there is a finite limit on the speed of information (namely, the speed of light) EPR concluded that the quantum theory is incomplete. A complete theory would offer a value for this hidden variable. This value, in satisfaction of the principle of locality, must then originate at the source of the system of the two particles (the source in our experiment being a pion decay).

But upon what grounds can we assert the criterion for reality? Equivalently, what justification exists for the above thesis? Any justification seems to be an infinite regress. If we ascribe a value to a physical quantity, the question of reality does not stop there. A proponent of a complete theory might rebut, "What variable gives rise to the value indicated?" Perhaps a set of experiments can be formulated to answer this question. But then again, a complete theory would demand we give value to the conditions which produced this variable. The regress would continue until there were hidden variables proposed for the formation of the physical laws themselves. The answer, then, would be wholly rationalist: It would necessarily be a theory of everything, attributing all physical truths to either an abstract chain of infinity or to a supreme being as a first-mover.

Meanwhile, the empiricist retreats to a similar dogmatic defense of the antithesis. A superficial account of the Copenhagen interpretation might suggest such a position. A measurement is the act that collapses the possibility inherent in the wavefunction to a finite value. We can find patterns in the collapse of the wavefunction in the same way that we can find constant conjunctions from a Humean point of view. But in the end, the collapse of the wavefunction is a result of the measurement as per the observer and not a trait of the particle. While the empiricist does not doubt the reality of the particle, they do doubt whether such a fundamental claim can be made about how reality corresponds to our descriptive framework.

We must also remember that the thesis and antithesis both generalize to include *any* description of the world. The antimony proposed here does not ignore the possibility of an alien civilization that has a language which *can* yield a complete description of the world; for the sake of argument we must agree that our mode of understanding and intellect is not the best the universe has to offer. However, the empiricist approach will concede that there may exist really smart aliens, but it will not concede that such a complete theory is possible. The empiricist will argue that the rationalist justification for reality-value correspondence is unintelligible in that it specifically negates our experience (here I mean the results of our quantum experiments).

The conclusion of Kant's antinomies is that *a prori* synthetic metaphysical claims are impossible. Such metaphysical truths are bound to a dialectic. (Grier 2007, p. 5) Here we find a similar situation. We have stated that the classical criterion for reality is both *a priori* and synthetic. We expanded this criterion into an antinomy, where both thesis and antithesis are bound to an *a priori* synthetic judgment. Furthermore, I have claimed that this question is inherently a metaphysical one in that, while it makes a statement regarding our knowledge, it more fundamentally makes a statement regarding the metaphysical nature of physical things. That nature, to be precise, is that every piece of possible information (every event, every cause, every effect, every particle, every polarization, every spin, every decision the electron can make, etc. *ad infinitum*) can be represented and predicted with certainty in a complete theory.

My argument now is that the Copenhagen interpretation attempts to step outside the antinomy. I said that superficially, it seems the Copenhagen interpretation argues in support of such an antithesis as an answer to the classical thesis. Instead, as had been stated already, the Copenhagen interpretation suggests that our classical framework is *both* objective *and* subjective. It does *not* claim that there exist no physical values outside our description. Instead, it argues that these values are inherently statistical and bound intimately to possibility. One might say that this is the same as the thesis, and that a value is only that which can be ascribed with predictive certainty. But to make this argument is to assign too strict a definition to value here. We want to maintain that the wavefunction is real and its collapse at the instant of observation is also real. We want to maintain complimentarity of the wave-particle model, that the electron is *really* a wave as well as *really* a particle. We want to maintain that the quantum world is governed by harmonic oscillations as beautiful as Beethoven, at the very least to maintain the modest elegance of the quantum theory.

Yet while this last paragraph argues agreement with the Kantian doctrine of metaphysical antinomies, it also signals a departure. For we are now claiming that something *can* be known about the thing-in-itself; namely, its statistical nature, its tendency towards possibility. Is such a description of the thing-in-itself even tangible?

Quantum mechanics is not the only sect of physics that argues that the tendency of a physical system is always towards more possibility. (See Schroeder 2000) Statistical mechanics and thermodynamics argue that all systems tend to increase entropy. Many think of entropy as a 'chaos' factor. It is simpler to think of it as the physicists define it: The number of ways you can arrange a given system. The Bose-Einstein condensate described at the end of Part II was strange because it violates this law as all the bosons collect in a single state, thus taking the entropy to zero. But let's not get off track – physics seems to stating something about the thing-in-itself. How, though, can the thing-in-itself be purely *possibility*? This is hardly intuitive. The next and final chapter will reveal what can be meant by this. We do not attempt to answer this question wholly epistemologically. In my life, philosophy imparts the greatest implication when it speaks of the human. Thus, the capstone of this thesis is to speak of what we, as humans, can learn from the strange world quantum theory.

Chapter 8

Heidegger and Heisenberg

It is undeniable that Heidegger finds science and technology extremely dangerous. But what he finds disturbing is not that there are so many things wrong, but rather that (most of the time) things function so well. At times Heidegger is so pessimistic about the possibility of changing our technological schema of thought, he goes so far as to say only a god can save us. (Heidegger 1976, p. 277) At the same time, however, Heidegger understands science and technology as essentially positive and able to provide the most confident source of salvation. (Heidegger 1968, p. 14) But first, from where does Heidegger's caution arise? Heidegger's discomfort is one that might have had its origin in Nietzsche's position on the sciences. Nietzsche argues that the more-or-less classical-mathematical schema begins to fall apart when its father, Socrates,

> withdraws 'into the cocoon of logical schematism' by insisting that the world is completely intelligible and comprehensible, that is, 'that thought, using the thread of causality, can penetrate he deepest abysses of being, and that thought is capable not only of knowing being but even *correcting* it.' It is this kind of excessive optimism and faith in the universal applicability of the principle of causality that . . . is also dangerous in science and technology. (Seigfried 1990, p. 621)

The scientist will inevitably reach limits in their drive to uncover truth and knowledge. Physics will continually be forced to come to grips with the fact that, with new understanding, things that were once truths are now mere appearances. (1990, p. 622) Hans Seigfried suggests that the appropriate scientist must "affirm the creative character of their work." (1990, p. 622) Here, Seigfried is pointing out that every physical theory is a "poem" in that it uses language (*i.e.* the classical-mathematical schema) to *create* knowledge. To predict the future with determinist certainty is a misuse of the classical schema. Theories are creations and reflect only on the way in which we understand appearances. Assuming a complete theory exists, then, is to claim that theory itself *mirrors* the physical world and has the potential to mirror the physical world in its detail and in its entirety. But as the title of Part II suggests, theory itself is more so *an image of ourselves.*

Perhaps, then, the only synthetic, metaphysical *a priori* claims we can make are those statements regarding ourselves. We found that making such a statement regarding criterion for reality is in vain. We were instead required to alter this statement such that it no longer posited the observer as separate from the system. On the surface, it seems we are not making an *a priori* metaphysical claim. But let us dive a little deeper. First, the claim does seem to be an *a priori* claim. We are saying that there is no way to understand the world outside our descriptive framework. So, regardless of the reality of the world, the way in which we describe it is necessarily through a web of interpretation. We can see how this stems for Descartes' Archimedean point: We can only know our descriptive framework exists; *what* we describe, on the other hand, we cannot know. Therefore, positing this claim as an *a posteriori* piece of knowledge seems to miss the point. In fact, the classical-mathematical, vehemently empiricist, Newtonian description of the physical world *led back* to paradox, that paradox namely being our *a posteriori* descriptions are embedded in a classical language *a priori.*

How, though, is statement regarding *our* descriptive framework a 'metaphysical' statement? It is true that we can only speak of ourselves and our language. The Copenhagen interpretation is essentially a statement regarding our relation to the natural world. Yet quantum mechanics necessitates a restructuring of our cosmological metaphysics. The criterion for reality and the principle of locality are without a doubt metaphysical claims in that they presuppose any sort of physical action. They are (assumed) laws that all bodies must obey. Furthermore, the Copenhagen conception of cause falls directly into the Kantian antinomy (unlike the Copenhagen interpretation of reality): It is true that everything we experience, we must experience through an understanding of cause-necessary-connection. Even the quantum system is viewed this way; for the paradox stems precisely from a language that is bound to a cause-necessary-connection schema. On the other hand, cause-necessary-connection is an empty concept. Hume was fundamentally right in that we cannot directly perceive such a necessary connection; such a connection can only be impressed upon us and then completed by the imagination of our intellect. The Copenhagen interpretation is, then, a synthetic metaphysical *a priori* claim regarding *ourselves*. Perhaps, then, such claims are possible only in relation to *our own* being.

Additionally, let us not restrict ourselves: We found that the Copenhagen interpretation of cause went further than our Kantian analogy. Heisenberg argued that our notion of causality is fundamentally *a posteriori*. Heisenberg must be referencing his German philosophic ancestors. We must understand cause as *a posteriori* because the object gains constancy only upon observation. To Heisenberg, every observation and every experimental apparatus is different. The notion of 'repeatable' is misguided in that no situation can be an exact replica of another through the lens of quantum mechanics. Nietzsche agrees by arguing that the classical physicists fails to realize

> that there neither are nor can be actions that are the same; that every action that has ever been done was done in an altogether unique and irretrievable way, and that this will be equally true of

> every future action ... as one contemplates or looks back upon *any* action at all, it is and remains impenetrable. (1974, p. 265)

As such, causality is an appearance and can only be affirmed through *a posteriori* means. The principle of causality is thus a creation of the classical physicists, and a beautiful creation at that. The law of causality has explained an essentially infinite amount of things in the physical world and holds a level consistency that should be admired (and utilized!). Yet to "become fully ourselves," the task is to recognize *our* possibility; for just like a quantum particle, each individual can be modeled as a function of infinite possibility until a certain possibility is realized. As Nietzsche put it, "to that end we must become the best learners and discoverers of everything that is lawful and necessary in the world: we must become *physicists* ... Therefore: long live the physicists!" (1974, p. 266).

"It is in the natural sciences and physics [*i.e.* quantum mechanics] where we finally come to realize that the whole world of experience is the product of our organization." (Seigfried 1990, p. 624) With the Copenhagen interpretation, we learned that the our mode of experience is defined through the classical-mathematical schema, a schema that proves problematic with quantum experiment. Seigfried is suggesting a very similar thing here by saying that our experience comes forth from our structuring of the world. It is in this recognition of the true nature of experience where we can fully realize ourselves and grasp our experience in the Heideggerian sense. But how can physics help us attain such a goal of 'finding ourselves?' Is not physics responsible for a world in which "precisely nowhere does man today any longer encounter himself"? (Heidegger 1977, p. 27) Classical physics assumes that the world is constant and determinist, that the observer, the 'I' does not bare on the world in any special way. The answer to the last question lies in the positing of this 'I' that is so essential to the Copenhagen interpretation of quantum mechanics:

> For if we accept such objects as things 'which always [already] are

> what they are' and 'constantly remain' the same, then we are prevented from recognizing our human 'behavior' (Verhaltungen) 'in a manner which is ontologically appropriate' and phenomenally adequate. Instead we are forced (as was Descartes at the beginning of our modern age) to misconstrue the relationship between us and the world as a correspondence-relationship between things equally fixed and ready-made. From the outset Heidegger made it a prime task of his discussions 'to prove that if we posit an 'I' or subject' as something given – something which already is what it is, then 'we shall completely miss' the phenomenal findings about our own being, that is, what we actually experience ourselves to be. (Seigfried 1990, p. 624)

Leaving the observer out of the description of the physical world is just the type of static humanity that Heidegger is attacking. Being in-the-world, for Heidegger, is a constant recognition that our experience comes forth from our conceptualization of the world, and our beliefs in our concepts likewise comes forth in our experience. (Heidegger 1962, p. 131) Any paradox of experience will take root in a descriptive schema that assume constancy. A constant piece of knowledge is only a temporal phenomenon, and never something that should define a descriptive schema as independent from the person. Classical physics has been burdened by the chore to consistently and systematically remove the observer from any theory.

Quantum mechanics, however, necessitates the person, necessitates the observer. There *is* no way to describe the system outside the collapse of the wavefunction. The collapse of the wavefunction, the action of the observer, is what defines the course of events. The course of physics then changes:

> He [Heidegger] learns from Heisenberg that the aim of the natural sciences and physics is no longer *die Natur an sich*: nature in itself, but *die der menschlichen Fragestellung ausgesetzte Natur*: nature in the setup of human concerns and demands. (Seigfried 1990, p. 626)

Heisenberg and Heidegger agree that the classical-mathematical schema of describing the physical world has proven very advantageous for technological advances. They also agree, however, that these advances have shaped the object of questioning of physics. In shaping the questions physics answers, the technological advances also delineate a purpose to physics. This purpose is as much a prison as the technology is convenient.

So, modern physics is a way in which the human can encounter themsef. By this I mean the human is given an opportunity to understand that the world is a construction of experience, and there is no way to relate to the world outside our web of experience. Quantum physics *forces* this realization by stating a fundamental paradox. Superficially, the paradox lies within all the experiments we discussed in Part I. As we dug deeper, however, we found that this paradox was rooted in deeper assumptions. These assumptions were predicated on the belief that the classical-mathematical schema can accurately and completely mirror the workings of the physical world. The fundamental paradox of quantum mechanics then becomes one of language, one of how we experience the world. Heidegger argues that being in-the-world necessitates two-way experience: Our conceptual schema frames our experience, and experience continues to build our conceptual schema.

Heidegger claims that this mode of understanding is always wrapped up in our experience. Whenever we 'encounter' a circumstance or event, we are encountering a web of interpretation that separates us in some way from the thing-itself. I quoted Heidegger earlier saying that man no longer encounters himself; on the same page, Heidegger claims further that man "*can never* encounter *only* himself." (Heidegger 1977, p. 27) Heisenberg, on the other hand, believes quantum physics is like no other situation in humanity. To him, quantum physics is the realm in which "for the first time in history man encounters only himself on this earth." (Heisenberg 1984, p. 412) Heisenberg argues that quantum physics utilizes physical descriptions that are entirely meaningless without positing the observer as a unique part of the physical reality. Heisenberg and the Copenhagen interpretation do this by deconstructing classical binaries, such as observer/experiment, subjective/objective, and mind/body.

But is Heisenberg the first to bring this type of deconstruction to the table? Most certainly not. I feel Heisenberg's argument goes further than the deconstruction of this binary. As stated many times now, a superficial reading of the Copenhagen interpretation will claim merely that we must be careful with such distinctions, distinctions which drive the classical experimental mode of thought. Heisenberg skips this point almost entirely because it is of no pertinent matter to him: Instead, what is at stake is our understanding of *ourselves*. The classical experimental schema will always prevail for our technological purposes. Now, the question is whether we can save *ourselves* from the classical-mathematical-logical schema (Heisenberg 1984, p. 415) that has more or less destroyed the rest of the world.

> The uncertainty relations show that what we originally conceived as the ultimate object of reality, namely, the elements of matter, cannot be observed 'in themselves,' that is, their objective determination in space and time is impossible. . . . The new situation in physics indicates that such received distinctions as subject/object, inside/outside, mind/body are no longer applicable and useful. Heisenberg mostly develops the implications for nature and what we ordinarily call objective reality. But, of course, there are also similarly radical implications which need to be drawn out for what we ordinarily call the self. (Seigfried 1990, p. 628)

Heidegger agrees in that the only task worth pursuing for physics not a technological feat, but rather a perceptual 'turning' that could (re)insert the human back into his/her description of the natural world. (Heidegger 1977, p. 39) After all, what else is there to do with a classical-mathematical schema that "no longer mirrors nature, but only our knowledge of nature." (Seigfried 1990, p. 628) We have no choice but to accept that the mirror with which we tried to see nature has been turned back on ourselves, and is nothing more than a mirror image of ourselves.

> The objective representation of natural processes is no longer possible in quantum physics. What quantum physics provides is not a representation of nature (*Bild von der Natur*), but a representa-

> tion of our relationship to nature. (Seigfried 1990, p. 629 citing Heisenberg 1984, p. 417)

The classical Cartesian distinction between body and mind is not only useless, but also dangerous in modern physics. Such a binary between *res extensa* and *res cogitans* leads to vast assumptions about the natural world, such as the classical criterion for reality and principle of locality. Heidegger argues that quantum physics, too, is wrapped in the Cartesian binary and can therefore cannot encounter either the natural world or itself (as a discipline). But,

> contrary to Heidegger, who claims that modern physics rests on a Cartesian ontology, 'which, in principle, is still the usual one today' (1962, p. 100), quantum physics deals this ontology a much harder blow than Heideggerian phenomenology. (Seigfried 1990, p. 629)

We must admit, then, that humans are participants more so than they are benign observers in the natural world. Our relationship with nature is a "transaction" that is clouded by uncertainty relations. Without such an understanding of ourselves, without such an understanding of the natural world, we are bound to a determinist framework. As Plato says, we are nothing but puppets of the Gods. (Plato 1969, p. 1244)

Heidegger has helped us realize everything quantum mechanics has to offer, even though he himself stated "Physics . . . will never be able to renounce this one thing: that nature reports itself in some way or other that is identifiable through calculation and that it remains orderable as a system of information." (Heidegger 1977, p. 23) To this statement, we must simply say Heidegger was wrong. Quantum theory states precisely the opposite – Nature is *not* identifiable through calculation. To say the thing-in-itself is calculable remains the ultimate claim this thesis has worked to debunk.

What, then, is the thing-in-itself? We stated in Section 7.2 that the Copenhagen interpretation seems to make at least one claim regarding the thing-in-itself, namely, that it tends towards possibility. The act of observation which destroys possibility is an invasive process. We do not meet invasive in such a negative way. Rather, we want to accept that every observation necessarily projects our being onto the system of inquiry. The thing-in-itself is wrapped up in our being in the sense that it cannot be observed without imposing ourselves upon it. We are not claiming the world is only our mind: Instead, we want to deconstruct the binaries that try to define a world as separate from our existence.

Remember, we do not want to claim that there exists not world separate from our experience. This is the inflationary and skeptical route. We want to claim that the world is comprised of infinite possibility until, that is, one discrete possibility is realized. The thing-in-itself tends towards possibility. As the observer, we effectively choose a possibility. In many cases, how possibility becomes actuality cannot be adequately explained using our classical-mathematical schema. Further, possibility becoming actuality is even more so mysterious in the context of the person. But if we are to take anything away from the juxtaposition of Heisenberg and Heidegger, it is this: Any observation is an *image of ourselves*, and accordingly offers us the opportunity to actualize our possibility and *create ourselves*.

Chapter 9

Conclusion

With the advent of quantum mechanics come fundamental questions. At first glimpse, these questions seem to be epistemological in nature. This is the knee-jerk reaction of any philosophy of physics. We are inclined to think that the goal physics is to present a wholly objective description of our knowledge of the world. The burden of physics, then, is quite large. In fact, this thesis has shown that that burden is impossible. This thesis has shown that we play a more intimate role in the workings of the physical world. By accepting our intimate relation, we have come to a metaphysical conclusion regarding the reality as well as a existential conclusion regarding the being of a person.

In Part I, we observed quantum phenomenon. We tried to image an electron; we tried to send an electron through one slit or the other (we did not care which one!); we tried to measure polarization without contradicting ourselves; we tried to measure spin, but instead only showed that our observations violate basic mathematical principles. With what were we left?

We were left with a paradox. The paradox was: While we know our descriptive schema *cannot* describe the natural world accurately, we also know this is only the descriptive schema we can adopt. Kant helped us understand why: Our concepts of cause, space, time, and thing-in-itself force us to search for sufficient reasoning in every event. Classical-mathematical physics has mostly accomplished this: There are *many* physical events that can be described using the classical schema. But still, the paradox carries dramatic assaults on our underlying assumptions. To rework these assumptions, we had to retreat all the way back to metaphysical claims regarding the natures of reality and the thing-in-itself, as well as our relation to these two concepts. A physical principle that began as seemingly a statement on knowledge flourished into an examination of our metaphysical presuppositions. We had no choice but to accept these ramifications.

We are now left with a rather confusing situation that goes against our intuition. The world can only be described using our conceptual schema. Yet this schema is developed through our observations of the world. Perhaps while bringing light to one paradox, this thesis has happened upon another: Which comes first, the schema or the experience? Our answer seems to be equally paradoxical: *Both* come first. We are able to make such a statement only by recognizing the intimate interplay between experience and concept. We have argued that it is just as meaningless as it is dangerous to separate these two. Some philosophy works to take things apart, and some philosophy works to put things back together. We have taken apart the schema through which we experience the world in order to put back together the binaries of object/subject, mind/body, self/world, and all those distinctions that only confuse our interpretation of ourselves. We did this by proving such distinctions are bound to paradox. And thus, in the paradox we rejoice.

As I said in the Introduction, quantum theory is as humbling as it is modest. It is humbling because it allows us to understand our significance in the world. We have no choice but to accept ourselves as that which actualizes possibility. Determinism is empty at its core. It is modest in that it does not treat the person as a particularly special entity. For a long time, physics thought we could observe the world objectively and arrive at a complete description of reality absent ourselves. This, however, is not the case. We are just another piece of matter, inextricably linked to the natural world around us. A theory that is both humbling and modest is sure to bring about enlightening conclusion. Our conclusion is that we are in charge of possibility. We are in charge of creating the descriptive language, and we are in charge of pushing probability into the realm of actuality.

Philosophy and physics are connected in that they ask fundamental questions. We can understand, then, why the two will run into each other. In order to answer such questions, we must take up our creative spirit and build a world out of our description. We can count on the world to forever be uncanny, and thus we can count on forever having inspiration. For this reason, we link the physicist and the philosopher and the artist; and after we attribute the deserved elegance to the theory of quantum mechanics, I myself can view it as nothing but a miracle of the human. But perhaps the paradox is more enlightening:

> "There are two ways to live: You can live as if nothing is a miracle;
> you can live as if everything is a miracle."
>
> –Albert Einstein

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