

More than One Way to Skin a Schrödinger Cat:
Considering Bohr's Philosophy-Physics and Everett's Many-
Worlds Interpretation

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INTRODUCTION: THE PROBLEM OF MEASUREMENT

"Anyone who is not shocked by quantum theory has not understood it."

–Bohr, *The Philosophical Writings of Niels Bohr*¹

Historically, science has always presumed an objective reality whose properties are independent of the observer and act of observation. Before the advent of quantum mechanics, Newtonian physics, based on classical epistemological and ontological assumptions, ruled the way we understood the world: as a place filled with individual objects with determinate properties that are independent of our observations. According to Newtonian physics, measurement is transparent and external; objects and observers occupy distinct locations, both physically and conceptually; objects are assumed to have individual, determinate properties; experimentation leads us to uncover pre-existing, observation-independent characteristics of the world; and observation is assumed to in no way influence the observables such that the experimenter is understood as removed from and having no effect on the experiment.^{2, 3} Once quantum physics became an established field of study during the first half of the 20th century, however, it became clear that some, if not most, of these classical assumptions needed to be revised.

The 17th and 18th centuries marked the start of scientific inquiry into the wave nature of light, contrary to Isaac Newton's adamantly held "corpuscular" theory of

¹ From Bohr, *The Philosophical Writings of Niels Bohr*, Vol. 4, quoted in Barad, *Meeting the Universe Halfway*, 254.

² Karen Barad, *Meeting the Universe Halfway: Quantum Physics and the Entanglement of Matter and Meaning* (Durham, North Carolina: Duke University Press, 2007), 106.

³ *Ibid.*, 247.

light. From 1600 to 1900, physicists around the globe were caught in a heated debate over whether to think of light in terms of particles or waves, and this contention can be viewed as the ember of what grew into a seemingly irreconcilable blaze of interpretational issues surrounding quantum mechanics. Isaac Newton was unwavering in his belief that light was composed of particles, but other physicists, including his contemporary, Christiaan Huyghens, saw it as constituted by wave phenomena. By 1900, physics was organized into two domains: particle dynamics versus continuum dynamics, where rocks and balls were particles, obeying the laws of discrete mechanics, while light and sound were waves, requiring a continuum treatment.⁴ Quantum mechanics then complicated and blurred this neat division between waves and particles, marking the beginning of scientists being forced to more closely scrutinize their previously unchallenged views of the nature of the universe.

In January of 1926, there existed two formulations of the laws of quantum mechanics. Heisenberg, Born, and Jordan had posited matrix mechanics while Schrödinger pushed for wave mechanics, but by February of the same year, Schrödinger realized that these two formulations were mathematically equivalent. Matrix mechanics was describing the particle behavior of matter while wave mechanics was describing the wave behavior of matter.⁵ This mathematical formalism is most commonly referred to as the Schrödinger equation (SE). The SE is a

⁴ George Greenstein and Arthur G. Zajonc, *The Quantum Challenge: Modern Research on the Foundations of Quantum Mechanics*, 2nd ed. (Sudbury, Massachusetts: Jones and Bartlett Publishers, 2006), 19-20.

⁵ Barad, *Meeting the Universe Halfway*, 249-50.

deterministic, differential equation, like Newton's famous equation $F = ma$,^{6, 7} but instead of solving for a specific value, such as a particle's trajectory as with Newton's equation, one solves for the wave function, which varies through space and time. So, in quantum theory, the state of a system at a given time is described by a complex wave function, representing the calculation of probabilities of outcomes of a given experimental situation. For example, the SE allows us to calculate the probability that an electron is in a particular position around the nucleus of an atom at a particular time, but the exact values of these properties are unknown. Generally, definite values are not assigned, and instead, the SE makes a prediction using a probability distribution. In other words, Schrödinger's equation describes the probability of obtaining various possible outcomes from an experimental situation.⁸

The problem with the Schrödinger equation is that no one quite knows what a wave function is, and this is a foundational problem in quantum theory with different interpretations of the theory understanding the wave function in different ways. However, no matter the interpretational issues that arise, the formalism always works, and when doing calculations, the "standard" Copenhagen interpretation is used. This usually means the wave function is taken to represent the probability that a particle of some mass will be found in a given position at a given time. What is agreed on is that the SE gives us the ability to calculate everything we could possibly know about a given physical situation, and this is a probability, not a determinate value, thus

⁶ In classical physics, Newton's second law ($F = ma$) is the equation of motion, describing what state a particular system will be in any time after the initial conditions of that system. The analogue of Newton's second law in quantum mechanics is the Schrödinger equation.

⁷ More specifically, Newton's second law is a second-order differential equation and the SE is a partial differential equation.

⁸ Ibid., 250-251.

making it possible to use the wave function to calculate specifications of probabilities for a wide variety of physical situations. Quantum mechanics has proven itself to be able to account for nearly all phenomena while being empirically efficient and accurate.⁹ It is with the interpretational difficulties that the puzzles and paradoxes come flooding in.

When subjected to closer scrutiny, the Copenhagen interpretation, usually taken as the standard interpretation, turns out not to be a coherent interpretation at all, but most have focused on quantum's success in its calculations rather than the failures of its interpretation. Karen Barad describes it as "a pastiche of different elements, a partially negotiated and indeterminate combination or superposition of contributions from leading physicists who worked on the founding of quantum mechanics rather than a coherent account."¹⁰ Two key factors have contributed to the interpretational aspects of quantum being raised for discussion: 1) technological advances have allowed for classic thought experiments to be realized, and 2) the growing prominence of quantum information theory has profound practical applicability. Physicists have begun to realize that the philosophical issues related to quantum theory have consequences for computations, especially for discoveries such as quantum computing, quantum cryptography, and quantum teleportation, because of their practical implications.¹¹ In my view, the biggest interpretational issue is the problem of measurement, including the subsequent difficulties that follow.

⁹ Ibid., 251-252.

¹⁰ Ibid., 252.

¹¹ Ibid., 253.

Classically, making a measurement is a passive act that allows us to find out about a pre-existing state of affairs, but quantum mechanically, measurement plays an active role.¹² In classical physics, measurement poses no problems because it is simply the observation of what the pre-existing state of affairs is, but in the quantum world, measurement is more mysterious because the SE allows for all kinds of possible states of affairs, even those that are mutually exclusive, until a measurement interaction occurs and one of the possibilities is actualized. The measurement problem includes the interpretational issues that arise from the puzzle of how to understand the wave function (which is mathematically described by the SE) and collapse of the wave function (which we perceive as something that happens but is not described by the SE). There is something crucial and mysterious about the transition of the state of the system during the process of measurement; there is an important difference between the state of the system before and after measurement. This aspect of quantum weirdness comes from the SE accounting for superpositions, entanglements, and everything that happens to the wave function between measurements but not accounting for the transition, or "collapse," that appears to happen as a result of measurement.¹³

Superpositions exist mathematically as a consequence of the linearity of the SE,¹⁴ which represents the wave behavior of particles. Waves, rather than being entities, are disturbances extended through space and can be superimposed on one

¹² Greenstein and Zajonc, *The Quantum Challenge*, 215.

¹³ Barad, *Meeting the Universe Halfway*, 280-281.

¹⁴ Linear differential equations are differential equations (which can be ordinary or partial) with differential solutions that can be added together to create additional solutions. There does exist a nonlinear Schrödinger equation (NLSE), but unlike the SE, the NLSE does not describe the time evolution of a quantum state.

another. When two waves overlap, the amplitude of the wave that results is the combined amplitude of each of the original waves, and the resulting wave is understood as a linear combination, or superposition, of the component waves. This is also how the SE works: wave functions can be added together to form superpositions. If Ψ_1 and Ψ_2 are both solutions to the SE, then any arbitrary linear combination of these two solutions is also a solution of the SE. In other words, if Ψ_1 and Ψ_2 are solutions to the SE, we can multiply each of the individual solutions together by a complex number (although each complex number must be appropriately normalized such that $|a|^2 + |b|^2 = 1$) and add them together to get a sum, which is also a solution. This is the same calculation as with water waves, but instead of just adding the component waves together, we're first multiplying each component by a number, so when $a = b = 1$, the equation reduces to the same simple addition as with component waves. Put another way, superpositions of individual solutions are also wave functions, and this is because the SE is a linear equation. Therefore, that superpositions even exist is a feature of the wave behavior of matter.¹⁵

To illustrate this, let's pretend we want to measure some property, "color," of a particle, and whenever we measure the color of a particle, we always get one of two possible values, "red" or "green." Any system in which a measured property can take on one of the two possible values is called a two-state system (and n possible values denotes an n -state system). A two-state system has two characteristic solutions, or eigenstates (also eigenfunctions), coming from "eigen," the German word for characteristic. In this example, one eigenstate is Ψ_r (red) and the other is Ψ_g (green)

¹⁵ Ibid., 255-256.

where the measured values "red" and "green" are the corresponding eigenvalues. Because the SE is linear, any arbitrary linear combination of Ψ_r and Ψ_g is also a physically allowed state and therefore a solution. The most general solution to the SE for any two-state system is of the form of a linear combination of two eigenfunctions: $\Psi = a\Psi_r + b\Psi_g$ where a and b are complex numbers and $|a|^2 + |b|^2 = 1$. Because the coefficients of a and b are any complex numbers (that are appropriately normalized), there is an infinite number of possible physical states. However, there are two (or n) special states (the eigenstates). The first eigenstate, Ψ_r , is a special case of the general solution where $a = 1$ and $b = 0$ while the other eigenstate, Ψ_g , is where $a = 0$ and $b = 1$.¹⁶

Next, imagine we've created a device for measuring the color superposition of eigenstates. This device is a black box with one input and two possible outputs that sorts particles by color. We send particles in from the left side with the color measured inside the box, and the particle exits on the right through the top slit if the color is measured "red" or through the bottom slit if the color is measured "green." If we send 100 particles with eigenstate Ψ_r into the measuring device, all 100 particles will exit through the top slit because they all have the eigenvalue red. If we send 100 particles represented by the eigenstate Ψ_g , all 100 particles will exit through the bottom slit because they have the eigenvalue green. These two experiments show that the device is working correctly and that the special nature of eigenstates is that they're the states with definite characteristics for a given property. If the wave function isn't an eigenstate and is instead represented by the wave function $\Psi = (\sqrt{1/4})\Psi_r +$

¹⁶ Ibid., 256.

$(\sqrt{3}/4)\Psi_g$, which is just one of countless superpositions that satisfy the requirement $|a|^2 + |b|^2 = 1$ (in this case $a = \sqrt{1}/4$ and $b = \sqrt{3}/4$ which satisfies the normalization because $|\sqrt{1}/4|^2 + |\sqrt{3}/4|^2 = 1/4 + 3/4 = 1$) then 1/4 of the 100 particles come out of the top slit as having the eigenvalue red and 3/4 of the 100 particles come out of the bottom slit having the eigenvalue green. Or, for any given particle, there's a 25% chance that it'll be found with an eigenvalue red and a 75% chance that it'll be found with an eigenvalue green. This example also demonstrates that the constraint equation, $|a|^2 + |b|^2 = 1$ is necessary because it means that for each measurement, the outcome will be one of the allowed eigenvalues. In other words, the constraint equation is that the probability that red is measured plus the probability that green is measured equals 100% because there are no other permissible outcomes.¹⁷ Thus, the mathematics of superpositions is accounted for by Schrödinger's equation.

On the other hand, collapse of the wave function, in which the superposition of states as described by the SE is resolved into one determinate result or another rather than a probability,¹⁸ is not predicted by the SE. An experiment to find evidence for the existence of photons was performed, the results of which showed that individual grains of silver halide became blackened one at a time, meaning that light was being detected as arriving in a single place at a single moment in time.^{19, 20} We can also use this experiment to understand whether the blackening of each silver halide grain constitutes a measurement of the location of a photon, because if a photon weren't present at a given location, the grain at that location couldn't have

¹⁷ Ibid., 256-257.

¹⁸ I.e. we perceive the world as being in one state or another, not in a probability of states.

¹⁹ Greenstein and Zajonc, *The Quantum Challenge*, 216.

²⁰ Ibid., 24.

been exposed. The blackening of the silver halide is caused by the interaction between a photon and atom in the grain, so the measurement involves each photon being detected by a single atom. The mysterious thing about this is that the shape of the wave function has changed: it went from being a broad wave packet representing the photon across the film to collapsing to a single point centered on the atom that registered the event. If this collapse hadn't happened, there would be a finite probability of finding the photon somewhere else, but it's impossible to find the photon somewhere other than where it was found to be. The measurement is made at some definite time and place, and if a second measurement is made arbitrarily soon after the first and arbitrarily far away, we can imagine that this second measurement would have a finite probability of finding the photon, but this is impossible because a photon, restricted by general relativity, can't travel arbitrarily quickly. Therefore, collapse must occur instantaneously over all space.²¹

The problem is that quantum theory gives us an inadequate account of the phenomenon of light causing a silver halide grain to darken. All light can do to an individual atom is excite it, and the darkening must somehow follow from this excitation, but quantum theory says nothing about this. Although we know the transition an atom makes between a ground and excited state occurs, the formalism of quantum mechanics does not explain it. Presumably, this transition is related to the collapse of the wave function, but quantum theory has nothing to contribute regarding this either. Collapse, as a phenomenon, lies outside the issues addressed by the Schrödinger equation. In no situation does the application of the SE to some process

²¹ Ibid., 216-218.

yield a discussion of the collapse of the wave function associated with that process. Collapse is required by the fact that observations occur, but it isn't predicted by quantum theory; collapse appears to be an additional postulate necessary to make quantum mechanics consistent.²²

According to the formalism, measurements never happen, and instead, what happens is an infinite regress. The SE predicts complex entanglements, and rather than collapse occurring, the entanglement just grows, resulting in an infinite regress. In order to make a measurement, we need to end this regress and replace the entanglement with a single term, but this cannot be done within the SE. To get around the problem of infinite regress, mathematician John von Neumann proposed the "collapse postulate," or "projection postulate," which suggests that when a measurement occurs, the entanglement is replaced by a single term. The collapse postulate is basically a mathematical restatement of the wave function collapse, positing that, at the moment of measurement, the state is collapsed into one of the possibilities such that, upon measurement, we get a definite value for the property in question. The problem with the collapse postulate is that it appears to be ad hoc, not playing any larger role in quantum theory other than functioning as a mathematical addendum. It doesn't correspond to an actual physical process, and in some situations, the postulate isn't needed in order to make a measurement, so many physicists don't support it.^{23, 24, 25} Bohm, who did not take the projection postulate as fundamental, described a quantum state as a "set of potentialities," and other physicists have since

²² Ibid., 220-221.

²³ Barad, *Meeting the Universe Halfway*, 286.

²⁴ Greenstein and Zajonc, *The Quantum Challenge*, 224-225.

²⁵ See chapter 2 for more information on von Neumann and the collapse postulate.

described measurements as actualizing one of these potentialities. In this sense, measurements don't simply allow us to gain knowledge about a pre-existing reality: they create reality, and a state of affairs found through experimentation didn't exist until the measurement had been made.²⁶

The quantum Zeno effect, named after Zeno's paradoxes that appear to show that motion is impossible, describes how the act of observing a process can actually slow the process and completely stop it in the limit of continuous measurement. An experiment by Itano, Heinzen, Bollinger, and Wineland illustrated this phenomenon for induced transitions by studying the excitation of an atom by light. An electromagnetic wave can raise an atom from its ground state to an excited state if an appropriate electromagnetic pulse is applied, and Itano et al. showed that the probability of this transition happening was reduced if they looked to see whether the transition had occurred. Quantum theory can't predict exactly when any individual atom will make the jump to an excited state, but it can predict that after a certain amount of time, the transition will have happened. If we start at $T = 0$ and make a measurement at some time t to find the atom to be in its ground state, the wave function collapses, effectively resetting the atom back to its ground state, as if the time elapsed between 0 and t never happened, thus slowing the rate of decay. Conversely, if the measurement shows the atom to be in the excited state, the collapse leads to this state, meaning the measurement has hastened the rate of decay. When measurements are frequent, t will be much shorter than the time it takes for an atom

²⁶ Ibid., 227.

to reach its excited state, so the net effect is a slowing or complete halt of decay.²⁷

While the quantum Zeno effect is real, the interpretation of it isn't as clear. The above interpretation of Itano et al.'s experiment uses the language of the collapse of the wave function, but other physicists have argued that the results can be predicted without invoking collapse.²⁸ The main issue lies in how to understand the abrupt changes in state between the superposition that occurs as it resolves into a mixture of definite values once a measurement is made. When this state is taken to be physical, it's referred to as collapse of the wave function, but collapse is mysterious in part because it must take place instantaneously over all space and the formalism can't account for it.²⁹

There are many attempts at solving this measurement problem, but as of now, there's no consensus over a solution. Different interpretations of how to understand the wave function lead to different interpretations of quantum theory. Some physicists think that the wave function has no physical meaning and only describes our information about a system, meaning that the collapse of the wave function has no real significance. For example, there may be a 30% chance of it raining at noon, so at noon we go outside and the instant we become aware of the weather, the 30% chance "collapses" to either 100% (if we find that it's raining) or 0% (if we find that it isn't raining). Most physicists, however, understand a change in the wave function as corresponding to a physical process rather than a change in our knowledge of that process.³⁰ Some physicists claim that decoherence, an environmental effect on

²⁷ Ibid., 231-233.

²⁸ Ibid., 237.

²⁹ Barad, *Meeting the Universe Halfway*, 285.

³⁰ Greenstein and Zajonc, *The Quantum Challenge*, 237.

quantum systems that rapidly induces classical behavior, solves the measurement problem by ridding us of the need for the projection postulate and providing a physical basis for collapse through the interaction of the object with its randomly fluctuating environment, but whether this is actually the case isn't clear.^{31, 32} The GRW theory (Ghirardi, Rimini, and Weber) introduces a term that details a continually fluctuating field whose effect is to cause superpositions to quickly evolve into mixtures such that the collapse of the wave function is physical, as described by an added term as an alternative to the SE. Wigner proposed that measurement occurs and the wave function collapses when a person becomes aware of the state of the experimental apparatus, so human consciousness is what causes the collapse. Penrose claimed that gravity causes the wave function to collapse, and Bohm argued that there is no need for collapse because determinism is restored through a nonlocal hidden-variable theory.^{33, 34} Unfortunately for quantum physics, none of these theories have provided a completely sufficient or convincing account of how to reconcile the interpretational issues raised by the measurement problem.

The two interpretations that I will be focusing on are those proposed by Niels Bohr and Hugh Everett. Bohr's position, as interpreted by Karen Barad, is that the measurement problem is explained through entanglements and agential separability, not physical collapse, thereby rejecting many of the metaphysical assumptions on which classical physics is based, including an observation-independent reality and

³¹ Ibid., 237.

³² Barad, *Meeting the Universe Halfway*, 287.

³³ Ibid., 287.

³⁴ Greenstein and Zajonc, *The Quantum Challenge*, 242.

pre-existing distinctions between entities.^{35, 36} In his many-worlds interpretation, as popularized by Bryce DeWitt, Everett argued that the wave function doesn't collapse and the entanglement of the system and observer is never resolved, and this is because each measurement increases the number of branches that the system and observer simultaneously maintain, each branch representing an alternative state of affairs for the universe, all of which are simultaneously real.^{37, 38} Historically, Bohr and Everett were seen as butting heads regarding their respective interpretations of quantum mechanics, but I maintain that their views are not as incompatible as commonly thought. Ultimately, I will argue that Bohr's theory, as interpreted by Barad, lays down the metaphysical framework for the most consistent understanding of Everett's many-worlds theory, which, I claim, is the most compelling way to understand the nature of the universe.

³⁵ Barad, *Meeting the Universe Halfway*, 129.

³⁶ *Ibid.*, 346.

³⁷ Greenstein and Zajonc, *The Quantum Challenge*, 242.

³⁸ Barad, *Meeting the Universe Halfway*, 287.

ONE: BOHR'S PHILOSOPHY-PHYSICS

"There is no quantum world. There is only an abstract quantum-physical description. It is wrong to think that the task of physics is to find out how nature is. Physics concerns what we can say about nature (...) What is it that we humans depend on? We depend on our words. Our task is to communicate experience and ideas to others. We are suspended in language.

–Bohr, *Philosophy of Science*³⁹

Bohr's interpretation of quantum theory undermines representationalism, which is the basis for more familiar, conventional forms of realism and antirealism, but Bohr himself can be understood as a realist, albeit an unconventional one. While most commonly portrayed as a positivist, this isn't consistent with either his philosophical perspective or the way he practiced science. Bohr himself claims that the core problem with quantum theory is that it reveals an "essential failure of representationalism," because representationalism places us outside of the world, allowing us only to reflect on it, instead of situating us within the nature we're trying to understand. His commitment to realism brought him to adopt an antirepresentationalist method for understanding the nature and role of concepts. Historical evidence shows that it was Bohr's dedication to certain realist principles that led to his analysis of quantum mechanics, or else, like Heisenberg, he would have been content to let mathematical formalism bear the brunt of quantum paradoxes. Bohr wanted to understand what science could tell us about the universe and our relationship to it rather than being satisfied with mere agreement between data and calculations. When he realized that measurement interactions are indeterminate, he

³⁹ Attributed to Bohr in *Philosophy of Science*, Vol. 37 (1934), 157.

stated that this indeterminacy necessitated "a final renunciation of the classical idea of causality and a radical revision of our attitude towards the problem of physical reality."^{40, 41}

One of the most integral aspects of Bohr's interpretation of quantum mechanics is his rejection of the two fundamental assumptions that otherwise support the Newtonian notion of measurement as transparent: 1) that the world is made of individual objects with individually determinate boundaries and properties with defined values that can be understood through the use of abstract concepts with unambiguous meanings that are independent of the specific experimental situation in question, and 2) that measurements involve continuous⁴² and determinable interactions that allow us to obtain values of the properties in question which can then be assigned to the pre-measurement properties of the objects in question, which are separate from the agencies of observation. These assumptions involve belief in representationalism (the independently determinate existence of things), belief in the metaphysics of individualism (that that world is composed of individual entities with individually determinate properties and boundaries), belief in there being an intrinsic separation between the knower and known (that measurements show a distinction between the measuring agent and the pre-existing properties and values of independently existing objects), and belief in the strict determinism that describes Newtonian physics (that the past, present, and future states of any entity should be entirely predictable).⁴³

⁴⁰ Barad, *Meeting the Universe Halfway*, 123-133.

⁴¹ From Bohr, "Essays, 1933-1957," quoted in Barad, *Meeting the Universe Halfway*, 126.

⁴² (as opposed to quantized)

⁴³ Barad, *Meeting the Universe Halfway*, 107.

Bohr's criticism of measurement transparency rests on two points. The first is that measurement interactions are discontinuous. This discontinuity, called "essential discontinuity," is an empirical fact discovered at the beginning of the 20th c. that disproves the classical assumption that measurement interactions are continuous. It was introduced in 1900 by Max Planck to account for data on blackbody radiation that couldn't be accounted for by classical physics. Planck's constant (h) tells us that energy is quantized and exchanged in discrete amounts, and Newtonian physics fails to account for this. Even though the constant is small, the fact that $h \neq 0$ tells us that there is a fundamental discontinuity in nature. It's important to keep in mind that just because Planck's constant is small relative to the mass of large objects doesn't mean that Bohr's insights regarding Planck's constant apply only to microscopic objects; the crucial point is the existence of essential discontinuity, not its size. The significance of essential discontinuity is that it places a lower limit on how small a disturbance made by measurement can be. Newtonian physics now has to reconcile this with its previous assumption that measurement interactions can always be reduced to a negligible amount, because if they can't be reduced to a negligible amount, it becomes necessary for the effects of measurement interactions to be determined. Unfortunately for Newtonian physics, Bohr claims there is no such simple fix as determining the effects of measurement interactions. He argues that it's impossible to determine the effects of a measurement interaction and have the measurement still function as designed; because a measuring apparatus cannot be both object and observer, there can be no measurement transparency.⁴⁴

⁴⁴ Ibid., 108-110.

The second point, which is alluded to in the previous paragraph, is that measurement interactions are indeterminate. Bohr's account for this is based on his belief that "concepts are defined by the circumstances required for their measurement."⁴⁵ In other words, concepts are given meaning by specific, physical arrangements. Measurement (physical) and description (conceptual) entail each other because, epistemologically, they mutually imply one another. For example, the concept of position must be semantically determinate, or meaningfully defined, such that the detection device is fixed relative to the frame of reference because if it were allowed to move, the measurement of the particle's position would be indeterminate. This is just like what happens when you take a picture with the shutter open while the camera moves, resulting in a blurry photo where you can't obtain information about the position of anything in the frame. On the other hand, to measure momentum, the detection apparatus must be movable because it's only by measuring its disturbance that we can obtain momentum information, or else momentum will be absorbed and its value will be indeterminate. Therefore, position and momentum are not simultaneously determinate because they require mutually exclusive experimental configurations. We can't determine the effect of a photon on a particle because this would require a determinate value of the photon's position and momentum simultaneously: observation is only possible if the effect of the measurement is indeterminate, meaning that we can't subtract the effect of measurement to calculate

⁴⁵ Ibid., 109.

the properties the particle in question is presumed to have had prior to the measurement.⁴⁶

This also means that, because observations involve an indeterminable, discontinuous interaction, there's no unambiguous way to differentiate between the object and observer. Because we can't find the effect of measurement, we can't subtract it from the experiment to find the properties that a particle was presumed to have before the measurement. Put another way, we can accurately measure position, but we can't attribute a value obtained for position to some measurement-independent object because the value obtained for position is dependent on our measurement. Without there being a specific physical arrangement of the experimental apparatus, the distinction between the object of observation and agencies of observation is indeterminate: there does not exist an inherent distinction between object and observer. The experimental apparatus is what provides this distinction, and it follows that observations don't refer to properties of observation-independent objects because nothing pre-exists as an object of observation. Although no inherent distinction exists, every measurement involves a choice of apparatus configuration, and this gives meaning to a particular set of variables by delineating between object and observer.⁴⁷ Bohr's interpretation thus involves "quantum wholeness," or lack of an inherent distinction between object and observer, and he uses the term "phenomenon" to identify instances of wholeness. An apparatus must be introduced in order to

⁴⁶ Ibid., 108-113.

⁴⁷ Ibid., 114-115.

distinguish between object and observer, but then the apparatus itself becomes part of what's being described.⁴⁸

Bohr claims that quantum mechanical measurements are objective in the sense that results are reproducible and unambiguously communicable, which stands in contrast to any Newtonian account where objectivity denotes pre-existence and observation independence.⁴⁹ Bohr's analysis accordingly entails the physical apparatus as being responsible for the subject-object distinction such that concepts have meaning only in relation to a particular physical arrangement. Objectivity therefore depends on the physical apparatus delineating between the object and agencies of observation because the bodies involved in the experiment are what define the experimental conditions, giving the foundation for objectivity in the first place. Therefore, Bohr is reconceptualizing referentiality, where the referent is a phenomenon, not an observation-independent object. His account puts forward a new interpretive framework where measurement processes are part of and cannot be independent of the results obtained.⁵⁰

To fully understand quantum phenomena requires the use of two mutually exclusive concepts, whereas classical physics allows us to unify them, and Bohr identified this "doubleness" as complementarity. Complementarity can refer to the way we understand physical reality (e.g. Bohr would say that the particle nature of an object is complementary to its wave nature), what quantum mechanics allows us to know (e.g. position is complementary to momentum because we can't know both

⁴⁸ Ibid., 118-119.

⁴⁹ Ibid., 128.

⁵⁰ Ibid., 120-121.

accurately and precisely), and what an experiment can reveal (e.g. no experiment can allow us to know two complementary properties at the same time). Bohr didn't see dualistic aspects of quantum mechanics as contradictory, but rather, as interdependent, and it's only taken together that we can fully understand quantum phenomena. Although we need to put our understanding of quantum behavior in terms of concepts and language drawn from the world that we directly perceive, our classical understanding alone is not sufficient. The principle of complementarity means that, contrary to what classical physics would have us believe, we can never know everything about the world: we can only know half of everything.⁵¹

Bohr came up with his theory of complementarity at the same time as Heisenberg came up with his uncertainty principle, although these two views of the nature and implications of the measurement process are fundamentally different and even incompatible.⁵² Heisenberg's uncertainty principle is based on the notion of disturbance, and he pointed out that there are two critical limits to measurement: 1) while classical physics tells us that we can make the disturbance that arises as a result of measurement as small as we want, quantum mechanics, because of Planck's constant, tells us we can't, and 2) this disturbance is uncontrollable and unpredictable, reflecting the deeply probabilistic nature of quantum mechanics and explaining why we can't correct for the disturbance.⁵³ Heisenberg's famous "uncertainty microscope" thought experiment demonstrated his focus on the discontinuous change in an electron's momentum, where the electron is disturbed by the photon in the

⁵¹ Greenstein and Zajonc, *The Quantum Challenge*, 91-95.

⁵² Barad, *Meeting the Universe Halfway*, 115.

⁵³ Greenstein and Zajonc, *The Quantum Challenge*, 47.

measurement attempt to find its position. An incident light ray is scattered by the particle into a lens, which subsequently focuses the light toward the observer; when we try to observe the particle positions, we change their momentum, and when we try to observe the particle momentum, we change their positions. The goal is to reduce the product of the change in momentum and change in position to accurately determine both at the same time.^{54,55}

In classical physics, we can reduce this product by choosing either a short wavelength light or low momentum light. By using light of arbitrarily short wavelength and arbitrarily low intensity, we can make the product of position and momentum uncertainties as small as we'd like because classical physics gives us no fundamental lower limit to the product of these uncertainties. Quantum mechanics, on the other hand, maintains that uncertainties can never be reduced below a fundamental lower limit. The classical analysis is only valid until the scale of the light's interaction with matter becomes important, which it is at the quantum level, because the degree of accuracy required is below the fundamental limit given by quantum mechanics. Nothing prevents us from measuring the particle's position more and more precisely, but as we do this, the momentum measurement will become less and less accurate (and vice versa): there appears to be an unavoidable trade-off.⁵⁶ This led Heisenberg to believe that the uncertainty principle is an epistemic principle in that it provides us with evidence that there's a limit to what we can know.⁵⁷

⁵⁴ Barad, *Meeting the Universe Halfway*, 116.

⁵⁵ Greenstein and Zajonc, *The Quantum Challenge*, 47-49.

⁵⁶ *Ibid.*, 49-50.

⁵⁷ Barad, *Meeting the Universe Halfway*, 116.

Classical physics posits an objectively real universe with objectively real properties⁵⁸ all in agreement with the laws of nature such that the world is completely knowable and evolves according to these laws. Heisenberg's uncertainty principle places restrictions on our knowledge of the world so that we can't give a complete description of it but still allows for the assumption that determinate values of an entity's properties exist independently of measurement. We simply can't have knowledge of this because of the inevitable disturbance that the measurement interaction causes. Understood this way, Heisenberg's uncertainty principle assumes classical ignorance, or being unsure about a state of affairs. For example, we're in a state of classical ignorance when we don't know today's date. We may not know the facts, but we're sure that the facts exist; the world has a well-defined state although we don't happen to know what that is. In other words, uncertainty arises because, although the quantum world has a well-defined state, we can't know it. Bohr's complementary, on the other hand, assumes ontological, rather than epistemic, quantum uncertainty, or that the world doesn't have a definite classical state. In this case, uncertainty arises not from any limit on our capacities for obtaining knowledge about the world but because the quantum world doesn't have a well-defined state.⁵⁹

Bohr pointed out the flaws in Heisenberg's interpretation, to which Heisenberg agreed and added a postscript saying, "Bohr has brought to my attention that I have overlooked essential points in the course of several discussions in this paper,"⁶⁰ but most people are unaware that this postscript exists and that Bohr introduced his own

⁵⁸ "Objective" in this sense being of the conventional usage

⁵⁹ Greenstein and Zajonc, *The Quantum Challenge*, 52-55.

⁶⁰ Quote attributed to Heisenberg in Barad, *Meeting the Universe Halfway*, 115-116.

interpretation that can be contrasted with Heisenberg's uncertainty principle. Ironically, the uncertainty principle is what is conventionally taught and used even though Heisenberg himself admitted that it was based on a fundamental error.^{61, 62} Instead of uncertainty, Bohr's complementarity involves an indeterminacy principle, where the problem isn't that there are things we can't know but instead there are things that can't be said to exist simultaneously. For Bohr, the real problem is semantic and ontic, not epistemic: we can't know something definite about something for which there's nothing definite to know. The two main takeaways are: 1) concepts are only meaningful relative to their physical manifestation, so we can't attribute an independent, physical reality to properties or objects because their reality is dependent on the way we measure them,^{63, 64} and 2) this leads to problems for classical assumptions because variables we presume to be classically objective together require incompatible experimental configurations for their measurement, because measurements can be made on only one side of any pair of complementary variables and simultaneous measurements of both variables is impossible.⁶⁵

In 1935, Albert Einstein, Boris Podolsky, and Nathan Rosen (EPR) wrote a paper in which they attacked quantum theory, claiming that it's incomplete because it is possible to make simultaneous measurements of a pair of complementary variables. They proposed that there exists a way to obtain a more complete description of physical reality than quantum mechanics allows, and this is known as the EPR

⁶¹ Barad, *Meeting the Universe Halfway*, 115-116.

⁶² *Ibid.*, 301.

⁶³ *Ibid.*, 117-118.

⁶⁴ *Ibid.*, 300.

⁶⁵ Greenstein and Zajonc, *The Quantum Challenge*, 125-126.

argument, or the EPR paradox.^{66, 67} It wasn't until about 30 years after it was written that Bell's theorem proved it was possible to design an experiment to decisively test whether the EPR argument was correct. In the mid-1960s, John Bell published two theorems that showed there is a connection between the context of observation and the observed characteristics of the quantum world, the result of which was proof that quantum mechanics is correct and the EPR argument relied on faulty assumptions. The EPR paper claimed to show how to measure any pair of complementary variables, and Bell's theorem addresses a particular version of the EPR paradox that was developed by David Bohm.⁶⁸

A particle's spin is usually measured using a Stern-Gerlach (SG) analyzer, which only measures one component of spin at a time (the component along the analyzer's vertical axis). Additionally, the operators for the x- and z-components of spin aren't commutative, so the measurements of spin of these components obey an uncertainty relation. Therefore, no apparatus could measure all three components at once. The EPR argument claims that there does exist a device that could measure to an arbitrarily high degree of accuracy all three components, and it would contain three parts. The first part is a device that shoots out two particles in opposite directions, polarized with their spins pointing in opposite directions. The other two parts are SG analyzers, which measure the component of particle spin along a certain axis: one particle is sent toward the first analyzer and the other toward the second, and they're at widely separated places in space (locations A and B). (This wide

⁶⁶ Ibid., 126.

⁶⁷ Barad, *Meeting the Universe Halfway*, 269.

⁶⁸ Greenstein and Zajonc, *The Quantum Challenge*, 125-127.

separation is important because it means that whatever happens at one location has no causal effect on what happens at the other location.) At each location (A and B) the analyzers can be oriented in any direction. When the experiment begins, the emitter sends a pair of particles toward the two analyzers, and when the particle enters the analyzer, it will be measured as having either "spin up" or "spin down."

Measurements on the pair of particles will always have opposite results, so if location A reads its particle as having "spin up," it also knows that location B's particle has "spin down." EPR concluded that the particle at location B must have had spin down even before the measurement at location A was made. Observation at A was required in order to learn the spin at B, but it couldn't have affected the spin; observation at A is only necessary to find out about a pre-existing state of affairs, and no matter the orientation of the analyzer, the same argument can be made. In other words, if A orients the analyzer along the z-axis and B orients the analyzer along the x-axis, A can infer the spin along z of B's particle and B can directly measure the spin of its particle along x, so definite conclusions can be drawn about two complementary variables. Both of the complementary variables exist and have definite values, which is a claim in opposition to the principles of quantum mechanics.⁶⁹

The basic argument requires us to think about two independent systems, particle A and particle B, which interact with each other over some finite length of time, during which the states of these systems become correlated with one another. EPR use this correlation to claim that they can obtain information about the properties of one system, B, by performing measurements on the other system, A. The key to

⁶⁹ Ibid., 129-130.

this is that all measurements performed on A happen after A and B have finished interacting with each other, which EPR believed to mean that nothing done to A will affect anything in B. The heart of their argument thus lies in the "entangled state" correlation between A and B, where entangled states are a special kind of quantum mechanical correlation, or quantum entanglement. Quantum entanglements are unique to quantum mechanics and describe a feature of particle behavior for which there is no classical counterpart. An entanglement can be thought of as a generalization of a superposition to the case of more than one particle.⁷⁰

For an example, we can think of a particle with two possible spin eigenstates, "up" or "down." Particles A and B can be represented by $(\uparrow)_A$ or $(\downarrow)_A$, and $(\uparrow)_B$ or $(\downarrow)_B$, and an entangled state of systems A and B can be represented by $\Psi = c_1 (\uparrow)_A (\downarrow)_B + c_2 (\downarrow)_A (\uparrow)_B$ where c_1 and c_2 are complex numbers. This means that when A's state is measured and the eigenvalue is "up," B's state is measured to have the eigenvalue of "down," and vice versa, because the states of systems A and B are oppositely correlated. The entangled state of systems A and B cannot be understood as a composite system, or a mixture, made up of two independent components; the entangled state of systems A and B must be understood as a single entity. This understanding of quantum entanglements took decades to develop and most of the research was done after Einstein's death, so EPR thought Newtonian metaphysics was the only way to understand correlations, leading them to assume locality, which is the idea that anything that happens at a certain location only has local effects and nothing that happens at A can have any effect on what happens at B. Without the locality

⁷⁰ Barad, *The Quantum Challenge*, 269-270.

assumption, we can imagine that the measurement made at A could have affected the state of the particle at location B and the spin of the particle heading toward location B may not exist independently of the measurement made at location A.⁷¹

Heisenberg's uncertainty microscope thought experiment shows that we always disturb an object when we observe it, so EPR got around this by never directly observing particle B and instead observed it indirectly by making measurements on the other particle of the pair, A. Locality justifies this through the assumption that any measurement made on A can't affect B, so properties of B can be inferred through measurements on A without disturbing B.⁷² The only thing that changes regarding B through observation of A is our knowledge of real, pre-existing properties. EPR argued that if the spin of A is measured along some axis, say the z-direction, and is found to be "up," then by performing measurements only on A and in no way disturbing B, we could know with certainty that B's spin is "down," and vice versa, allowing us to obtain information about one component, the z-component, of B's spin without having disturbed it.⁷³ Then, because there's a special state, called a singlet state, where spin components are always oppositely correlated no matter the axis of rotation, we can repeat this process but this time determining the spin of B in another direction by performing an experiment on A. Singlet entangled states allow us to obtain this kind of information because B's spin value will always be oppositely correlated with A's, no matter the axis of rotation chosen, even though the systems are

⁷¹ Ibid., 270-271.

⁷² Ibid., 270.

⁷³ Greenstein and Zajonc, *The Quantum Challenge*, 131.

no longer interacting. In other words, measuring the spin of system A instantaneously determines the spin of system B along the axis in question.⁷⁴

EPR argue that because we can determine the spin value of B along any axis without directly measuring it, B must have always had these properties because the only other explanation is an instantaneous, faster than light communication, which violates the theory of special relativity, thus implying that there is a real, pre-existing reality and quantum mechanics is incomplete. EPR wrote that "if, without in any way disturbing a 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 quantity,"⁷⁵ but Bohr rejects this definition of physical reality, thinking instead that it's related to and connected with phenomena.^{76, 77, 78}

Bohr believed measurement interactions show that the indeterminable discontinuity subverts the classical assumptions that there exists an inherent distinction between subject and object and that objects have an existence independent of the determinability conditions set by the experimental apparatus. Bohr's complementarity isn't just about what we can know (epistemic) but also what we mean (semantic) and what actually exists (ontic). In claiming that this indeterminacy is ontic rather than merely epistemic involves rejecting the Newtonian metaphysical assumption that there exist determinate objects with determinate properties that correspond to determinate concepts with determinate meanings, which are

⁷⁴ Barad, *Meeting the Universe Halfway*, 272.

⁷⁵ A. Einstein, B. Podolsky, and N. Rosen, "Can Quantum-Mechanical Description of Reality Be Considered Complete?" *Physical Review* 47, no. 10 (1935): 777.

⁷⁶ Greenstein and Zajonc, *The Quantum Challenge*, 131.

⁷⁷ Barad, *Meeting the Universe Halfway*, 273-274.

⁷⁸ *Ibid.*, 126.

independent of the conditions needed to resolve the inherent indeterminacies. The specific measuring apparatus is the necessary condition required to resolve the inherent indeterminacies, so measuring devices are what provide the conditions for determining boundaries and properties of objects within phenomena. Therefore, measurements don't imply an interaction between distinct entities; distinct entities emerge from the interaction. (The word "interaction" relies on the metaphysical assumption of individualism, so it's important to keep in mind that Bohr thought of entities as ontologically inseparable, and I will borrow Barad's term, "intra-action," to represent the conceptual shift necessary to better understand Bohr's perspective.) Objects and measuring devices emerge from, rather than precede, the intra-action that produces them, and phenomena are specific intra-actions rather than objects in themselves.⁷⁹ Ontological indeterminacy is only resolved through particular physical arrangements, and when the arrangement is changed, the ontological determinacy and future behavior of the system changes with it. Physical reality can therefore only be meaningfully understood when put in the context of a phenomenon, which includes the entire experimental configuration.⁸⁰

Put more concisely, Bohr's rejection of the EPR paradox rests on two points: 1) the notion of physical reality used by EPR is ambiguous because the boundaries between observed and observer aren't determined without a given experimental configuration, and 2) because EPR use different experimental configurations to measure complementary spin values, there is ambiguity inherent in their

⁷⁹ Ibid., 127-128.

⁸⁰ Ibid., 274-275.

appropriation of physical reality.⁸¹ In the 1950s, the Aspect experiments⁸² confirmed Bohr's rejection of the EPR understanding of physical reality. These experiments involved the entangled states of photons produced by atomic cascades, which are themselves created by the transitions between states in atomic calcium. If we excite the calcium atom, as it comes back down to its ground state, two photons are emitted in the process in an entangled state, meaning their histories are intertwined and measurements on one photon affect the other. Using time-varying analyzers, Aspect, Dilibard, and Roger performed an experiment that would allow them to change the experimental configuration more quickly than the time it would take light to travel from one end of the apparatus to the other, assuming the principle of relativity to be true meaning that the signal between intertwined particles can't travel faster than light. The results showed that it's no longer sufficient to think of the world as EPR wanted, and instead, we must think either in terms of nonlocality or, as Bohr advocated, reject the notion that individual objects have discrete attributes.⁸³

A more concrete example of Bohr's claim that quantum mechanics tells us that properties and boundaries are only determinate if the appropriate conditions for measurement are present involves measuring spin where the values obtained are either "up" (Ψ_u) or "down" (Ψ_d). The following are four experiments that illustrate how Bohr's indeterminacy principle, and the elements of his interpretation that follow, present a more accurate, consistent understanding of quantum mechanics than does Heisenberg's uncertainty principle. (1) If we send a beam of particles

⁸¹ Ibid., 275.

⁸² Alain Aspect et al. performed three Bell tests using calcium cascade sources.

⁸³ Greenstein and Zajonc, *The Quantum Challenge*, 151-162.

represented by the superposition $\Psi = (\sqrt{1/2})\Psi_u + (\sqrt{1/2})\Psi_d$ into the SG_z device (measuring spin along the z-axis), then 1/2 of the particles will come out of the top slit and the other 1/2 through the bottom. So, if we send 200 particles through the SG_z device, 100 particles will have eigenvalue up in the z-direction and 100 particles will have eigenvalue down in the z-direction. If we then block the lower beam of the SG_z device and send the top beam into a second SG_z device, all particles that come out of the top slit of the first SG_z continue into the second SG_z and come out of the top slit, meaning that all of these particles have measured eigenvalues up in the z-direction.⁸⁴

(2) If we replace this second SG_z device with an SG_x device with 200 particles represented by the same superposition, then sending them through the SG_z device with the lower beam still blocked results in 100 particles coming out of the top slit with eigenvalue up in the z-direction, and their subsequent entry into the SG_x device results in 50 particles coming out of the top slit with eigenvalue up and 50 particles with eigenvalue down in the x-direction. This indicates that the particles coming out of the top slit of the SG_x device have Ψ_u in both the z- and x-directions and the particles coming out of the bottom slit of the SG_x device have Ψ_u in the z-direction and Ψ_d in the x-direction, which is consistent with the assumption that a superposition represents a mixture of particles with different spins and the device merely sorts them.⁸⁵

(3) If we add a third SG_z device to the previous experiment, the assumption would be that this is superfluous because we've already measured spin in the z-direction. However, performing the experiment shows that 1/2 of the particles, or 25

⁸⁴ Barad, *Meeting the Universe Halfway*, 258.

⁸⁵ *Ibid.*, 260.

particles, come out of the top slit of the last SG_z device and another 1/2, or 25 particles, come out of the bottom slit. These results make it look like the middle SG_x device has done something to muddle the second SG_z measurement, as if the measurement of spin value in the x-direction has disturbed the spin value in the z-direction, and this is a consequence of the uncertainty and indeterminacy principles for spin components. Heisenberg believed that this happens because the various spin components are not simultaneously knowable; measurements disturb existing values, putting a limit on what we can know. He claims that a precise measurement of spin value of the x-component disturbs the particle, changing the previously measured spin value in the z-direction. This is in agreement with the Newtonian view of metaphysics where individual objects have individually determinate properties and measurements simply show us these pre-existing values. Bohr, on the other hand, states that this happens because the various spin components are not simultaneously determinable. Properties are only determinate relative to specific material arrangements that give definition to the concept in question, and when these conditions aren't given, the corresponding properties don't have determinate values; one set of properties being determinate prohibits a complementary set of properties from being simultaneously determinate. When the first SG_z device is in place, Ψ_z is determinate, but when the SG_x device is in place for the second measurement, the spin value of the x-component becomes determinate and the z-component loses its determinacy. This explains why when Ψ_z is measured again after the second SG_z device is put in place for the third measurement, particles come out of both the bottom and top slits: the middle measurement of Ψ_x plays an important role because once the x-component is

measured, the z-component is no longer determinate. Then, when the last SG_z device is put in place, the z-component becomes determinate again, but it had previously been indeterminate, so there should be an equal number of up eigenvalues as down, based on the superposition we've been using to represent the particles. However, the results are also compatible with Heisenberg's uncertainty principle, and it's the fourth experiment where Bohr's interpretation succeeds while Heisenberg's can't explain the results.⁸⁶

(4) If we modify the SG_x device such that the up and down beams can recombine before entering the second SG_z device, then the configuration is essentially the same as the third experiment but now neither path is blocked before the particles exit the modified SG_x and enter the second SG_z . The weird thing is that all of the particles still exit from the top slit of the last SG_z device, as in the first experiment, as if the modified SG_x device weren't there. It appears as if the beam recombination has exactly undone the disturbance, meaning that the problem doesn't have to do with disturbance but with something else related to measurement. To reiterate Bohr's view, quantum mechanics tells us that quantities are only determinate if the appropriate conditions for measurement are present. So, if there is no device in place for measuring the z-component of spin, then the value of the corresponding property won't be determinate. In other words, if an SG_z device is configured, it's the specific material arrangement of this device that creates a distinction between the object of observation and agencies of observation so that the boundaries and properties being examined will become determinate. Without this, the concept of spin in the z-

⁸⁶ Ibid., 261-264.

direction is meaningless and there are no determined boundaries or properties of the object. Bohr's account explains the results of this fourth experiment: the device isn't configured to measure the spin value of the x-component and so remains indeterminate while the z-component is determinate. The determinate spin value of the z-component measured with an SG_z device results from the intra-action of the particle with the device, or, the property "spin" is a characteristic of the phenomenon instead of some pre-existing, measurement-independent object.⁸⁷

The results of these experiments are compatible with Bohr's notion that it's specific material configuration that gives the property in question meaning by creating a distinction between the object measured and the measuring device, thereby allowing us to obtain determinate values for corresponding measured quantities and prohibiting us from obtaining determinate values for complementary quantities. By measuring some property, we always find one of the permissible eigenvalues, meaning each particle is "in" one of the permissible eigenstates. This is also congruous with Bohr's notion of objectivity, which states that even though measurements don't reveal pre-existing values, these values are consistent and reproducible. Furthermore, this provides evidence that superpositions represent ontologically indeterminate states, not mixtures of particles with determinate properties.⁸⁸

It's important to note the interpretational significance of the physical difference between superpositions and mixtures. A mixture is a collection of particles, each with a determinate value of the property in question so that the state of any given

⁸⁷ Ibid., 262-263.

⁸⁸ Ibid., 264-265.

particle is determinate but unknown. Mixtures are usually described statistically, but the use of probabilities is not out of quantum indeterminacy but because the value of a property for some particle is unknown.⁸⁹ Instead, measurements are related to classical ignorance in that they describe a state of affairs whose nature we're unsure of although we know that the state of affairs has a definite value.⁹⁰ Superpositions embody quantum indeterminacy, where values themselves are indeterminate before measured. They're also described statistically, but this use of probabilities comes from the nature of quantum phenomena, not our ignorance about some state of affairs. A crucial fact about superpositions and mixtures is that they're physically distinguishable: superpositions allow for interference effects while mixtures don't. This point is especially important in relation to Einstein's thought experiment in which a double-slit apparatus, consisting of a particle-emitting source and a detecting screen, would have a movable diaphragm with two slits in order to obtain which-path information, or information about which slit a particle had passed through. In his unrelenting quest to prove that quantum mechanics was incomplete, Einstein thought he could measure the transfer of momentum between the particle and movable diaphragm, or the disturbance the particle experiences as a result of the which-path measurement, to obtain both its momentum and position. Bohr pointed out that this movable diaphragm configuration would destroy the interference pattern because of the necessary trade-off between which-path information, exemplifying particle behavior, and interference, exemplifying wave behavior. His main point was that if we introduce an element into the apparatus that requires the presumption of particle

⁸⁹ Ibid., 265.

⁹⁰ Greenstein and Zajonc, *The Quantum Challenge*, 188.

behavior, then we will find particle behavior and no wave-behavioral interference pattern.⁹¹

If we had a double-slit apparatus that could give us which-path information, we would label each particle depending on whether it goes through the top (Ψ_t) or bottom (Ψ_b) slit. This would give us a mixture of particles, some represented by the wave function $\Psi = \Psi_t$ and others by the wave function $\Psi = \Psi_b$, and the distribution pattern found on the detecting screen would be the sum of the individual distribution patterns, one for particles passing through the top slit and one for particles passing through the bottom slit. Most importantly, there would be no superposition and no interference pattern. If we had a double-slit apparatus that doesn't give us which-path information, no determinate slit value would exist and the wave function would be a superposition of the two eigenstates, $\Psi = a\Psi_t + b\Psi_b$ where a and b are nonzero. Here, the which-path information is not just unknown: it's ontologically indeterminate because there's no fact of the matter about which slit a particle passes through, and the distribution pattern found on the detecting screen would form an interference pattern.⁹² The point is that superpositions exhibit interference patterns while mixtures don't, and an interference pattern is the indicator of a superposition: superpositions are a fundamental feature of quantum mechanics and mark quantum behavior.^{93, 94}

In 1936, Bohr replied to Einstein's double-slit thought experiment by arguing that there's a complementary relationship between using an experimental configuration that can determine which-path information and the existence of an

⁹¹ Barad, *Meeting the Universe Halfway*, 265-267.

⁹² *Ibid.*, 268.

⁹³ *Ibid.*, 269.

⁹⁴ Greenstein and Zajonc. *The Quantum Challenge*, 188.

interference pattern on the detecting screen, and a debate ensued between Bohr and Einstein about whether it was possible to garner which-path information without disturbing the interference pattern. As it turns out, there is a trade-off between obtaining which-path information and an interference pattern. In 1979, Wootters and Zurek looked at the possibility of acquiring which-path information only partially rather than with certainty and the effect this had on the interference pattern. The findings were that if which-path information is completely determined there's no interference pattern, and if which-path information is completely undetermined there is an interference pattern. There also exists a continuum between these two extremes where intermediate particle-wave behavior is observed, like a partial smudging of the interference pattern. This is in line with Bohr's principle of complementarity: there is a necessary trade-off between definition of the interference pattern and determining which-path information. In other words, the more matter behaves like a particle, the less it behaves like a wave, and vice versa. Wootters and Zurek actually confirm Bohr's point that the concepts "wave" and "particle" aren't simultaneously determinate by showing that one can, to a degree, simultaneously determine two complementary properties, but one cannot determine them both sharply. Furthermore, all that's necessary to interrupt the interference pattern is the possibility of obtaining which-path information, or that two possible particle paths have become distinguishable. What's at issue is possibilities of definition of variables in question, not disturbance. It doesn't matter whether the which-path measurement is made, because all that matters is that it could have been made, and this possibility for distinguishing the photon's path is enough for the interference pattern to disappear. The key point is that

contextuality, the conditions of possibility of definition rather than the actual measurement of definition itself, matters.⁹⁵

Bohr is most fundamentally rejecting the metaphysical foundations of Newtonian physics that presume individually determinate entities with inherent properties, instead claiming that entities don't have inherently determinate boundaries or properties and words don't have inherently determinate meanings. Bohr questions the notion of an inherent subject-object distinction by challenging Newtonian metaphysics and epistemology. He claims that theoretical concepts like position, momentum, and spin are not abstract ideas but are directly related to specific physical arrangements; phenomena make up physical reality in that they're relations without pre-existing relata, and the intra-action that occurs between (or within) entities requires us to engage in a conceptual shift where we no longer presuppose the pre-existence of independent relata. Intra-action is what marks the determinate boundaries and properties of the parts that make up the phenomenon and is what gives particular concepts meaning. It includes the entire system, which contains "subject" and "object," between which there is an agential cut rather than an "interaction" that presupposes this distinction. An agential cut provides the distinction between subject and object but only within a particular phenomenon, and the relata that we perceive to exist within phenomena come about through specific intra-actions. Intra-action also restructures causal relationships by enacting the measuring agencies as effect and the measured object as cause. Measurements, as causal intra-actions, therefore express particular facts about what is measured, and apparatuses aren't just measuring devices

⁹⁵ Barad, *Meeting the Universe Halfway*, 302-306.

but also draw distinctions.⁹⁶ Barad phrases this clearly when she writes, "Phenomena are constitutive of reality. Reality is composed not of things-in-themselves or things-behind-phenomena but of things-in-phenomena... It is through specific agential intra-actions that a differential sense of being is enacted in the ongoing ebb and flow of agency."⁹⁷ The primary ontological unit is not "things" but phenomena, and the primary semantic unit isn't "words" but materially-based intra-actions through which ontic and semantic boundaries are made determinate. Measuring apparatuses, therefore, play an active role in experimentation that classical physics doesn't acknowledge; they produce, and are part of, phenomena.⁹⁸

Bohr claims that an objective account of quantum phenomena must include a description of all relevant features of the experimental arrangement. To measure the relevant features, the experimental apparatus must be an object of observation and not an agency of observation, so it must be situated within and intra-acting with a larger phenomenon. An apparatus can't simultaneously be both the observer and observed, so to measure the apparatus's properties requires that it be situated within a larger apparatus so that it's no longer an agency of observation, and to measure the connection between these apparatuses would require a third, larger apparatus inside of which these first two are situated. Inside and outside boundaries aren't determinate until the apparatuses in question are involved in a larger phenomenon, so there are no intrinsic boundaries; "inside" and "outside" are inherently indeterminate. Bohr's logic

⁹⁶ Ibid., 137-140.

⁹⁷ Ibid., 140.

⁹⁸ Ibid., 141.

thus undermines the notion of the apparatus as unchanging and bounded and the human as the passive designer and collector of data.⁹⁹

A particularly appropriate example of this is the story of Otto Stern and Walther Gerlach performing an experiment to reveal traces of space quantization.¹⁰⁰ Gerlach initially didn't find the traces of space quantization his experiment was designed to reveal, but when Stern held the plates in his hands at a distance close enough to his breath so the plates could absorb the fumes from his cigar-ridden breath, the sulfur turned the faint, silver traces to jet black silver sulfide, which would have otherwise gone unnoticed: "My salary was too low to afford good cigars, so I smoked bad cigars. These had a lot of sulfur in them, so my breath on the plate turned the silver into silver sulfide, which is jet black, so easily visible."¹⁰¹ This kind of outside influence on the experimental apparatus is not one that could have been prevented through visual clues and clearly illustrates how the outside boundary of an apparatus can't be assumed visually. What was thought to be "outside" (the human experimenter) was actually the reason the result was noticed: a specific kind of cheap, sulfuric cigar was among the most important materials in the experiment's success. We also have to consider the material practices that contributed to all of the factors that resulted in the cigar's presence in this experiment, such as those that contributed to gendered individuals, men expressing masculinity through smoking cigars, Stern residing in a class that he expressed through smoking cheap cigars, etc. This goes to show that material practices are intra-acting, ongoing, and entangled.¹⁰² Spatiality and

⁹⁹ Ibid., 160-161.

¹⁰⁰ Ibid., 162-168.

¹⁰¹ Quote attributed to Stern in Barad, *Meeting the Universe Halfway*, 164.

¹⁰² Barad, *Meeting the Universe Halfway*, 162-167.

temporality need to be accounted for through intra-activity, because space and time are both intra-actively produced, not situated within the world. Further, matter itself is not fixed and needs to be accounted for through intra-activity.¹⁰³ Humans aren't fully bounded, pre-existing subjects but are intra-acting and co-constituting through the material practices in which we engage.¹⁰⁴ Barad pushes this further to claim that agency is thus no longer necessarily connected to humans or possibilities for human action; agency is a process of acting something out, not a property that something has.¹⁰⁵

All of this leads Bohr to the belief that measurements don't necessitate any physical collapse but just configuration-dependent distinctions between entities. Boundaries and properties are only determinate within a specific phenomenon through the enactment of a cut, which is determined by the materiality of the larger experimental configuration. If we were to look inside a phenomenon, we would see that the measuring instrument specifies a definite value that corresponds to an eigenvalue, and when we perform a measurement, this is essentially what we're doing. It isn't possible for us to have an external view of the phenomenon, which is necessary for us to observe the entanglement. We can never get outside of the phenomenon because we'd have to implement a further apparatus to measure the first phenomenon, but this just creates an extended entanglement of the first phenomenon and the new apparatus, creating a new phenomenon, and so on. Therefore, there is no collapse, or at least no physical mechanism, that resolves a superposition, and this

¹⁰³ Ibid., 177-183.

¹⁰⁴ Ibid., 162-168.

¹⁰⁵ Ibid., 168.

question is really about how to account for the measurement-dependent distinctions within phenomena. The measurement problem, for Bohr, is explained through entanglements and agential separability, not physical collapse.¹⁰⁶

Put differently, there is no measurement problem for Bohr because the problem is resolved by the difference between describing mixtures classically and superpositions quantum mechanically. The problem is that measuring instruments can't take themselves into account and therefore can't measure their own entanglement with the measured object. This means that the distinction we make between object and observer during measurement doesn't disentangle the phenomenon into its component parts, but it just allows for a description in terms of mixtures. The measurement-dependent distinction only gives a resolution of ontological inseparability within the phenomenon that is contingent on the apparatus's material configuration. It allows for a description in terms of mixtures, but only within the phenomenon in question, because really, there is only one entity, the phenomenon.¹⁰⁷ Bohr's interpretation doesn't allow for an exterior observational point because there is no such externality. We're part of the nature we're trying to understand, so we can't remove ourselves from it.^{108, 109} However, Bohr has a more humanist understanding of "we," and one of the major faults of his interpretation, in my opinion, that Everett's many-worlds interpretation and my subsequent expansion on the many-worlds interpretation tries to address, is his inability to relinquish this ingrained anthropocentrism.

¹⁰⁶ Ibid., 343-346.

¹⁰⁷ Ibid., 347-348.

¹⁰⁸ Ibid., 184.

¹⁰⁹ Ibid., 247.

TWO: EVERETT'S MANY-WORLDS INTERPRETATION

"It was Everett who gave us permission to think about the universe as wholly quantum mechanical."

–W. H. Zurek, 2006¹¹⁰

During his time as a PhD student at Princeton University, Hugh Everett, opposed the two leading orthodox interpretations of quantum mechanics: the von Neumann-Dirac collapse formulation and the Copenhagen interpretation, because they both encountered a quantum measurement problem. Collapse theory involves two laws, one saying that the state of a system evolves in a linear, deterministic fashion when no measurement occurs while the other says that the state of a system evolves in a random, nonlinear manner when measurement does occur, but nothing is said of what constitutes a measurement, so it's not clear when each law applies to the system in question. The measurement problem here arises out of the inconsistency between its two dynamical laws, and Everett noted that the theory itself is self-contradictory if we consider multiple observers and try to describe them quantum mechanically. The Copenhagen interpretation, as Everett understood it, claims to be consistent by not treating observers quantum mechanically at all. He agreed that this was consistent but also believed that the solution was arbitrary and meant that the classical behavior of macroscopic systems couldn't be explained through the quantum mechanical behavior of their microscopic parts. Everett thought that, because observers are made up of simpler systems that behave quantum mechanically, we should be able to explain the apparent classical behavior that emerges from

¹¹⁰ W. H. Zurek, tape recorded interview with Peter Byrne, April 2006.

macroscopic systems, like observers, quantum mechanically.¹¹¹ Although they do so in different ways, both of these interpretations assume that the rules of quantum mechanics break down into two parts: 1) the rules of unitary formalism, or the Schrödinger equation, that govern the evolution of the quantum state deterministically, causally, and linearly, and 2) the rules that govern the collapse of the wave function indeterministically, nonlinearly, stochastically, and provide no obvious way to empirically understand the collapse process. This dualistic assumption results in a tension between the two rules, and trying to understand state collapse and its relationship to the SE is the measurement problem of quantum mechanics.¹¹²

In the fall of 1954, Everett was working on his dissertation while taking one class, "Methods of Mathematical Physics," taught by Eugene Wigner, during which he ran into the mathematical contradiction between the continuous, linear evolution of the state of a quantum system as governed by the SE and the discontinuous, nonlinear collapse dynamics described by the measurement postulate of the standard collapse theory. Wigner questioned von Neumann's collapse postulate and Bohr's complementary principle of quantum mechanics. He then abandoned any realist approach to understanding quantum theory and instead posited a theory based on human consciousness. Everett rejected Wigner's human consciousness hypostatization but was inspired by the interpretational contradictions he pointed

¹¹¹ Jeffrey Alan Barrett and Peter Byrne, "Conceptual Introduction," in *The Everett Interpretation of Quantum Mechanics: Collected Works 1955-1980, with Commentary*, eds. Jeffrey Alan Barrett and Peter Byrne (Princeton: Princeton University Press, 2012), 26.

¹¹² Simon Saunders, "Many Worlds? An Introduction," in *Many Worlds? Everett, Quantum Theory, and Reality*, eds. Simon Saunders, Jonathan Barrett, Adrian Kent, and David Wallace (Oxford, England: Oxford University Press, 2010), 2-3.

out.^{113, 114} Everett thought he could come up with a way to describe determinate measurement records by taking account of how an observer becomes correlated with the system in question, evolving quantum mechanically in accordance only with standard linear dynamics. He proposed dropping collapse dynamics, instead accepting a pure wave mechanics in which every physical system, including observers, is treated in exactly the same quantum mechanical way.¹¹⁵ The claim was that collapse, a human-constructed illusion, merely reveals a change in dynamical influence, or decoherence, of one part of the wave function over another.¹¹⁶

Everett's idea for what is now famously known as the many-worlds theory¹¹⁷ was initially brought up as a joke at a cocktail party in response to the puzzle of how to understand what happens when the wave function "collapses" in Schrödinger's cat parable. He joked that perhaps the superposition of states is never resolved because the wave function never collapses. Eventually, he took this idea seriously and proposed it in 1955 while working on his PhD. His view claims that when an observer makes a measurement, the wave function does not collapse, and instead, the entire universe, including the observer, splits. All of the possible outcomes are equally likely and so equally real. In one branch of reality outcome A happens, while in

¹¹³ Barrett and Byrne, "Biographical Introduction," in *The Everett Interpretation*, 12.

¹¹⁴ Peter Byrne, *The Many Worlds of Hugh Everett III: Multiple Universes, Mutual Assured Destruction, and the Meltdown of a Nuclear Family* (New York: Oxford University Press, 2010), 81.

¹¹⁵ Barrett and Byrne, "Conceptual Introduction," in *The Everett Interpretation*, 26.

¹¹⁶ Saunders, "Many Worlds? An Introduction," in *Many Worlds?*, 4-5.

¹¹⁷ Everett's formulation of quantum mechanics wasn't labeled a "many-worlds" theory until the early 1970s when Bryce S. DeWitt, a supporter of Everett's, popularized his theory. In 1973, DeWitt and his student, Neill Graham, published *The Many-Worlds Interpretation of Quantum Mechanics*, and it is DeWitt's interpretation of Everett's theory that gained popularity. Everett advocated a relative states theory while DeWitt pushed a splitting-worlds interpretation, and it is the latter that is most commonly discussed today. Barrett and Byrne, "Biographical Introduction," in *The Everett Interpretation*, 20-23.

another branch of reality outcome B happens, and so on. Everett was able to express this through the mathematical formalism of quantum mechanics and show that his interpretation was identical in every testable way to the other leading interpretations.¹¹⁸

In the 1930s, John von Neumann wrote *Mathematical Foundations of Quantum Mechanics*, which was one of the authoritative texts on quantum well into the 1950s, claiming that the collapse postulate is a remedy for the measurement problem. This proposal, although challenged by theorists like Schrödinger and Bohm, was widely accepted until Everett came along, opening up the space for critics of von Neumann's theory to more assertively claim that there is a problem with his axioms, where axioms are unproven rules, or postulates, from which other rules can be derived. The first of von Neumann's axioms states that the SE describes each superposed constituent of a quantum system as changing continuously and deterministically over time as it evolves. The other axiom, known as the "collapse postulate" or the "projection postulate," says that the act of measurement instantaneously and arbitrarily collapses one part of a superposition into classical reality. This axiom describes a discontinuous, random process, interrupting the continuity of the way the SE describes reality.¹¹⁹

Von Neumann understood from his experience of physical reality that when measurement occurs, one result emerges, but he couldn't mathematically derive this experience from quantum mechanics. Consequently, he adopted a dualistic approach

¹¹⁸ John Gribbin, *In Search of the Multiverse: Parallel Worlds, Hidden Dimensions, and the Ultimate Quest for the Frontiers of Reality* (Hoboken, NJ: John Wiley & Sons, 2009), 25-26.

¹¹⁹ Byrne, *The Many Worlds of Hugh Everett III*, 102.

and claimed that if both axioms were correct, then there must be two kinds of change in quantum mechanical states: the collapse postulate, which describes discontinuous, arbitrary changes by measurement, and the SE, which describes continuous, causal changes that evolve over time when no measurement occurs. Von Neumann reasoned that collapse overpowers the unseen continuity described by the wave equation such that observation of a quantum system occurs from outside of the system. The problem is that if the observer and observed are entangled, which von Neumann believed to be the case, where is the distinction between them? Trying to say where and when the wave function collapses leads to the problem of infinite regression because the observer can never get outside of the continually entangling system to observe it without being a part of it.¹²⁰

Everett claimed that *rule 4I* and *rule 4II* of the axioms of the standard von Neumann-Dirac collapse formulation of quantum mechanics, where H = Hilbert space (vector space) and S = the state of a physical system,

4. Dynamical laws:

I. Linear dynamics: *If no measurement is made* on a physical system, it will evolve in a deterministic, linear way. More specifically, if the state of S is given by $\psi(t_0)_S$ at time t_0 , then its state at a time t will be given by $\hat{U}(t_0, t_1)\psi(t_0)_S$, where \hat{U} is a unitary operator on H that depends only on the energy properties of S .

II. Nonlinear collapse dynamics: *If a measurement is made*, the system S will randomly, instantaneously, and nonlinearly jump to a state where it either determinately has or determinately does not have the property being measured, with the probability of each possible postmeasurement state determined by the state's initial state. More specifically, if a measurement is made of the system S , it will randomly, instantaneously, and nonlinearly jump to an eigenstate of the observable being measured such that if the initial state is given by ψ_S and if ϕ_S is an eigenstate of O , then the probability of S jumping to ϕ_S when O is measured is equal to $|\psi_S \phi_S|^2$ (the square of the magnitude of the projection of the premeasurement state ψ_S onto the eigenstate ϕ_S). Equivalently, when a measurement is made, S instantaneously

¹²⁰ Ibid., 102-104.

and randomly jumps from the initial superposition on the left to the eigenstate of the observable being measured on the right

$$\psi = \sum_k c_k \phi_k \rightarrow \phi_i$$

with probability $|c_i|^2$.¹²¹

can't be applied consistently as the collapse postulate conceives of them. Everett showed that a paradox arises if there is more than one observer, because the state of the composite system $A + S$ depends on who's observing it. A logical contradiction comes to light when we imagine that quantum state assignments are objective and independent of perspective, notions which Everett took to be part of the standard understanding of quantum mechanical states on the orthodox view.¹²²

Suppose observer A is going to perform a measurement on system S, after which A will record the result in a notebook. Suppose also that A knows the state function of S and it isn't an eigenstate of the measurement he's about to perform. A believes that the outcome of his measurement is undetermined and the process is described correctly by the stochastic *rule 4II*. Meanwhile, observer B has information about the state function of the entire room, including the composite system $A + S$. B calculates the state function of the room for one week in the future, according to deterministic *rule 4I*. One week later, B still knows the state function of the room, and he understands this to be a complete description of the room and its contents. B then opens the door to the room, looks at A's notebook, and "turns to A and informs him in a patronizing manner that since his (B's) wave function just prior to his entry in the room, which he knows to have been a complete description of the room and its contents, had non-zero amplitude over other than the present result of the measurement, the result must have been decided only when B entered the room, so

¹²¹ Barrett and Byrne, "Conceptual Introduction," in *The Everett Interpretation*, 28-29.

¹²² *Ibid.*, 30.

that *A*, and his notebook entry, and his memory about what occurred one week ago had no independent objective existence until the intervention by *B*."¹²³ The problem Everett saw was that if the standard quantum state is taken to be complete, *A* and *B* can't both be correct in how they attribute the states of the system in question. If *A* got a single determinate result from his measurement of *S* as specified by the collapse postulate and if the quantum state is complete, then this result has to be described in the quantum state that *B* attributes to the composite system *A* + *S*, but the state that *B* computes from *rule 4I* doesn't single out any specific result as the one that was obtained and therefore can't be complete. In other words, both that the quantum state is complete and that *A* gets a single determinate measurement result are supposed by the standard collapse formulation while simultaneously producing a contradiction.¹²⁴

This example is extremely hypothetical because between decoherence effects among observer *A* and his environment and the technical difficulty in actually performing the experiment, it would be near impossible, in practice, to ever determine the state function of this macroscopic system. The fact that Everett saw a profoundly hypothetical scenario as posing such a far-reaching problem for the standard theory illustrates that Everett took the measurement problem to be one of principle, not practice. That this experiment is practically impossible to perform doesn't excuse quantum mechanics from the requirement of clearly explaining what would happen if it were performed. What Everett wanted was an interpretation of quantum theory that could provide a complete model of any and all physical interactions.¹²⁵

¹²³ Hugh Everett, "Long Thesis: Theory of the Universal Wave Function (1956)," in *The Everett Interpretation*, 74-75.

¹²⁴ Barrett and Byrne, "Conceptual Introduction," in *The Everett Interpretation*, 31.

¹²⁵ *Ibid.*, 31-32.

Rule 4I and *rule 4II* predict different physical states, so the von Neumann-Dirac formulation needs to provide separate conditions for when each rule is to be applied in order for their formulation to be logically consistent. The theory says to use *rule 4I* all of the time except for when a measurement is made, but, because it doesn't explain what constitutes a measurement, the theory is, at a minimum, incomplete. If we suppose that observers and their measuring apparatuses are made up of simpler systems that follow the deterministic *rule 4I*, then the theory also predicts that composite systems made of observers and their measuring apparatuses also necessarily evolve linearly and deterministically as described by *rule 4I*. However, this means that no nonlinear and stochastic evolution, as described by *rule 4II*, would ever occur. Everett's overall problem with the von Neumann-Dirac collapse formulation is that it leads to a contradiction if we understand measuring apparatuses as we would any other physical system (i.e. made up of quantum systems) because this implies a universe of multiple observers, and inconsistencies arise if we consider a universe containing more than one observer.¹²⁶

Everett also took issue with the Copenhagen interpretation, which he viewed as the interpretation developed by Bohr.¹²⁷ His understanding of Bohr was that, although he didn't use the same wave collapse terminology as von Neumann, his interpretation was still analogous to wave function collapse. Bohr distinguished between observer and observed by letting experimental context play a special role and making experimental results the standard for knowledge. Additionally, Bohr understood that classical language doesn't completely describe the quantum world,

¹²⁶ Ibid., 32-33.

¹²⁷ Ibid., 32.

but he felt that classical language is all we have. He thought that while there may be a world of quantum phenomena, we can't know this world because it's only understandable to humans through experimentation and classical language. Everett saw this as leading to the undesirable notion that there's no quantum reality independent of experimental results and that the SE, while useful for calculations, isn't a literal description of reality.¹²⁸

The two main claims of the Copenhagen interpretation, as understood by Everett, are: 1) the only understandable parts of quantum mechanics are those that can be described using the language of classical mechanics, and 2) a physical system only has a quantum mechanical state relative to classical experimental configuration and classical terms of the experiment. Everett's main concern was that he viewed the Copenhagen interpretation as unable to provide a complete model of any and all physical processes, which was something he sought from an interpretation of quantum mechanics. Classical specifications of the experimental arrangement give complementary quantum mechanical descriptions of the system in question. This mutual incompatibility implied by complementarity isn't a problem for the Copenhagen interpretation because all it means is that classical specifications are descriptions in terms of quantum mechanical states, or superpositions of classical states, and not themselves objects that we can understand through our world of experience, but Everett did not like that this relies on classical physics to describe the quantum world. Everett's overall worry about the Copenhagen interpretation is that

¹²⁸ Byrne, *The Many Worlds of Hugh Everett III*, 105-106.

although it's consistent, it's only so because it requires that measurement interactions be understood classically, not quantum mechanically.¹²⁹

Neither the von Neumann-Dirac collapse formulation nor the Copenhagen interpretation allows for a coherent account of quantum mechanics with regard to the measurement process and classical behavior of physical systems, and this contradiction between the SE and the collapse postulate is what Everett understood as the measurement problem. Everett viewed the observer of a quantum system to itself be a quantum system and therefore entangled with the observed system; we should treat measurement interactions in exactly the same way as all other physical interactions. He wanted to drop the stochastic *rule 4II* from the standard theory, taking the remaining deterministic pure wave mechanics as a complete and accurate description of all physical systems and convert the probabilistic claims of *rule 4II* into subjective appearances, better aligning these claims with everyday experience. The formal theory is thus objectively continuous and causal while subjectively discontinuous and probabilistic, considering observers to be physical systems that can be treated within pure wave mechanics.^{130, 131}

Everett's general process for reaching this conclusion stems from his claim that there are two kinds of probabilities: objective and subjective. His conception of the measurement problem as the contradiction between the SE and the collapse postulate can, for purposes of the elucidation of what he means by differentiating between two types of probabilities, be restated as the tension between subjective and

¹²⁹ Barrett and Byrne, "Conceptual Introduction," in *The Everett Interpretation*, 32-33.

¹³⁰ *Ibid.*, 34.

¹³¹ Byrne, *The Many Worlds of Hugh Everett III*, 138.

objective probabilities. Subjective probability refers to a calculation by an observer based on incomplete information and is not a property of the system in question but only a property of the state of information of the observer. Objective probability refers to an intrinsic property of a system, or "to what might be called 'really' random processes."¹³² To help illustrate this distinction, consider an experiment where a deck of cards is shuffled and one card is chosen and placed face down on a table. Observer A is asked whether or not the card is the ace of spades, and he responds by giving the probability that the card is in fact the ace of spades, $1/52$. This probability is a subjective probability because it refers to the state of information of the observer, not to the system (the card), which in actuality either is the ace of spades or is not the ace of spades, not some probability. A's response that the probability is $1/52$ is still meaningful, because if the experiment were repeated over and over with A responding each time that the card were the ace of spades, he would be correct about $1/52$ of the time. If there were also an observer B, who is told the color of the card, then he would answer with the probabilities 0 or $1/26$, depending on the color he is told, and B would be correct in the same way that A is correct. If there were also an observer C, who caught a quick glimpse of the card as it was placed on the table, he would have another type of answer that is not a probability. Subjective probabilities change from observer to observer because of differing states of information.¹³³

An objective probability, on the other hand, is understood as a property of a system and therefore independent of states of information and invariant from observer

¹³² Everett, "Minipaper: Objective versus Subjective Probability (1955)," in *The Everett Interpretation*, 57.

¹³³ *Ibid.*, 57-58.

to observer. If two observers attach different probabilities to one aspect of the same system, then at least one of those probabilities is subjective. Everett thought that the two postulates of the objective interpretation of quantum mechanics, which assume that all probabilities of quantum mechanics are objective probabilities, are inconsistent:

1. Every physical system s possesses a state function, ψ_s , which gives the *objective* probabilities of the results of any measurement which might be performed upon the system.
2. The state function ψ_s of an isolated system changes causally with time as long as the system remains isolated.¹³⁴

Suppose we have a system S_1 that's connected to a recording device that will record all results in classical terms (e.g. position) and a measuring apparatus M_1 that measures some property of S_1 which is configured to automatically make the measurement. Suppose also that the whole system, S_2 , consisting of S_1 and M_1 , is removed from any environmental interaction. S_1 has a state function ψ_1 that gives the objective probability of the results of the measurement, and we assume that ψ_1 isn't an eigenstate of the measurement, meaning the probability is neither 0 nor 1. S_2 , before the measurement, has a state function ψ_2 , which is strictly determined by the initial ψ_2 as long as there are no external interactions such that ψ_2 after the measurement is determined solely by its value before the measurement.¹³⁵

Now consider what the later measurement of ψ_2 says about the arrangement of the recording device. If it gives a probability mixture over the arrangements, then these probabilities must be subjective because they describe something that actually exists in a pure state; the arrangement of the recording device has already been

¹³⁴ Ibid., 58.

¹³⁵ Ibid., 58-59.

determined, just as in the example with the observer and the card. If it gives the exact arrangement of the recording device, then the result of the measurement must have been determined before the measurement occurred because the later ψ_2 was discovered solely from the earlier ψ_1 , meaning the probability given by ψ_1 wasn't objective. The lesson is that at least one of the probabilities must be subjective, so the postulates of the objective interpretation of quantum mechanics are inconsistent.¹³⁶

Everett proposed three possible modifications to the postulates in order to make the theory consistent. The first modification is to establish that not all physical systems have state functions. But even in principle, quantum mechanics can't describe the process of measurement itself, so this is an insufficient solution because it leads to an artificial division of the universe into ordinary phenomena and measurements. The second modification is to claim that the wave function of an isolated system isn't always causally determined and instead is prone to discontinuities from mixed states into probability mixtures of pure states, corresponding to some internal process, which we view as measurement. This solution is also inadequate because we still don't know what constitutes a measurement, so there's no available formalism from which we can obtain the points of discontinuity. The third modification is to maintain that the probabilities that occur in quantum mechanics aren't objective, and instead, they correspond to our ignorance of some hidden framework. This is Everett's solution, which he believed to be sufficient because it allows the inconsistency to resolve itself. The wave function that describes the larger, composite system – the universal wave function – contains more information than the wave function of a

¹³⁶ Ibid., 59.

subsystem.¹³⁷ The observer is confined to a single classical world,¹³⁸ missing most of the information that's contained within the universal wave function. The observer only has partial information, the information relevant to his world branch, so the probabilities he observes are subjective, essentially acting as a measure of his ignorance of the information in the universal wave function.¹³⁹

The observer sees what is apparently an indeterministic wave function collapse, but this isn't really a collapse: what's happening during "collapse" is that information is being lost to the observer while the deterministic universe continues to be governed by a non-collapsing wave function. Everett argues that each copy of a branching observer will subjectively experience determinism (everything happens) as indeterminism (one possibility happens by chance), because each copy of a branching observer can only access partial information about the total quantum state of the universe.¹⁴⁰ In other words, subjectivity occurs because, for each branching universe, the wave function contains less information than the total amount of information contained within the universal wave function. The branching process, caused by measurement, involves an objective loss of information to each copy of an observer within a single world line.^{141, 142}

¹³⁷ Ibid.

¹³⁸ Classical worlds are thus subjective, as all individual worlds are, because they contain only partial information.

¹³⁹ Byrne, *The Many Worlds of Hugh Everett III*, 141.

¹⁴⁰ Ibid.

¹⁴¹ Ibid., 151.

¹⁴² This may seem ironic because, being confined to one world branch, we experience measurement as an increase in information. This is a consequence of making a measurement, which allows us to gain information about the probability that performing the experiment again will produce a specific result. Ibid.

After establishing the distinction between objective and subjective probabilities, Everett continued to pursue his theory, breaking from the notion that there are two different ways in which the state of the system changes: 1) discontinuously and probabilistically, brought about by the measurement of some quantity, and 2) continuously and causally, as dictated by the SE. He noted that if (2) is applied to the measurement process itself, then the discontinuity of (1) can't occur and we have to either reject (1) and the statistical interpretation of quantum mechanics and instead adopt the purely causal description (2), or we have to limit the way (2) can be applied to systems where measurements aren't occurring. If we limit the applicability of (2), then the problem of how to distinguish between a measurement process and any other process arises. We would have to differentiate between processes of two kinds: the usual processes that are governed by (2) and measurement processes that are governed by (1), but, as already explained, this is inadequate. Instead, Everett proposed a purely causal theory that asserts the existence of a wave function for the entire universe and for which only (2) holds.¹⁴³

Assume we have a system S and an apparatus A and the system variable of interest is x while the apparatus variable of interest is y. Before making a measurement, the system and apparatus are in definite states and independent of one another such that the wave function of the entire system before the measurement is the product wave function. Measurement then occurs by allowing the system and apparatus to interact so the system variable x and apparatus variable y become correlated. Additionally, each system eigenstate ϕ_i with value x_i corresponds to a

¹⁴³ Everett, "Minipaper: Probability in Wave Mechanics (1955)," in *The Everett Interpretation*, 64-65.

definite apparatus state with value y_i after measurement. If the system isn't originally in an eigenstate of x but in a state of the form of the wave function, then, after measurement, the state of the apparatus will be indefinite to the same extent as the system is indefinite (this follows from the linearity of the SE and the superposition principle). Nothing discontinuous has happened, the system hasn't been forced to jump into an eigenstate, and the relative amplitude for the various eigenstates of the system has remained unchanged: nothing like process (1) has occurred. What has happened is that the apparatus has become correlated with the system because, after the measurement, the wave function for $S + A$ is "in a higher dimensional space" than the wave function of either S or A alone.^{144, 145}

Looking at a "cross section" of the total wave function where x has the definite value of x_i , we see that y has the definite value of y_i such that x and y correspond to one another. ("Cross sections" is a language tool Everett used to talk about correlations between subsystems of a larger composite system.) Wave mechanics tells us that when a measuring apparatus interacts with a system that isn't

¹⁴⁴ Ibid., 65-66.

¹⁴⁵ Wave equations are in $3N$ dimensional space rather than 3 dimensional space, because whenever several systems interact, some degree of correlation arises. If we consider a large number of interacting particles, assuming them to be initially independent, "then throughout the course of time the position amplitude of any single particle spreads out farther and farther, approaching uniformity over the whole universe, while at the same time, due to interactions, strong correlations will be built up, so that we might say that the particles have coalesced to form a solid object." In other words, even though the position amplitude of a single particle is smeared out, a cross section of the total wave function shows the particle as having a definite position and all of the other particles are nearby, forming a solid object. This is the phenomenon that accounts for the way we classically perceive solid objects of the macroscopic world, because we ourselves are strongly correlated with our environment. While it's possible for a macroscopic object to smear out, we would never be aware of it because the interactions between the object and our senses are so strong that we become correlated nearly instantly. It is because of strong correlations that the wave mechanical description is compatible with our conception of classical definiteness. Everett, "Minipaper: Probability in Wave Mechanics (1955)," in *The Everett Interpretation*, 68.

in an eigenstate of the measured variable, the apparatus "smears out" and is indefinite, even when the apparatus in question is "classical." However, the apparatus is correlated with the system, and this is what allows us to give a sufficient interpretation of the theory. Although this "smearing out" is implied by wave mechanics without aligning with our experience, it doesn't mean that quantum mechanics fails at a classical level. The observer doesn't see a smeared out system but instead sees the system in one determinate state or another, because he behaves just like the system. When the observer looks at the system in question, thereby interacting with it, he himself becomes smeared out and correlated with it. For the definite system value x_i , the measuring apparatus has the definite position y_i and the observer has split into multiple observers, each of whom sees a different definite result of the measurement. If the observer were to summon his lab assistant, he would also split but be correlated in such a way that he always agrees with the first observer as to the result of the measurement to disallow inconsistencies.¹⁴⁶

From the point of view of wave mechanics, when an observer makes a series of measurements, he's splitting each time a measurement is made so that, relative to each copy of the observer, there exists a "life tree." Looking at any particular branch of this tree would reveal an observer who always experiences definite results of his measurements, each of which, to him, appears to have jumped discontinuously into an eigenstate of the measurement. From our point of view, the observer has split into multiple versions of himself, one for each eigenstate of the system, and this process is continuous and causal. This shows that process (1) and the probabilistic laws that

¹⁴⁶ Ibid., 66-67.

come from process (1) are successful. Although the system doesn't participate in probabilistic jumps, it appears to the observer as if it has, but in actuality, the observer has just split into multiple versions of himself.¹⁴⁷

Everett believed that his non-collapse model thus explained the emergence of classical objects from quantum superpositions.^{148, 149} He further elucidated this with his amoeba analogy in which an amoeba is described as being in a superposition of states relative to the quantum state of the experimental apparatus. As time goes on, the amoeba is constantly splitting, and each version of the amoeba shares a common

¹⁴⁷ Ibid., 68-69.

¹⁴⁸ Byrne, *The Many Worlds of Hugh Everett III*, 139.

¹⁴⁹ The axioms of quantum theory don't say anything about "worlds" or "branches." These axioms only describe a unitarily evolving quantum state. We can write this state as a superposition of what appear to be classically determinate states, but these states aren't directly represented as "worlds" in the basic axioms of quantum theory. Many physicists therefore believe that the axioms of quantum theory must be modified to include the many worlds or the existence of these worlds must be an illusion, but this is a misguided dilemma; many scientific theories contain perfectly sufficient and accepted entities that aren't directly represented in the underlying axioms. For example, it took decades to understand that general relativity itself actually posits the existence of gravity waves and black holes, and these entities aren't mathematical artifacts. These kinds of entities are referred to as "emergent" entities: they aren't directly definable in microphysical language, but they're still dependent on the underlying microphysics. You can't define "language" within the standard microphysical model, but you also won't deny its existence. We all (or most of us) agree that tigers are real, objective, physical objects, but the standard microphysical model contains only quarks, electrons, and other such subatomic particles, but no tigers. Tigers are understood as patterns or structures within the states of microphysical theory. In other words, there are structural facts about microphysical systems that are real and objective but can't be seen if we describe these systems in a purely microphysical language. To view the world through a purely microphysical lens would reveal a description of macrophysical entities in terms of swirls of molecules and regularities in particulate patterns, but not in terms of the objects we're familiar with. Decoherence is an emergent process that manifests itself within the pre-stated microphysics of quantum mechanics. Decoherent histories are emergent structures within the underlying quantum state, but they're no less real than all other objects of science, like tigers. One consequence of this is that if the fundamental dynamics are unitary, then there is no collapse of the quantum state on the fundamental, or objective, level: there is only decoherence, which causes certain components of the state to become autonomous of others. If each decoherent history is an emergent structure within the underlying quantum state and the underlying quantum state doesn't do anything to prioritize one decoherent history over another (which it doesn't), then all histories must exist. Put more simply, a unitary quantum theory with emergent, decoherent histories is a many-worlds theory. David Wallace, "Decoherence and Ontology," in *Many Worlds?*, 55-65.

history with its most recent ancestor; amoebas have shared memories up to a point, after which they diverge and continue along their own world history. The amoeba continues to split as it interacts with its fluctuating environment, in accordance with the SE, and its history therefore resembles more of a life-tree than a single life-line. The wave function of the smeared out amoeba never collapses because each of its possible states is actualized in a branch of the universal wave function.^{150, 151} Everett writes,

After a while we would have a large number of individuals, sharing some memories with one another, differing in others, each of which is completely unaware of his 'other selves' and under the impression that he is a unique individual. It would be difficult indeed to convince such an amoeba of the true situation short of actually confronting him with his 'other selves.' The same is true if one accepts the hypothesis of the universal wave function. Each time an individual splits he is unaware of it, and any single individual is at all times unaware of his 'other selves' with which he has no interaction from the time of splitting.¹⁵²

This analogy was the beginning of Everett forming the keystone of his theory:

physical reality is the wave function of the entire universe.

This led Everett to introduce his "relative states" theory (which became popularized by DeWitt as a many-worlds theory), a name he chose in order to stress the relationship of his idea to Einstein's general theory of relativity. Einstein's theory didn't allow for a special place in the universe, claiming instead that all observers are entitled to their own point of view. Similarly, Everett claims that there is no special universe in the multiverse because all quantum states are equally real. Put in terms of Einstein's theory, all observers in the multiverse are equally entitled to their own

¹⁵⁰ Byrne, *The Many Worlds of Hugh Everett III*, 139.

¹⁵¹ Everett, "Minipaper: Probability in Wave Mechanics (1955)," in *The Everett Interpretation*, 69.

¹⁵² *Ibid.*, 69-70.

point of view, and all observers are equally real.¹⁵³ Everett's ideal observer is a physical system with a memory, the states of which become perfectly correlated to the states of object systems over the course of the measurement interaction. Because the dynamics of pure wave mechanics is linear, an ideal observer M would begin in a state ready to make a measurement, then measure the observable O of system S, and M's memory becomes correlated to S's state with repeated measurements leading to more complicated, entangled superpositions. It's then necessary to be able to interpret the final absolute state of the unentangled system, given by the universal wave function, but because the states of physical subsystems are usually entangled, they don't have absolute states, instead possessing only relative states.¹⁵⁴

Everett was agreeing with the standard interpretation of quantum states in that subsystems of entangled composite systems don't have absolute physical properties or absolute physical states of their own. Instead, these subsystems possess relative states that are determined by the correlation structure described by the absolute state of the universe (the universal wave function and all of the ways it could be broken down depending on one's choice of basis and how much to individuate the subsystems). We can arbitrarily choose a state for a particular subsystem to find the relative state for the rest of the related composite system, and this doesn't require any specification of a preferred choice of basis. Just like no specific relative state for an observer has the special role of being the actualized relative state, there's no privileged way of breaking down the composite state into a preferred set of relative states. Relative

¹⁵³ Gribbin, *In Search of the Multiverse*, 27.

¹⁵⁴ Barrett and Byrne, "Conceptual Introduction," in *The Everett Interpretation*, 34.

states basically gave Everett a platform for discussing the correlation structure determined by the universal state in the context of pure wave mechanics.¹⁵⁵

He thought that the relative state formulation of quantum mechanics is in accord with our experience because it predicts that no observer would be aware of any branching worlds. A relative observer's experience is completely described by his relative physical memory sequence, which doesn't contain records of branching events because a memory sequence exhibits standard quantum statistics.¹⁵⁶ The SE describes the continuous, causal evolution of quantum systems through time, and all possible events are contained within the wave function.¹⁵⁷ Everett claims that the SE "ruthlessly evolves everything in a huge number of universes through stages of causal change regardless of how static or disconnected things may appear to humans" such that observers are entangled with macroscopic objects, which, because they're composed of microscopic systems, exist in superpositions.¹⁵⁸ Each copy of the branching observer moves ahead in its own world history, branching over and over again, echoing the superpositions with which it is ceaselessly entangled. All copies of observers can be traced back to common ancestors, just as branches of a tree can be traced back to the trunk; collapse would be like chopping off all but one branch.¹⁵⁹

Everett used classical information theory to deduce an explanation for the apparent existence of probability in the quantum world where everything that could possibly happen does happen. Entropy measures disorder and information measures

¹⁵⁵ Ibid., 35-36.

¹⁵⁶ Ibid., 52.

¹⁵⁷ The wave function does not describe one outcome or another: it gives probabilities. The SE describes a superposition of all possible outcomes (i.e. the evolution of the wave function is such that it describes many possible states of affairs).

¹⁵⁸ Byrne, *The Many Worlds of Hugh Everett III*, 146.

¹⁵⁹ Ibid.

order, so obtaining information reduces uncertainty and is therefore subject to the rules of probability. To reiterate, all information is contained within the universal wave function, which is the fundamental entity of the universe, always obeying a deterministic wave equation. However, the word "probability" implies the idea that observation takes place from outside the measured system. Everett needed to find a probability measure from within a particular branch of the universal wave function because he believed the observer to be situated within the system and the measurement process also to occur from within the system, which is a problem because the SE doesn't allow for this kind of probability measure. This is why the collapse postulate (aka "projection" postulate) projects the description of a quantum system into a different mathematical space ("phase" space) where probability can be measured classically. Everett attempted to measure the amount of information available after some event happened and an observer split and match the result to a probability statement instead of collapsing the wave function to find a probability. In other words, Everett found a classical probability measure over branching events without invoking collapse. He thought this explained why an observer residing within a single world branch subjectively experiences probability in a multiverse that contains branches corresponding to every physically possible event.^{160, 161}

Next, Everett rendered his information theoretic model into one that was purely quantum mechanical. He noted that if X and Y are correlated, it means that if we learn something about one variable, we also learn something about the other, and entangled subsystems, such as X and Y in a composite system Z, don't have states

¹⁶⁰ Ibid., 103.

¹⁶¹ Ibid., 149-151.

independent of the rest of the system and it's meaningless to seek out absolute states of a subsystem because we can only learn about a state relative to the rest of the system. After a measurement interaction, all elements of the superposition of the measured object are entangled with their respective copies of the observer. Every copy exists relative to the state of the observed object and to the rest of the branching multiverse, and each copy and each state of the observed object is correlated to the branching multiverse. All parts of the superposition exist simultaneously, and the whole process is continuous.¹⁶² In opposition to both Bohr and von Neumann, Everett thought of measurement as "a natural process within the theory of pure wave mechanics."¹⁶³ The observer has no special role and measurement is just a case of interaction between physical systems that correlates a quantity in one subsystem with a quantity in another.¹⁶⁴

The measurement problem was therefore a mere misunderstanding that arose from adding the unnecessary postulate of measurement as being a special process to a theory that works without this postulate. On its own, pure wave mechanics, the unitary evolution of quantum states without any collapse postulate, gives a complete account of quantum mechanics.¹⁶⁵ Everett took his theory to be objectively causal and continuous while simultaneously probabilistic and discontinuous. It applies to all systems of any size and can explain the appearance of the macroscopic world.¹⁶⁶ Everett thought pure wave mechanics described a complete and accurate physical

¹⁶² Ibid., 151-152.

¹⁶³ Ibid., 153.

¹⁶⁴ Ibid.

¹⁶⁵ Barrett and Byrne, "General Introduction," in *The Everett Interpretation*, 7.

¹⁶⁶ Everett, "Minipaper: Probability in Wave Mechanics (1955)," in *The Everett Interpretation*, 69.

theory. He believed particular relative measurement records explained our particular experiences and showed that measurement records in relative states reveal standard quantum statistics.¹⁶⁷ He saw the wave function as an objective characterization of a physical system, as long as the system in question is isolated, or interacting independently of an external system. No subsystem of the multiverse is completely and eternally isolated, so the only truly isolated system is the multiverse, and every subsystem can be described as existing relative to the rest of the multiverse.¹⁶⁸ Everett wanted a theory that could be used to provide a consistent physical description of the multiverse as a whole.¹⁶⁹

In summary, Everett's interpretation claims that the universal wave function, or the quantum state of the totality of existence, has an objective reality and the wave function itself never collapses. Instead of the wave function collapsing into a single history, it "collapses" only subjectively, and every possible quantum outcome is realized. This reconciles the observation of indeterministic events, such as the randomness of radioactive decay, with the fully deterministic equations of quantum theory. The subjective appearance of the wave function collapse that causes any observer to claim that the world is in a determinate state is explained by quantum decoherence, or the reduction of possibilities into a single state of affairs as experienced by an observer, meaning that every possible outcome of every event exists in its own world history. In other words, collapse never really happens, and the universe explores all of the possible outcomes, each of which should be considered

¹⁶⁷ Barrett and Byrne, "Conceptual Introduction," in *The Everett Interpretation*, 37.

¹⁶⁸ Byrne, *The Many Worlds of Hugh Everett III*, 145.

¹⁶⁹ Of course, Everett posited a single universe containing branching histories, but the current terminology used in many-worlds theories involves a multiverse containing branching universes.

equally real. Physical reality is therefore the wave function of the entire universe. Everett's many-worlds theory gives a complete causal account of quantum mechanics while also explaining the probabilistic aspects of the subjective level of experience. It doesn't involve any new postulates, instead taking wave mechanics seriously and assuming its general validity. Internal correlations of the wave function explain our perception of the macroscopic world as well as its apparent probabilistic nature.¹⁷⁰ Everett's views can be understood as lying somewhere between realism and Platonic idealism: he believed that the many worlds each had their place in reality, but ultimately, the theory – the universal wave function – behind the worlds is the true reality.¹⁷¹

¹⁷⁰ Everett, "Minipaper: Probability in Wave Mechanics (1955)," in *The Everett Interpretation*, 70.

¹⁷¹ Byrne, *The Many Worlds of Hugh Everett III*, 155.

THREE: COMPARING EVERETT AND BOHR

"Reality is bigger than us."

–Ian Hacking, *Representing and Intervening*¹⁷²

3.1 THE LIMITATIONS OF HUMAN EXPERIENCE

Many of the interpretational difficulties facing quantum theory stem from the relationship and dramatic differences between classical and quantum physics. It appears that the macrocosm, or the classical world, behaves irreconcilably from the microcosm, or the quantum world, making it difficult to unify these two domains to create one comprehensive model of physical reality. One important factor to keep in mind about quantum physics is that nothing about it makes sense in terms of our everyday experience; the best we can do is make analogies with things we do experience in our everyday world. For example, quantum entities are neither waves nor particles and also not some mixture of the two, but in order to make sense of quantum behavior, we discuss these entities in terms of waves and particles. It seems to us that when asked one question, matter responds like a particle, but when asked another question, it responds like a wave, but what if we're just limited by our human experience? What if we don't know what questions to ask or how to interpret the answers because we can't even fathom how things "really" are? Just as we can't wrap our heads around what a new color might look like,¹⁷³ our human experience of the world limits the ways in which we can understand physical reality. Our use of

¹⁷² Hacking, Ian, *Representing and Intervening: Introductory Topics in the Philosophy of Natural Science* (New York: Cambridge University Press, 1983), 274.

¹⁷³ Based on research into the optical mechanisms of other animals, we have empirical evidence that colors humans can't see do, in fact, exist.

quantum mechanics where we implement the formalism without understanding how to interpret it is like knowing how to drive a car by using the controls without understanding what's going on underneath the hood. It's as if something unknown is behaving in a way that we can't even begin to comprehend.¹⁷⁴ The recent debate over whether light is a particle or wave echoes the way that physicists treat the nature of the universe as dualistic in order to reconcile the quantum and classical worlds.

In the early 1800s, Thomas Young, following Christiaan Huyghens' lead, posited a double-slit experiment that provided devastating evidence to the particle, or "corpuscular," theory of light previously held by Newton by showing that light is actually a wave. Although historians of science claim it isn't clear whether Young himself ever performed this experiment, it was eventually carried out and yielded an interference pattern, which could not manifest were light a particle. The replacement of particle theory by wave theory came as a function of many changes in the sciences, and Young's account of light as a wave wasn't accepted until 1816 and the debate over light as a particle continued through the mid 1830s. It was a multitude of factors coming together that brought physicists to believe, by the end of the 19th c., that light is a wave. In 1860, James Clerk Maxwell posited a unified field theory of electric and magnetic phenomena that allowed him to derive instead of merely postulate that light is a wave. However, the beginning of the 20th c. brought new empirical evidence that contradicted the recently established view of light as a wave. Novel experiments showed that light exhibits wave-like properties under some sets of experimental conditions and particle-like properties under others, and new evidence demonstrated

¹⁷⁴ Gribbin, *In Search of the Multiverse*, 13-14.

that, under complementary circumstances, matter also has wave-particle properties: wave-particle duality appeared to be a characteristic of both light and matter.¹⁷⁵

This information indicated that our understanding of the nature of scientific inquiry, and of nature itself, was flawed. Before the 20th c., everything could be divided neatly into categories of waves or particles because everything had a distinct identity that classified it as either a wave or particle. Waves and particles were understood as distinct phenomena with mutually exclusive characteristics: particles are localized bodies, occupying one distinct location at every moment in time, while waves are disturbances extended in space, occupying multiple locations at a given moment in time, able to overlap with one another. The trouble is, entities were understood as capable of being either extended or localized, but not both at the same time.¹⁷⁶ A conceptual shift came in 1924 when Louis de Broglie introduced the idea of matter waves, and the challenge became how to understand the apparent duality between particles and waves.¹⁷⁷

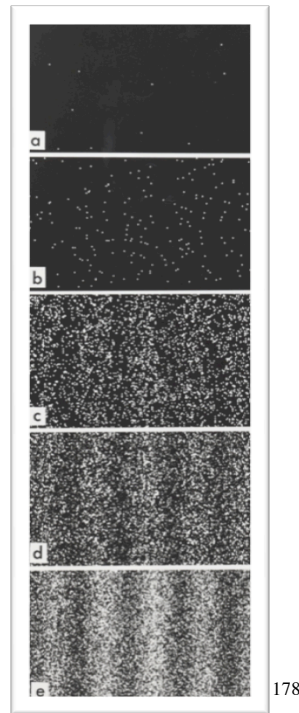
In 1989, an experiment by A. Tonomura, J. Endo, T. Matsuda, T. Kawasaki, and H. Exawa was performed at the Hitachi Advanced Research Laboratory and Gakushuin University in Tokyo that demonstrated the conundrum over matter waves. They positioned a source of electrons to fire a particle through a barrier with gaps equivalent to a pair of slits in it. After passing through this barrier, each electron hit a sheet of fluorescent film, resulting in a burst of light in the spot where the electron fell. Recording each burst of light allowed the experimenters to document where each

¹⁷⁵ Barad, *Meeting the Universe Halfway*, 97-100.

¹⁷⁶ *Ibid.*, 100.

¹⁷⁷ Greenstein and Zajonc, *The Quantum Challenge*, 1.

electron arrived after passing through the slits. At first, these bursts of light appeared to be distributed evenly over the film, but as more electrons were fired, a pattern began to emerge:



Next, consider a modification to this experiment where first, gap A is covered. Although Tonomura et al. did not perform this modification, there is no question as to what their results would have been. The interference pattern disappears; the alternating series of parallel bands becomes a single band, positioned directly across from the open slit, B. This implies that in the original experiment, electrons were passing through slit A, because if they had not been, covering slit A wouldn't have

¹⁷⁸ "Figure 1-3 shows a sequence [Tonomura et al.] obtained of five such 'time exposures' of successively longer and longer duration. In the initial frames of this figure, which document the arrivals of a relatively small number of electrons, little can be discerned. But by the third frame, hints of an orderly pattern are beginning to emerge. By the final frame, in which fully 70 000 arrivals have been documented, a pattern has become evident: an alternating series of parallel bands." Ibid., 3-4.

made a difference to the pattern that emerged. Conversely, if slit B is closed and A is left open, the same result is obtained but with the single band positioned directly across from A. Taken together, these two modifications show that each electron passed through both slits, A and B. Of course, this seems impossible! If an electron is a particle and being a particle means being something that is located at a particular point in space, we would assume that an electron can pass through slit A or slit B but not both, because it can't be in two places at the same time. That being said, this experiment appears to show that the single electrons were in two places at once, interfering with themselves.¹⁷⁹

We could imagine that something like a traffic jam is happening such that each electron is passing through only one slit but that during its passage, it collides with other electrons which have passed through the other slit, making the pattern of arrivals of electrons depend on whether one or both slits were open. Tonomura et al. showed that this isn't the case by turning down the intensity of the electron source so that only one electron at a time was in the apparatus, yet their experimental results remained the same: in the initial frames where the passages of relatively few electrons were documented, no pattern can be made out, but as more and more electron arrivals were documented, an interference pattern emerged.¹⁸⁰ Greenstein and Zajonc write, "the logic seems irrefutable. Tonomura's electrons were in two places at the same time,"¹⁸¹ and these results aren't unique to electrons. The experiment has been replicated using other types of matter, such as neutrons, atoms, and Bose-Einstein

¹⁷⁹ Ibid., 1-5.

¹⁸⁰ Ibid., 5-7.

¹⁸¹ Ibid., 7.

condensates, and the results have shown that regardless of the particle, atom, or molecule, they all display matter-wave interference effects.¹⁸² The problem with quantum mechanics that stems from experiments such as this is that the theory correctly reproduces the results but hasn't explained how indivisible particles apparently pass through two slits at once, presenting us with a condition that violates our understanding of physical reality.¹⁸³

Although we tend not to be able to understand how or why what happens within quantum mechanics happens, the formalism makes it possible to at least describe what's going on, and the various interpretations of quantum mechanics are tools we use to try to understand what's happening in terms of human experience. The more widely accepted interpretations, such as the Copenhagen interpretation, have maintained their status as orthodox interpretations because no other interpretation has been posited that predicts better or more than these have already. Most accepted, alternative interpretations are just as good at predicting the outcomes of quantum behavior but no better, and the interpretation one chooses to work with is based on which aspects of quantum weirdness one is most comfortable with.¹⁸⁴ Everett's many-worlds interpretation (MWI), as far as experimental tests go, is exactly as good as Bohr's interpretation, for example, and the difference is in how they each influence our understanding of the world.

In the 1950s, Everett was considered a heretic at Bohr's Institute for Theoretical Physics in Copenhagen, and in 1959, Bohr and Everett met to discuss

¹⁸² Ibid., 7-12.

¹⁸³ Ibid., 18-19.

¹⁸⁴ Gribbin, *In Search of the Multiverse*, 19-23.

Everett's ideas, but Bohr dismissed him.¹⁸⁵ Despite their history, I see both Everett and Bohr as sharing a common goal by trying to understand quantum mechanics as fundamentally as possible, without adding extra postulates to it. Their interpretations, while they have their disagreements, make many compatible claims with one another, although the conclusions they reach are different. They went about modeling physical reality in distinct ways, but I'm arguing first that these apparent incompatibilities are not so dissimilar as commonly believed and second that Everett manages to improve upon Bohr's theory for a more coherent account of physical reality. I make this argument in five steps: I will 1) present Everett's interpretation of Bohr's theory of quantum mechanics, 2) summarize aspects of Barad's interpretation of Bohr's theory of quantum mechanics relevant to Everett's MWI, 3) summarize Everett's MWI with focus on the relationship between branching and observation, 4) compare and contrast Everett's philosophy-physics with that of Bohr, as interpreted by Barad, in order to show that Bohr's interpretation is applicable to Everett's interpretation and that Everett's interpretation leads to a more cogent account of physical reality, and, in the conclusion, 5) explicate the appeal of Everett's MWI. My argument is that Bohr's theory of quantum mechanics as understood by Karen Barad – which we have to keep in mind is different from the Copenhagen interpretation, commonly attributed to Bohr, but which Barad, among other scholars, claims is incoherent compared to Bohr's own theory – lends itself to Everett's MWI, which leads to an ontologically satisfying, sufficient, and not so counterintuitive as most people claim, understanding of the nature of reality.

¹⁸⁵ Barrett and Byrne, "General Introduction," in *The Everett Interpretation*, 7-8.

3.2 EVERETT'S INTERPRETATION OF BOHR'S PHILOSOPHY-PHYSICS

Everett equated Bohr's philosophy with the Copenhagen interpretation,¹⁸⁶ understanding Bohr to be placing an artificial barrier between the microscopic world, governed by the SE, and the macroscopic world, governed by classical laws. Bohr was seen not as denying the existence of quantum particles but as thinking that we can only experience the quantum world through experimentation. In other words, the unseen quantum event corresponds to a classical event. Bohr didn't think we could describe the world in quantum mechanical terms, insisting instead that we should only discuss experimental results, which can only be considered in classical language out of epistemological necessity, since that's all we can know.¹⁸⁷ Everett believed he was in direct opposition to Bohr, claiming that the universe is fundamentally quantum mechanical: quantum physics explains classical physics and the wave function represents physical reality, not just our knowledge of reality.¹⁸⁸

Everett wrote, of the Copenhagen interpretation:

The Copenhagen Interpretation is hopelessly incomplete because of its a priori reliance on classical physics (excluding in principle any deduction of classical physics from quantum theory, or any adequate investigation of the measuring process), as well as a philosophical monstrosity with a 'reality' concept for the macroscopic world and denial of the same for the microcosm.¹⁸⁹

¹⁸⁶ This is perhaps where the problem lies: Everett's interpretation shares common goals with the Bohrian philosophy presented by Barad, although it is not so compatible with the Copenhagen interpretation as generally understood, which Barad takes to not be equal to Bohr's philosophy.

¹⁸⁷ However, Barad doesn't take Bohr's view to be as simple as this (see Chapter 1).

¹⁸⁸ Byrne, *The Many Worlds of Hugh Everett III*, 87-89.

¹⁸⁹ Everett to DeWitt (5/31/57), quoted in Byrne, *The Many Worlds of Hugh Everett III*, 142.

He believed that it deals with measurement by positing one set of physical laws for the macroscopic world and another set of laws for the microscopic world, claiming that knowledge about what goes on inside the quantum world is inaccessible to us and instead we have to describe the quantum world through the use of classical language.¹⁹⁰ Still, Everett wasn't completely rejecting complementarity. His main concern was that he saw Bohr's barrier between the classical and quantum worlds¹⁹¹ as unnecessary and hindering understanding and didn't like that complementarity prevents the classical world from being deduced from pure wave mechanics. Everett felt that he was improving upon Bohr's dualistic model by explaining how the classical world comes from and is contained within the quantum world.¹⁹² He saw Bohr as perpetuating duality through his theory of complementarity: instead of remedying this duality, Bohr was maintaining it by coming up with a model of the physical world that hinged on the notion of duality being a necessary quality of the universe. Everett wanted to reject duality and instead claim that the world is most fundamentally quantum mechanical and the dualism comes from our inability to separate our understanding of the workings of the world from our limited human experience of it. That being said, I see Everett's realism, where all possibilities are actual, as stemming from Bohr's realism, where, although inherently indeterminate, phenomena refer to real, physical entities, not just to perceptions of the mind. In a sense, Bohr's notion that the world is inherently indeterminate and there is no intrinsic

¹⁹⁰ Barrett and Byrne, "Biographical Introduction," in *The Everett Interpretation*, 13.

¹⁹¹ Barad explains away this barrier in her interpretation of Bohr.

¹⁹² Byrne, *The Many Worlds of Hugh Everett III*, 142.

separation between entities or pre-existing properties of entities is not so different from Everett's claim that all possible world histories are actual.

3.3 BARAD'S INTERPRETATION OF BOHR'S PHILOSOPHY-PHYSICS

Barad sees Bohr as a realist who understands scientific theories as describing physical phenomena. The main difference between Bohr and other realists is that Bohr isn't advocating a correspondence theory of truth; he's advocating a correspondence between theories and phenomena and rejecting an observation-independent reality. Bohr's realism is an account that doesn't rely on pre-existing entities or distinctions between entities, because it is not a representationalist account.¹⁹³ Representationalism places us outside of the world and all we do is reflect on it. Barad's understanding of Bohr frames him as having developed a performative account of physical reality, placing us within the world, engaging with it and understanding ourselves as part of it. Performativity forces us to reevaluate our use of language and the agency language has as it actively shapes the way we perceive the world, instead asking us to reject this power that language has, disallowing it to determine what is real.¹⁹⁴ Representationalism assumes that separation is fundamental and the world is divided into neat, distinct categories of words and things, making it impossible to step outside of the metaphysics it postulates.¹⁹⁵ We act as captives to our use of language because it has determined for us what is real, but language is a human construction and reality is bigger than we are.

¹⁹³ Barad, *Meeting the Universe Halfway*, 129.

¹⁹⁴ *Ibid.*, 133.

¹⁹⁵ *Ibid.*, 137.

We are trapped in an anthropocentric perspective that the metaphysical assumptions of individualism and representationalism serve to reinforce. Bohr, however, rejects these assumptions, and Barad proposes a posthumanist performative interpretation of Bohr to account for the workings of the universe. She reads Bohr as taking issue with human exceptionalism, rejecting the assumption of separateness of any "thing":¹⁹⁶

Just as there are no words with determinate meanings lying in wait as so many candidates for an appropriate representationalist moment, neither are there things with determinate boundaries and properties whirling aimlessly in the void, bereft of agency, historicity, or meaning, which are only to be bestowed from the outside, as when the agency of Man pronounces the name that attaches to specific beings in the making of world-thing pairs. 'Things' don't preexist; they are agentially enacted and become determinately bounded and propertied within phenomena. Outside of particular agential intra-actions, 'words' and 'things' are indeterminate. Matter is therefore not to be understood as a property of things but, like discursive practices, must be understood in more dynamic and productive terms – in terms of intra-activity.¹⁹⁷

This agential, realist ontology rejects the presupposition that separateness is an inherent feature of the world while simultaneously maintaining that separateness is more than a mere illusion because differences do matter.¹⁹⁸ Distinctions between entities are intersubjective and carry empirical significance because they shape both us and our understanding of the world. Instead of the conventional understanding that relations follow relata, we can read Bohr as claiming that relata follow relations.¹⁹⁹

Imagine the world as a sphere covered in an undifferentiated, snow-like substance where we too are composed of the same substance. When we look around, we see only one entity: the snow. No part of it looks any different from any other

¹⁹⁶ Ibid., 134-136.

¹⁹⁷ Ibid., 150.

¹⁹⁸ Ibid., 136.

¹⁹⁹ Ibid.

part, and we could not tell here from there or this from that. It's only once we begin interacting (or more appropriately, intra-acting) within it that structures begin to emerge. We can tell here from there based on where we've left marks on the snow-like substance's body, and we can tell this from that based on the way our intra-actions have shaped the environment. Additionally, just as is the case when making a snowball, the intra-action between one part of the snow and another leaves traces on both bodies: there is no snowball separate from the rest of the snow until an intra-action occurs, one part distinguishing itself from the rest by making a mark on the total system, thereby creating and recreating itself. It is through our relation to the substance that differentiations, or relata, emerge. If something had not intra-acted with it, it would remain undifferentiated. This makes especially poignant the reason for choosing the word "intra-action" over "interaction": the relata that we perceive to exist within phenomena come about through specific intra-actions. There is no pre-existence of independent relata.

Apparatuses, therefore, understood as structures within a system, are not just measuring devices but also draw distinctions.²⁰⁰ Barad defines apparatuses as "specific reconfigurings of the world that do not merely emerge in time but iteratively reconfigure spacetime-matter as part of the ongoing dynamics of becoming,"²⁰¹ and this is just as how we can understand a snowball as emerging from the total snow system as well as influencing the total system as it emerges and grows. Apparatuses are discursive practices in that they determine and constrain the concepts we use to describe the world. Agential cuts are both ontic and semantic, and without agential

²⁰⁰ Ibid., 140.

²⁰¹ Ibid., 142.

cuts, ontic-semantic boundaries are indeterminate: apparatuses are practices that delineate boundaries. Meaning is only possible through specific material practices, and importantly, Barad's posthumanist understanding of discursive practices conceives of them as not specifically human phenomena. Meaning, therefore, is not a property of specific words, but rather, a practice. Barad's agential realist account of Bohr's philosophy-physics marks intelligibility as an ongoing, ontological process within the world, or as a feature of the world rather than a human-dependent property.²⁰² Knowing is not a specifically human practice, but "an ongoing performance of the world," coming about through intra-action, because "humans are neither pure cause nor pure effect but part of the world in its open-ended becoming."²⁰³ All bodies intra-act with the world, not just human bodies,²⁰⁴ and observation need not be so anthropogenic as our practice of it leads us to believe.

Bohr, similarly to Descartes, addresses the question of boundaries between subject and object, writing,

One need only remember here the sensation, often cited by psychologists, which every one has experienced when attempting to orient himself in a dark room with a stick. When the stick is held loosely, it appears to the sense of touch to be an object. When, however, it is held firmly, we lose the sensation that it is a foreign body, and the impression of touch becomes immediately localized at the point where the stick is touching the body under investigation.²⁰⁵

His point is that the stick can't function as an apparatus of observation if one is observing it. The line between subject and object cannot possibly pre-exist, because it's created through an agential cut and is otherwise ambiguous. Additionally, this cut

²⁰² Ibid., 148-149.

²⁰³ Ibid., 149-150.

²⁰⁴ Ibid., 152.

²⁰⁵ Niels Bohr, *The Philosophical Writings of Niels Bohr*, Vol. 1, *Atomic Theory and the Description of Nature* (Woodbridge, CT: Ox Bow Press), 99.

depends on a given practice and is not arbitrary. We choose to use the stick as an apparatus of observation or we choose to observe the stick, but, because its role isn't predetermined, the stick can function either as an observer or an observable and its function is the result of a meaningful choice by dint of the fact that agency was performed.²⁰⁶

The boundaries we see as separating one body from another are a consequence of specific bodily performance, not of an inherent distinction. We think the boundaries between bodies are visually self-evident, but this is in large part a result of our repeated intra-action with the bodies in question and the agential cuts we make; the cuts are not inherent but a result of repeated practice, and classical biases are deeply ingrained in our cognitive composition. Visual cues, such as lines and sharp edges, that we take as distinguishing between bodies, are not real. Optics tells us that when we look at an edge, what we see isn't really a sharp boundary between light and dark but a diffraction pattern, and the interface between objects isn't such that there are x atoms in object A and y atoms in object B. For example, accounts of sight restoration to individuals who were born blind or lost their vision while young provide documentation that even after optical apparatuses are repaired, sight does not always immediately follow. Information about sight restoration and studies on the perception of space show that concepts such as space, distance, objects, size, and depth don't always mean the same thing for those who can and cannot engage in visual perception.²⁰⁷

²⁰⁶ Barad, *Meeting the Universe Halfway*, 154-155.

²⁰⁷ *Ibid.*, 155-157.

Our visual experience of distinguishing between bodies is not just some inevitable consequence of our optical apparatus but actually results from the way we engage with the world. We see not only with our eyes, but intra-acting as part of the world also factors into our experience of seeing, and objects emerge through these intra-actions.²⁰⁸ Bodies are not simply located in space: bodies and environments are "intra-actively co-constituted."²⁰⁹ Bodies, of any kind, are fundamental parts of what there is in the world.²¹⁰ The agential realist account of Bohr's philosophy-physics doesn't consider humans to be outside observers (an antihumanist view) or independent, intervening subjects (a humanist view), but rather, integral parts of the composite system of the world, the components of which co-constitute themselves through intra-actions, human or not. Human bodies are like all other bodies: without inherent boundaries or properties. They're all phenomena, acquiring specific boundaries and properties in accordance with the relevant intra-activity.²¹¹

The agential realist account doesn't allow for an exterior observational point because there is no such externality. Gaining knowledge doesn't require standing in an external relation to the natural world. We're neither outside observers nor passively located at particular places; we're part of the world and its ongoing intra-activity. Barad reads Bohr as conceiving of "knowing" as one part of the world making itself intelligible to another part, where knowing and being are inexorably intertwined: we

²⁰⁸ Ibid., 157.

²⁰⁹ Ibid., 170.

²¹⁰ E.g. just as the snowball is not distinct from the snow, bodies are not distinct from the world, and just as the snowball is created from and within the snow, bodies are created from and within the world.

²¹¹ Ibid., 170-172.

know things about the world because we're part of the world.²¹² Bohr questions our dualistic understanding of nature, because dualism can't be an inherent feature of the world when there are no inherent features of the world. The qualities that the world possesses come about through intra-action and co-constitution. When Bohr claims that concepts aren't ideational but are given meaning only through specific physical arrangements, he is not claiming that concepts are supported by physical arrangements but that concepts are directly linked to physical configuration.²¹³ However, just as Everett laments that Bohr relies too heavily on classical language to discuss the quantum world, Barad argues that Bohr, in privileging the human experimenter by assuming him to have determinacy and individuation apart from the observed system when the total system, including the human, are really of the same ontological status, is too dependent on humans and human concepts as playing a key role in understanding nature for his argument to be convincing.²¹⁴

In short, we can understand Bohr as seeing the physical world as a place of ontological indeterminacy until an agential cut is enacted through intra-action and observation-dependent entities with observation-dependent properties emerge. While their views do reach different conclusions, I think, most fundamentally, that Everett is taking a similar stance on the nature of the world, or at least has similar goals in mind for trying to understand physical reality. We can read Everett as also seeing the physical world as a place of ontological indeterminacy in the sense that the universal wave function describes all possible world histories, so at the level of the ultimate

²¹² Ibid., 184-185.

²¹³ Ibid., 147.

²¹⁴ Ibid., 248.

reality (the universal wave function) there is no particular state of affairs, but instead, all possible states of affairs are occurring simultaneously and eternally. It is only according to one particular copy of one particular observer that one particular world history is in place, and this is all dependent on the observer's agency and intra-action within his universe and the specific outcomes that result, which lead this particular copy of a particular observer to experience one world history over another, had he performed his agency or intra-actions differently.²¹⁵

3.4 EVERETT'S MANY-WORLDS ACCOUNT OF OBSERVATION AND BRANCHING

Everett's original theory describes a single universe that produces many different versions of events, but this single universe is now commonly referred to as the "multiverse" to distinguish it from the particular version of reality perceivable to a single version of a single observer. In other words, "universes" and "worlds" are synonyms, and each universe/world is a single version of reality contained within the multiverse. An illustrative metaphor for this is a kind of optical computer, suggested in the 1980s, made up of bundles of glass fibers and other components that transmit light. These components were to be arranged in the same way as in an ordinary classical computer, but the optical computer could do multiple things at once by shining in slightly different wavelengths of light using finely tuned lasers. To observe the results of a calculation using a blue laser of 2.345 Angstroms, one would use a blue filter of the appropriate wavelength at the other end to filter out the light in the

²¹⁵ This gets into the topic of counterfactuals, where individual S's counterpart did make the observation in question differently resulting in a different world history, however, this is not the space to discuss such matters. See David Lewis's *On the Plurality of Worlds*.

computer coming from other users, so a single computer could process calculations for many different people at once. This is like Everett's multiverse wave function, which simultaneously calculates many versions of reality. Other versions of reality are not perceptible to our own.²¹⁶

The waves of the SE describe every possible way the system might develop, and we can think of particles in an isolated system,²¹⁷ in a state of superposition, as trying out all possible paths. Everett thought, why assume that collapse occurs at all? It's simpler to assume that the formalism of quantum mechanics tells us that the universe is participating in all possible histories rather than one arbitrary, privileged one. Everett demonstrated that different branches of outcomes naturally arise from the probability waves described by the SE. The peaks and troughs of the wave function illustrate where the particle involved is most likely to be and where it could never be.

Branching is caused by any process that enlarges microscopic superpositions to a point where decoherence can intervene, and further developments of Everett's theory have shown that there are three such processes. First is deliberate human experimentation, like Schrödinger's cat or the double-slit experiment, which is, relatively speaking, a recent and rare process. Second are natural quantum measurements, like when radiation causes cell mutation, which is, relatively speaking,

²¹⁶ Colin Bruce, *Schrödinger's Rabbits: the Many Worlds of Quantum* (Washington, DC: Joseph Henry Press, 2004), 135.

²¹⁷ When we talk about particles in a state of superposition, a useful metaphor, often implemented when discussing electrons orbiting the nucleus of an atom, is to think about particles as being smeared out in a "cloud," where we know, based on prior experience, that when we make an observation, we will find the entities that we refer to as particles located in one position or another, but absent of measurement, in a state of superposition, particles behave just as all matter does: indeterminately separate from their environment such that they can't rightly be referred to as "particles," or any particular entity whatsoever, because they are only determined as particles through intra-action. It is not the case that particles have some intrinsic integrity that macroscopic objects do not possess.

a ubiquitous process. Third are classically chaotic processes, which cause small variations in initial conditions to grow exponentially in such a way that quantum states, at first limited to small regions of space, spread out over large, macroscopic regions. Classically chaotic processes are also ubiquitous, and because chaos is everywhere and where there's chaos there's also branching, branching is everywhere.²¹⁸ This makes it clear that our anthropogenic conception of observation is not the only kind of measurement that results in branching; there is nothing specially "observational," in the human sense, about observation in relation to decoherence and branching world histories.

An important detail to remember about branching world histories is that these phenomena do not lead to naturally discrete branching processes. While quantum chaos leads to decoherence, which gives rise to the emergence of a branching structure, this structure does not have a natural "grain"²¹⁹:

To be sure, by choosing a certain discretization of (phase-)space and time, a discrete branching structure will emerge, but a finer or coarser choice would also give branching. And there is no 'finest' choice of branching structure: as we fine-grain our decoherent history space, we will eventually reach a point where interference between branches ceases to be negligible, but there is no precise point where this occurs. As such, the question 'how many branches are there?' does not, ultimately, make sense.²²⁰

It's common in emergence for there to be some indeterminacy. When we ask questions about the number of branches, we end up asking questions that have no answers, because while decoherence causes the multiverse to develop emergent branching structures – structures which are robust features of reality – "there is *no* non-arbitrary decomposition of macroscopically described histories into 'finest

²¹⁸ Wallace, "Decoherence and Ontology," in *Many Worlds?*, 67.

²¹⁹ Ibid.

²²⁰ Ibid., 67-68.

grained' histories, and *no* non-arbitrary way of counting those histories."²²¹ Asking how many worlds or branches there are is like asking how many experiences you had yesterday. Although it makes perfect sense to say that you had many experiences and even to list the most important categories of your experiences, it does not make sense to ask how many.²²² Experiences, like worlds or branches, are somewhat arbitrarily defined; there is no precise distinction that can be drawn between one experience and another. Branching is happening all around us, continually and eternally, and other than during deliberate human experimentation, which is a relatively rare process, anthropogenic observation is not the primary concern of the branching multiverse; humans are observables, just as much as or even more than we are observers, and the branching multiverse pays no mind to whether or not humans and anthropogenic observation are present.

3.5 EVERETT VS. BOHR: TWO SIDES OF THE SAME COIN

In this section, I will move through four comparisons between Everett and Bohr in order to show that their views are not so dissimilar as commonly believed and that Everett's interpretation of quantum mechanics improves upon Bohr's theory, presenting a more eloquent, cogent model of physical reality. First, I will show that Everett's understanding of the world as fundamentally determinate and Bohr's understanding of the world as fundamentally indeterminate actually stem from the same argument, and the tension is merely a result of language's ambiguity. Second, I will explain how Everett's dissatisfaction with Bohr's artificial barrier between the

²²¹ Ibid., 68.

²²² Ibid.

quantum and classical realms is a result of misunderstanding Bohr's notion of "classical concepts," and additionally, Everett reaches a more agreeable account of the relationship between objectivity and the nature of quantum mechanics. Third, I will describe how both Everett and Bohr reject particularism and attempt to remove the human being from the center of observation while arguing that Everett arrives at a more convincing and consistent rejection of anthropocentrism. Fourth, I will show that, although Everett and Bohr both claimed that there is no external point of observation, Everett's line of reasoning is more compelling because, rather than upholding puzzles about the relationship between quantum mechanics and cosmology, he provides a potential solution.

Subjective Determinacy For All

One major source of contention is that Bohr believed the world to be fundamentally indeterminate while Everett considered the world to be fundamentally determinate.²²³ My position is that although they made these claims that are seemingly in opposition to one another, they're really talking about two sides of the same coin. Everett thought of the world as determinate in that the universal wave function describes all possibilities, each of which is actualized in its respective world history. Determinate here means that all possibilities are actual and every world is in one distinct state or another. Bohr thought of the world as fundamentally indeterminate in that there are no pre-existing entities or properties and no inherent distinctions between entities, and it is only through intra-action that differentiation

²²³ Byrne, *The Many Worlds of Hugh Everett III*, 107-108.

and meaning emerge such that the world appears to be in one determinate state or another. Rephrasing this within the frame of Everett's theory, however, shows that these two ways of understanding the world are much more similar than their respective terminology makes it appear: the multiverse is fundamentally in a state of superposition such that there is not one particular state of affairs and therefore no pre-existing entities or properties, but rather, infinite universes that exist as a result of subjective wave function collapse, giving rise to one version of reality, or one determinate state of affairs, according to each individual copy of each individual observer, where each copy of each observer experiences his own world history.

Everett argued that each copy of a branching observer will subjectively experience determinism, where everything happens, as indeterminism, where one possibility happens by chance.^{224, 225} We could say that objectively, the multiverse is indeterminate, or in a state of superposition, where there is no particular way that things are, as a result of the universal wave function. Everett, however, uses the term "determinate" to convey the notion that all possibilities are actual, although, in Bohr's terms, this would be indeterminacy because the multiverse itself is not in one particular state or another but in a superposition of states. We could similarly say that subjectively, the world is determinate, or there is one particular way that things are, as a result of observation and decohering histories. Everett, however, uses the term "indeterminate" when talking about individual worlds to convey the idea that, although one possibility is being singled out, this state of affairs appears random to

²²⁴ Ibid., 141.

²²⁵ Note that Everett and Bohr use the terms "determinate" and "indeterminate" to convey very different notions from one another.

the observer because he lacks the complete information contained within the universal wave function, having access only to the wave function of his specific world, although, in Bohr's terms, this would be determinacy because the universe is in one particular state or another.

Put another way, the world is subjectively determinate based on the way intra-actions occur and entities and properties are co-constituted through "material-discursive" practices. There are a vast number of ways that things could turn out, so the multiverse, at its most fundamental level, is not one way or another, but contains the potential for infinite states of affairs. It is only once the observer, who can engage in the material-discursive practice of intra-acting within the world, performs its agency that any particular state of affairs becomes determinate. Or, within the frame of Everett's theory, the observer makes an observation, creating a subjective collapse of the wave function into one possible outcome or another. Determinacy and indeterminacy are merely language tools used to convey an idea and, as touched on by Barad and Bohr, do not carry meaning on their own, waiting in the void to be implemented by human agents. The contention thus appears to be more of an issue of how one chooses to use language to communicate ideas rather than a difference of ideas themselves.

The Quantum World Begets the Classical

A second major source of contention is that Everett understood Bohr to be placing an artificial barrier between the quantum and classical realms, advocating for discussing quantum theory in terms of classical concepts, which troubled Everett who

saw classical physics as stemming from quantum physics, not the other way around. While it is true that Bohr insists on using classical concepts to describe quantum phenomena, this, according to Barad, is only because he believed the main issue to be the cut that distinguishes between object and instrument. Bohr, unlike most physicists of his time, didn't assume a fixed, inherent distinction between object and instrument resulting from spatial separation. Instead, he thought it was the materiality of the experimental configuration that enacts the separation, not some metaphysical preconception or arbitrary choice made by the experimenter. Most importantly, he didn't believe that quantum and classical physics should be considered separate domains, explicitly stating that macroscopic systems should be accounted for using the quantum mechanical formalism. However, because Bohr rejected spatial separability as the condition for objectivity, he needed another way to assure objectivity, or else he could communicate hardly anything of scientific value about the physical world.²²⁶

Objectivity for Bohr isn't based on the classical notion of externality but instead on the unambiguous communication and reproducibility of experiments and results. The experimental configuration's enactment of a cut is what allows concepts to have semantic determinacy, making it possible to unambiguously account for and communicate results. This embodiment of concepts, where they're contingently determinate, is what Bohr means by "classical" concepts being necessary. Barad states this clearly when she writes, "Bohr does not ascribe a different physical nature to instruments but insists that to secure an objective description of the results of

²²⁶ Barad, *Meeting the Universe Halfway*, 325-329.

measurements one must use a classical rather than quantum description, that is, a description based on concepts that are given meaning by the larger material arrangement."²²⁷ Measuring devices are described by the laws of classical physics, but classical, in this sense, is to be understood as an identification of embodied terms that are given meaning through a particular agential cut, or a subject-object distinction in terms of epistemology, that is materially enacted, not inherent. Bohr's privileging of classical concepts is a point about the nature of description, not the nature of nature.²²⁸

Bohr's concern with embodied concepts, which he calls "classical," is necessary in order to secure objectivity without inherent spatial separation. Everett can be understood as not needing to secure objectivity through embodied, classical concepts because the postulation of many worlds allows for individual universes to be composed of spatially separated, observation-independent entities, which itself secures objectivity. It's important to remember that spatially separated entities within individual universes are only subjectively determinate, according to one particular version of one particular observer. Subjective determinacy is sufficient for obtaining spatial separability because, although each possible world history is subjectively experienced, all possibilities are actual, none any more real than another, and subjective separability can be understood as corresponding to an agential cut made within the world branch in question. Everett maintains that because we experience our own versions of reality and everything contained within them to be real, they, and everything they contain, must all be equally real, so if we perceive spatial separation and observation-independence to be attributes of our reality, then these attributes are

²²⁷ Ibid., 329.

²²⁸ Ibid., 229-230.

also real (at least subjectively). Essentially, Everett has maintained the conventionally accepted notion of objectivity in the sense that, according to any individual universe, entities are experienced as spatially distinct from one another and existing independently of observation, while simultaneously agreeing with Bohr that, according to the universal wave function, the underlying reality is indeterminately suspended in a state of superposition. Therefore, Everett more agreeably accounts for the way that we commonsensically perceive objectivity in the world around us without sacrificing the fundamental nature of quantum mechanics.

Humans: Not So Special After All

In a sense, both Everett and Bohr were rejecting particularism, or metaphysical individualism, the view that the world is made up of individuals, each of which has its own nonrelational properties. Bohr's primary ontological unit is phenomena, not individuals. Phenomena, the basic units of existence, are relations without pre-existing relata. To reiterate, on Bohr's account, relata do not pre-exist relations; relata exist within phenomena and emerge through specific intra-actions,²²⁹ and Everett can be understood as similarly rejecting the particularist view. That being said, he can be understood as also expanding on it, holding that relata, while not pre-existing entities and while also not mere illusions because they hold meaning in the way we experience the world, are only relevant to the subjective experience of a particular branch of world history. The multiverse, most fundamentally, is in a state of superposition, where nothing pre-exists and everything comes about through

²²⁹ Ibid., 333-334.

specific intra-actions,²³⁰ which can also be referred to as measurement interactions or observations.

Specific material practices, or specific ways that the world is materially configured, causally produce specific material phenomena. Phenomena are then specific material performances of the world, not just the result of human experimentation and human concepts, and matter is understood as a process, not a thing. For both Everett and Bohr, measurement interactions can be understood as physical, causal intra-actions, or entanglements, between component parts of a system or phenomenon.²³¹ The entities that emerge out of these material-discursive practices never existed and will never exist independently of their environments, just as the agency that an entity possesses is never isolated. Any entity within the world that performs its agency is doing so in a way filled with collaborative processes and intra-actions, inevitably involving co-constitution and joint effect. Parts of the world are always interacting with other parts of the world, and there is a constant ebb and flow of agency.²³²

Following from this, both Everett and Bohr wanted to remove the human being from the center of observation. Bohr signals to a posthumanist approach when he says that we should understand ourselves as part of the nature we seek to understand, but then he retreats to a humanist understanding when he claims that the human experimenter is individuated and determined before the experiment is performed and has the power to choose the apparatus for the experiment. The

²³⁰ While Everett doesn't use this Barad-Bohr terminology, it applies to his view as well.

²³¹ *Ibid.*, 335-337.

²³² *Ibid.*, 338.

problem with this is that if humans themselves are part of the processes and intra-actions of the world, we can't also stand apart from these processes and intra-actions, fully outside of ourselves, to obtain knowledge about the world; the knower cannot stand outside of the world he is trying to understand.²³³ The way we obtain knowledge is through the natural process of engaging with the world as part of the world. We understand nature as something revealed to us through scientific practice, but this requires the additional understanding that scientific practices are natural processes, not something external imposed on the world.²³⁴

Science is to be understood as a natural activity practiced within and by nature rather than from outside nature, and we therefore must also understand humans as part of nature.²³⁵ If scientific practices are natural processes, or causal intra-actions, then "knowing is a material practice, a specific engagement of the world where part of the world becomes differently intelligible to another part of the world in its differential accountability to or for that of which it is a part,"²³⁶ and this is precisely what Everett is saying when he discusses the subjective collapse of the wave function. What's really happening during "collapse" is that information is being lost to the observer while the multiverse continues to be governed by the non-collapsing universal wave function.²³⁷ Because each copy of a branching universe can only access partial information about the total quantum state of the multiverse, the branching process²³⁸ involves an objective loss of information to each copy of an

²³³ Ibid., 341-342.

²³⁴ Ibid., 331.

²³⁵ Ibid., 332.

²³⁶ Ibid., 342.

²³⁷ Byrne, *The Many Worlds of Hugh Everett III*, 141.

²³⁸ I.e. measurement

observer within a single world history. Being confined to one world history leads us to experience measurement as an increase in information, resulting in a determinate state of affairs where we perceive one or another event as happening.²³⁹

One of Bohr's biggest questions for measurement practices was how subjective components, such as human concepts, affect the possibility for objectivity in the measurement results. In other words, how do we account for the fact that science works? Bohr insists that concepts are materially embodied in the apparatus, and only concepts defined by this specific, material embodiment are semantically determinate. This embodiment of concepts within the physical apparatus is what makes objectivity, or communicability and reproducibility, possible. A glaring problem with Bohr's account here is that it places humans at the center and foundation of quantum theory as well as scientific practices more generally, claiming that humans are intimately connected to the conditions for the possibility of making measurements and determinations. Additionally, Bohr treats experimental apparatuses as ideal measuring devices, neglecting to take account of the complications involved in actual experimentation, especially in his failure to note that, in practice, apparatuses are subject to outside influences, instead assuming that, generally speaking, the scientist in no way intervenes but merely records objective data.²⁴⁰

Although he gestures to a posthumanist understanding of the nature of reality, Bohr still clings to the humanist view that people are separately determinate from the observables being examined, excluding the human from the natural domain, thereby

²³⁹ Ibid., 156.

²⁴⁰ Barad, *Meeting the Universe Halfway*, 143-144.

creating a human-nature duality.²⁴¹ Barad challenges the anthropocentric and idealized laboratory elements of Bohr's theory, writing that "to the extent that 'humans' emerge as having a role to play in the constitution of specific phenomena, they do so as part of the larger material configuration, or rather the ongoing reconfiguring, of the world. Thus no a priori privileged status is given to the human – and this is precisely the point. 'Humans' are emergent phenomena like all other physical systems."²⁴² My claim is that Everett meets and exceeds these challenges that Barad proposes for Bohr's theory, pushing them further toward a more coherent and intuitive understanding of the nature of reality.

Everett more successfully and consistently removes humans from the center of observation, arguing that the observer in question needs only to be physical. His sole requirement for observation is that an event create some sort of record on the relevant environment, which is similar to Bohr's criterion that measurement create a mark on the relevant body, and this does not require human agency.²⁴³ Because Everett maintains the conventional understanding of objectivity and posits many branching histories, he rids his theory of the necessity to insist that only concepts that are materially embodied in the measuring apparatus are semantically determinate, because the meaning of any particular concept is instead construed based on the particular version of reality depicted by a particular world branch. Put another way, all meanings, or ways of understanding reality, are accounted for within the set of possible worlds.

²⁴¹ Ibid., 339.

²⁴² Ibid., 338.

²⁴³ Byrne, *The Many Worlds of Hugh Everett III*, 147.

To reiterate a point from earlier in the chapter, deliberate human observation, as a relatively recent and rare process, only accounts for a tiny fraction of branching events. Most world branches come about in conjunction with natural quantum measurements or classically chaotic processes, both of which are relatively ubiquitous and require only physical interaction, or performed agency of a physical kind, but nothing specifically related to human beings. These branching processes occur without human intervention, including in universes where humans are not present at all. Most branching processes require nothing as "observational" as what we conventionally understand observation to be, and, based on Everett's claim that the only agency required in order for observation to occur is that an event create a mark on its environment, we could even go so far as to say that observers and branching processes would be just as prevalent in a universe devoid of life or cognition as we know it.

The Wave Function Includes All Observers

Both Bohr and Everett insisted that there is no external point of observation, but I believe that Everett's theory, because it implies many worlds, more effectively explains why this is the case and more successfully accounts for the consequences that follow. While Bohr's theory does distinguish between the observer and observed, it also recognizes them as part of a single phenomenon, or parts of one entangled state.²⁴⁴ A major puzzle for relating quantum theory to cosmology lies in the fact that quantum mechanics requires a relation of externality between measuring agencies and

²⁴⁴ Ibid., 351.

the measured system while cosmology implies that there is no "outside" to the universe that would allow measuring agencies to observe the universe as a whole. On Bohr's account, because there is no outside to the universe, the universe as a whole can't be described. Instead, the description always comes from within the universe, because "only part of the world can be made intelligible to itself at a time, because the other part of the world has to be the part that it makes a difference to."²⁴⁵ However, Everett restructures our conception of the universe by positing many branching histories within the universe, or in terms of our current language regarding many-worlds theory, many universes within the multiverse.

There is no outside to any individual universe because the observer is confined to his world history line, and within a single world history, there is no point of external observation, but the universal wave function provides a complete, or objective, description of all of these individual universes. According to Everett's theory, no particular "observer" (whatever may constitute an observer, from a quantum particle to a human being) can measure the universe as a whole, because all measurements imply subjective probabilities, but the universal wave function, as the underlying reality, does provide an "outside" to individual universes, on which the subjective state of any particular observation is based. Everett's theory of pure wave mechanics nullifies the necessity that observations take place outside of the observed quantum system, instead claiming that the wave function includes all observers, which would be especially useful in creating a theory of quantized gravity, a major conundrum for current physics, because an observer can't stand outside of the

²⁴⁵ Ibid., 350-351.

universe.²⁴⁶ Everett's theory thus allows quantum mechanics to meet its requirement of having a relation of externality between the measuring agencies and the measured system while also maintaining cosmology's implication that there is no outside to any individual universe that an individual observer could access to measure the universe as a whole, because this "outside" is the theory behind the many worlds: the universal wave function.

Although Everett's many-worlds interpretation goes against our common understanding of the nature of reality, it has been shown to make perfect sense in terms of the physics and mathematics while making few assumptions about the world.²⁴⁷ The MWI can be thought of as being simpler than all others, by way of Occam's razor, because it requires no new physical assumptions, necessitating only that we extend our acceptance of the rules that apply to small systems, such as particles, to larger systems, such as our universe, which is itself the simplest of extensions to make because assuming dualism, where different rules apply to micro- and macro-systems, requires taking an extra step and making an arbitrary division that holism, where the same quantum rules apply to all systems, does not. MWI can also be understood as the most intuitive of current interpretations because it allows us to maintain a universe of three dimensions of space and one of time, where nothing is random and the locality assumption prevails.²⁴⁸

²⁴⁶ Barrett and Byrne, "Biographical Introduction," in *The Everett Interpretation*, 18.

²⁴⁷ Gribbin, *In Search of the Multiverse*, 35.

²⁴⁸ Bruce, *Schrödinger's Rabbits*, 127-128.

CONCLUSION: GETTING TO KNOW THE MULTIVERSE

"We can believe that we will first understand how simple the universe is when we recognize how strange it is."

–J. A. Wheeler, *From Relativity to Mutability*²⁴⁹

4.1 A SUMMARY

In the introduction, I laid out what I see as the most crucial interpretational difficulties facing quantum mechanics: the problem of measurement and the subsequent puzzles regarding the nature of the universe that follow. While quantum mechanics has proven itself to be able to account for nearly all phenomena while being empirically efficient and accurate, the interpretational difficulties have become an ever-increasing problem for physicists because of the consequences they pose to the newly discovered practical implications of quantum theory, such as quantum computing, quantum cryptography, and quantum teleportation. The measurement problem includes the interpretational issues that arise from the conundrum of how to understand the wave function, which is mathematically described by the SE, and collapse of the wave function, which appears to be part of our experienced world but is not described by the SE. The SE accounts for superpositions, entanglements, and everything that happens to the wave function between measurements but does not account for the "collapse," where a superposition of states resolves into one particular state or another, which appears to occur as a result of measurement.

The project of this thesis was: 1) to look at Niels Bohr's interpretation of quantum mechanics, as understood by Karen Barad, and his solution to (or perhaps

²⁴⁹ J. A. Wheeler, *From Relativity to Mutability* (Dordrecht: Reidel, 1973), 245.

more appropriately, his denial of) the measurement problem, 2) to look at Hugh Everett's interpretation of quantum mechanics, in part as made popular by Bryce DeWitt, and his solution to (or denial of) the measurement problem, and 3) to compare and contrast Bohr and Everett's interpretations in order to show that Bohr's view can be understood as laying down the metaphysical framework for Everett's view, which ultimately leads to a more coherent, consistent, and compelling understanding not only of the measurement problem, but also of the nature of the universe (or in terms of current many-worlds theories, the multiverse).

One of the most foundational aspects of Bohr's interpretation of quantum mechanics is that he rejected representationalism, the independent determinacy of things, instead claiming that the world is fundamentally indeterminate, with things only having determinacy relative to and as a consequence of the intra-actions that occur with and within the world of experience. This rejection involves denying several foundational assumptions of Newtonian metaphysics: belief in individualism, in there being an intrinsic separation between the knower and known, and in the strict determinism that describes Newtonian physics.²⁵⁰ In other words, Bohr opposed the presumption that entities have inherently determinate boundaries and properties and that words are inherently semantically determinate, questioning the notion of an inherent subject-object distinction. Phenomena make up physical reality in that they're relations without pre-existing relata, and the intra-action that occurs as part of

²⁵⁰ Barad, *Meeting the Universe Halfway*, 107.

and within entities requires us to engage in a conceptual shift where we no longer presuppose the pre-existence of independent relata.²⁵¹

Intra-action is what marks the determinate boundaries and properties of the parts that make up the phenomenon in question and is what gives particular concepts meaning. It includes the entire system, which contains "subject" and "object," between which there is an agential cut rather than an "interaction" that presupposes this distinction. An agential cut provides the distinction between subject and object but only within a particular phenomenon, and the relata that we perceive to exist within phenomena come about through specific intra-actions, which restructure causal relationships by enacting the measuring agencies as effect and the measured object as cause. Measurements as causal intra-actions express particular facts about what is measured, and apparatuses are not mere measuring devices but also draw ontological distinctions. Bohr's primary ontological unit, therefore, is phenomena, not "things," and his primary semantic unit isn't "words," but materially-based intra-actions through which ontic and semantic boundaries are made determinate. Measuring apparatuses produce and are part of phenomena.²⁵²

Bohr's belief regarding the notion of collapse is that measurements don't entail any physical collapse; instead, they necessitate configuration-dependent distinctions between entities. Boundaries and properties are only determinate within a specific phenomenon through the enactment of a cut, which is determined by the materiality of the larger experimental configuration, and when we make measurements, we're essentially looking inside a phenomenon to see that the measuring instrument

²⁵¹ Ibid., 137-139.

²⁵² Ibid., 139-141.

specifies a value that corresponds to an eigenvalue. We can never get outside of the phenomenon to observe the entanglement, because this would require the implementation of a further apparatus to measure the first phenomenon, which only creates an extended entanglement of the first phenomenon and the new apparatus, creating a new phenomenon and so on, in an infinite regress. Therefore, there is no collapse, or at least no physical mechanism, that resolves a superposition, and the question of collapse is really about how to account for the measurement-dependent distinctions within phenomena. For Bohr, the measurement problem is explained through entanglements and agential separability, not physical collapse. In other words, Bohr denies that there is a measurement problem at all because the problem is resolved by the difference between describing mixtures classically and superpositions quantum mechanically. Measurement instruments can't take themselves into account and can't measure their own entanglement with the measured object, so the distinctions we make between subject and object during measurement don't disentangle the phenomenon into its component parts but just allow for a description in terms of mixtures. This measurement-dependent distinction gives a resolution of ontological inseparability within the phenomenon that's contingent on the apparatus's material configuration, allowing for a description in terms of mixtures, but only within the phenomenon in question because really, there's only one entity: the phenomenon.²⁵³

Everett claimed that the superposition of states is never resolved because the wave function never collapses. When an observer makes a measurement, instead of

²⁵³ Ibid., 343-348.

the wave function collapsing, the entire universe, including the observer, splits. All of the possible outcomes are equally likely and so equally real: in one branch of reality, outcome A happens, while in another branch of reality, outcome B happens, and so on.²⁵⁴ The SE describes the continuous, causal evolution of quantum systems through time, and all possible events are contained within the wave equation. All information is also contained within the universal wave function, which is the fundamental entity of the universe, always obeying a deterministic wave equation.²⁵⁵ Everett attempted to measure the amount of information available after some event happened and an observer split and match the result to a probability statement instead of collapsing the wave function to find a probability. In other words, Everett found a classical probability measure over branching events without invoking collapse, and he thought this explained why an observer residing within a single world history subjectively experiences probability in a multiverse that contains branches corresponding to every physically possible event.²⁵⁶

After a measurement interaction, all elements of the superposition of the measured object are entangled with their respective copies of the observer. Every copy exists relative to the state of the observed object and to the rest of the branching multiverse, and each copy and each state of the observed object is correlated to the branching multiverse. All parts of the superposition exist simultaneously, and the whole process is continuous. The observer has no special role and is just a case of interaction between physical systems that correlates a quantity in one subsystem with

²⁵⁴ Gribbin, *In Search of the Multiverse*, 25-26.

²⁵⁵ Byrne, *The Many Worlds of Hugh Everett III*, 146.

²⁵⁶ *Ibid.*, 150-151.

a quantity in another.²⁵⁷ For Everett, the measurement problem is a mere misunderstanding that arose from adding the unnecessary postulate of measurement as being a special process to a theory that works without this postulate. On its own, pure wave mechanics, the unitary evolution of quantum states without any collapse postulate, gives a complete account of quantum mechanics.²⁵⁸ Everett took his theory to be objectively causal and continuous while simultaneously probabilistic and discontinuous, applying to all systems of any size and explaining the appearance of the macroscopic world.²⁵⁹ He believed pure wave mechanics to describe a complete and accurate physical theory where particular measurement records explain our particular experiences and show that measurement records in relative states reveal standard quantum statistics.²⁶⁰

Everett's "relative states" theory claims that the universal wave function, or the quantum state of the totality of existence, has an objective reality and the wave function itself never collapses. Instead of the wave function collapsing into a single history, it "collapses" only subjectively, and every possible quantum outcome is realized. This reconciles the observation of indeterministic events with the fully deterministic equations of quantum theory, and the subjective appearance of the wave function collapse that causes any observer to claim that the world is in a determinate state is explained by quantum decoherence. Every possible outcome of every event exists in its own world history. Collapse never really happens, and the universe explores all possible outcomes, each of which is to be considered equally real. Everett

²⁵⁷ Ibid., 151-153.

²⁵⁸ Barrett and Byrne, "General Introduction," in *The Everett Interpretation*, 7.

²⁵⁹ Everett, "Minipaper: Probability in Wave Mechanics (1955)," in *The Everett Interpretation*, 69.

²⁶⁰ Barrett and Byrne, "Conceptual Introduction," in *The Everett Interpretation*, 37.

believed his theory to give a complete, causal account of quantum mechanics as well as explain the probabilistic aspects of the subjective level of experience. Internal correlations of the wave function explain our perception of the macroscopic world and its apparent probabilistic nature. Pure wave mechanics is thus logically consistent insofar as it's modeled by the correlation structure given by the evolution of the universal wave function, and Everett showed that it's also empirically faithful because actual experience is represented by the relative measurement records on a world history line that's associated with a probability measurement as determined by only pure wave mechanics.^{261, 262}

Taken together, Bohr and Everett can be understood as arguing for two sides of the same coin with regard to their metaphysical beliefs. First, I showed that Everett's understanding of the world as fundamentally determinate and Bohr's understanding of the world as fundamentally indeterminate actually stem from the same argument, and the tension is merely a result of language's ambiguity. Everett thought of the world as determinate in that the universal wave function describes all possibilities, each of which is actualized in its respective world history, and Bohr thought of the world as fundamentally indeterminate in that there are no pre-existing entities or properties and no inherent distinctions between entities. The pivotal move is to look more closely at Everett and Bohr's respective uses of determinacy and indeterminacy, which are commonly taken to be antonyms, and to realize that Bohr uses "indeterminacy" as Everett uses "determinacy," and vice versa. Uniting their

²⁶¹ Everett, "Minipaper: Probability in Wave Mechanics (1955)," in *The Everett Interpretation*, 70.

²⁶² Barrett and Byrne, "Conceptual Introduction," in *The Everett Interpretation*, 53.

terminology leads to an understanding of the world as subjectively determinate based on the way intra-actions occur and entities and properties are co-constituted through material-discursive practices.

Second, I explained that Everett's dissatisfaction with Bohr's artificial barrier between the quantum and classical realms is a result of misunderstanding Bohr's notion of "classical concepts," and additionally, Everett reaches a more agreeable account of the relationship between objectivity and the nature of quantum mechanics. Bohr's concern with embodied concepts, which he calls "classical," is necessary in order to secure objectivity without inherent spatial separation, but Everett doesn't need to secure objectivity through embodied concepts because the postulation of many worlds allows for individual universes to be composed of spatially separate, observation-independent entities, subjectively speaking, which itself secures objectivity. Everett manages to maintain the conventionally accepted notion of objectivity in that, according to any individual universe, entities are experienced as spatially distinct from one another and existing independently of observation while simultaneously agreeing with Bohr's claim that, according to the universal wave function, the underlying reality is indeterminately suspended in a state of superposition.

Third, I described how both Everett and Bohr reject particularism and try to remove the human being from the center of observation while maintaining that Everett arrives at a more convincing and consistent rejection of anthropocentrism. To merge their language, they both hold that the multiverse, most fundamentally, is in a state of superposition, where nothing pre-exists and everything comes about through

specific intra-actions. Phenomena are specific material performances of the world, not just the result of human experimentation and human concepts. While Bohr signals to a posthumanist approach only to then retreat to a humanist understanding where the human is excluded from the natural domain, Everett pushes the rejection of anthropocentrism further, arguing that the observer in question needs only to be physical. Branching processes most frequently occur without human intervention, including in universes where humans are not present at all: the human being is not a necessary element of the equation for branching to be a characteristic of the multiverse.

Fourth, I illustrated that Everett and Bohr both claimed there to be no external point of observation but that Everett's reasoning is more compelling because he provides a potential solution for the puzzles about the relationship between quantum mechanics and cosmology. Bohr's account claims that because there is no outside to the universe, the universe as a whole cannot be described, and instead, description always comes from within the universe. Everett manages to restructure our conception of the universe by positing many universes within the multiverse, which allows us to better approach the problem of relating quantum theory to cosmology. While no particular observer can measure the universe as a whole, the universal wave function, as the underlying reality, does provide an "outside" to individual universes, on which the subjective state of any particular observation is based. Pure wave mechanics renders null and void the necessity that observations take place from outside of the observed systems, instead claiming that the universal wave function includes all observers. Quantum mechanics can therefore meet its requirement of

having a relation of externality between the measuring agencies and measured system while maintain cosmology's implication that there is no outside to any individual universe that an individual observer could access, because this "outside" is the theory – the universal wave function – behind the many worlds.

4.2 A FURTHER ELUCIDATION OF MANY-WORLDS

Ultimately, my argument is that Everett's MWI provides the most coherent account of physical reality. While his theory may appear counterintuitive to some, its lack of appeal to common sense is no fault of the theory. Our intuitions about what's reasonable or commonsensical were designed to aid in our human survival, resulting from our limited experience of the world, and the universe is not required to conform to our mere human intuition. This is exactly Everett's point: just because we can't directly experience the quantum world does not mean that we should, or can, reduce it down to classical concepts, and just because we understand the world through classical language does not mean that the world isn't most fundamentally quantum mechanical. Everett's interpretation of quantum mechanics is just quantum mechanics taken literally, as a description of the universe, where the quantum state is all there is at the most foundational level. However, Everett's MWI is not immune to its own interpretational difficulties.

One problem that people have with MWI is how to understand the relative probability of different quantum outcomes, such as the likelihood of ending up in one world over another. How, through the mathematics, do we find out that we're a certain amount more likely to end up in one branch of world history than another?

Everett proposed a concept called "measure," conveying the idea that when outcomes diverge, an individual's subjective likelihood of ending up in a particular world line is in proportion to its measure. The difficulty is that many physicists view this as effectively introducing an extra dimension into MWI, where world branches have depth (their world history) and width (their probability of occurring). If one of the most convincing reasons for accepting MWI in exchange for the vast number of universes it implies is how few additional assumptions it makes, then positing some extra depth of dimension to reality adds an unfavorable complication.²⁶³

Lev Vaidman, a physicist and supporter of the MWI, answers this probability concern with a rewording of Everett's original answer to the measurement problem: "The probability of an outcome of a quantum experiment is proportional to the total measure of existence of all worlds with that outcome."²⁶⁴ He points out that when world histories decohere, we don't know the details of this decoherence until after it has happened. "Measure" doesn't have much meaning but is really just a restatement of the same probabilities described in the SE. He illustrates this with an example where we're asked to place a bet on a quantum coin toss, and right before the coin tossing apparatus is activated, we're given a sleeping pill. We then wake up in a world where the quantum coin toss has been performed and the outcome is known, although we don't yet know the outcome, and we are asked if we'd like to change our bet. There's no rational reason to change it, so in this case, there's no practical difference between the classical ignorance view of probability and the quantum interpretation where all outcomes have actually happened. Even in a classical coin toss, it takes time

²⁶³ Bruce, *Schrödinger's Rabbits*, 170-171.

²⁶⁴ Quote attributed to Vaidman in Bruce, *Schrödinger's Rabbits*, 174.

for all of the quantum outcomes occurring at the microscopic level to be amplified by decoherence to produce sets of worlds different enough that macroscopic events vary. If we bet on a classical coin toss and lose, we know there are other versions of ourselves in other worlds who won, but those versions of us have already decohered from our world. Similarly, if we bet on a quantum coin toss, by the time we become aware that we've lost, we can also assume that we've won in other worlds that decohered from ours once the toss finished. The point is that our knowledge of the results of these coin tosses is retrospective, so there's no practical difference between a quantum and classical coin toss. Accordingly, Vaidman thinks of measure as something like a percentage value tag attached to each world history, representing only the probability of its occurrence and nothing else, which is already given by the SE, such that "measure" proves not to be an obstacle for MWI.²⁶⁵

A second, more prevalent problem, which contains two difficulties that people have with MWI is that it implies an infinity of worlds. The first difficulty is that MWI implying an infinity of worlds is often construed as meaning there are worlds where the MWI is wrong. The simple answer to this is that infinity is not just infinity. A set being infinitely large doesn't mean that it includes everything. For example, the set of all positive, even integers is infinitely large $\{2, 4, 6, 8, \dots\}$ but there are many numbers, and many kinds of numbers, that it does not contain, such as 5, -4 , 9.46 , or $\sqrt{-1}$. In the same way, the mathematics of quantum mechanics might imply an infinity of worlds, but this infinity is a set which contains a specific type of worlds that follow specific rules, just like how all numbers in the set of positive, even integers is

²⁶⁵ Bruce, *Schrödinger's Rabbits*, 174-175.

infinitely large but only contains a specific kind of numbers that adhere to a specific set of standards.²⁶⁶

The second difficulty, and arguably the biggest struggle that people have with MWI, is the vast number of universes it implies exist. This is known as "ontological extravagance," posing a threat to MWI because even though it obeys Occam's razor in that it doesn't posit many new assumptions, it does posit an extravagant number of worlds. Be that as it may, this sounds eerily similar to the historical development of our understanding of the universe. It was only a few hundred years ago that most astronomers believed the universe consisted of only our own solar system, and the points of light we now know to be stars were thought to be insignificant. Astronomers then noticed that the apparent positions of some of these points of light shift relative to others, just as what happens with parallax on Earth and within our solar system. Measurements enabled astronomers to calculate the distance to the nearest stars, and we learned that, based on their luminosity, they must be objects similar to our sun with respect to size and power and might even have planets of their own orbiting them. About 100 years ago, when astronomers still thought the universe consisted of only our galaxy, we saw fuzzier, extended objects through telescopes among the stars. These were initially thought to be clouds of gas and dust within our galaxy, but under closer examination, they turned out to have luminosities unlike anything expected from a cloud of gas and dust. Astronomers faced a choice of either putting forth a new law of physics or accepting that the universe was vaster than just our galaxy,

²⁶⁶ Ibid., 170-171.

containing something more like a hundred billion galaxies. At the time, astronomers were hesitant to accept the latter option, but today, few would doubt it.²⁶⁷

We now accept that the universe contains 10^{22} stars, the information about which has been gathered entirely from observations and deductions, the nearest of which we will likely never be able to directly experience. Even though we can never visit distant galaxies, we understand them as being just as real as our own. It isn't as if our being able to see a galaxy makes it real either; an alien living in a galaxy far, far away doesn't fear that he'll blink out of existence once he's out of Earth's sight.²⁶⁸ Is it possible that positing many worlds is a continuation of this trend? A parable, given by Colin Bruce, demonstrates the appeal of MWI:

"Imagine that you are traveling on a ship, and you don a pair of special glasses that let you see a little way into diverging quantum world lines... To your astonishment, you see that the ship keeps blurring and then separating into two equally solid-looking copies, which rapidly diverge to left and right. Sometimes you are on the right-hand ship, and sometimes on the left-hand one. You can get only a very brief glimpse of the other ship each time, but you can see yourself on it, and you can just see the events on board beginning to diverge from those of your own vessel before it becomes lost in the mist."²⁶⁹

The question that arises is, why should you assume that the ship you're on just happens to always be the one that's real? Aren't all of the ships, even the ones you're not on, entitled to reality? Just as in the thought experiment that asks you to imagine that you're the only real person on Earth and the other 7 billion people are something

²⁶⁷ Ibid., 136.

²⁶⁸ Ibid., 137-139.

²⁶⁹ Ibid., 137.

like robots, the Copernican principle of mediocrity²⁷⁰ tells us that it's absurd to think that our particular world history is somehow privileged.²⁷¹

One of the best reasons for taking Everett's MWI seriously is that no one has found another way to describe the entire universe in quantum terms. Wheeler commented on Everett's 1957 paper, saying, "Apart from Everett's concept of relative states, no self-consistent system of ideas is at hand to explain what one shall mean by quantizing a closed system like the universe of general relativity."²⁷² A theory of quantized gravity is hard to postulate because the equations of general relativity involve the motion of macroscopic objects in classical terms while quantum mechanics is used to understand the microscopic realm, so the mathematical coordinate systems used to describe motion for the macro- and microcosms are incompatible. In other words, relativity can't describe the motion of particles through time and quantum mechanics can't describe the effects of gravity, which is a problem because "gravity and the quantum of action interlace."²⁷³ One potential solution to this dilemma is to consider quantized gravity to be a field rather than a particle, and, in his dissertation on quantizing gravity, Charles Misner wrote, "My Feynman path integral approach to quantum gravity is mostly considered an attempt to calculate the operations necessary to *evolve the wave function of the universe forward in time*. A rigid adherent of the Bohr observer-driven collapse of the wave function would have anathematized any attempt to evolve a wave function which served no observer. Thus

²⁷⁰ The Copernican principle of mediocrity tells us that if an item is drawn at random from several sets of categories, it's most likely to come from the most numerous category. In other words, we are to assume mediocrity rather than that some phenomenon is somehow exceptional.

²⁷¹ Ibid.

²⁷² Gribbin, *In Search of the Multiverse*, 31.

²⁷³ Byrne, *The Many Worlds of Hugh Everett III*, 179.

the awareness that Hugh's alternative view of quantum mechanics existed left me free to think about formulating the dynamics of quantum gravity."²⁷⁴

The potential to help quantize gravity that lies within Everett's theory centers around the fact that the MWI allows us to talk about the wave function of the universe; the MWI gives the term "quantum cosmology," a term initially coined by Misner that is now in popular use, coherency by positing that the wave function includes all observers, as discussed in section 3.5. If the wave function has to do with the information available to the observer after defining an experiment, as in Bohr's case, then there remains a question about how quantum mechanics could have ruled the early universe when there were no observers who could have performed experiments in the anthropogenic sense. Additionally, Misner explained that after Everett's theory was published, astrophysical discoveries, such as cosmic microwave background information about the early universe, caused some cosmologists to adopt many-worlds theories.²⁷⁵ Misner noted,

To interpret that kind of thing and make sense of it, they really had to say what do you mean by the wave function of the universe? That started a bunch of things, not all of which are the same as Hugh's. But, they're all within the viewpoint of believing, as Hugh did, that the standard equations always work and then you just have to understand within that framework how our human, everyday experiences arise.²⁷⁶

The more we learn about the universe and how to understand it, the more it seems that the only way to reconcile classical with quantum physics is to accept the MWI.

²⁷⁴ Quote attributed to Misner (private communication, 5/6/2008, italics added) in Byrne, *The Many Worlds of Hugh Everett III*, 180.

²⁷⁵ Byrne, *The Many Worlds of Hugh Everett III*, 180-182.

²⁷⁶ Mark Everett interviews with Harvey Arnold, Charles Misner, Susanne Misner, Hal Trotter, June 2007.

However true this may be, Everett's theory has proven to be the perfect example of how hard it can be to linguistically describe a logically consistent formalism.²⁷⁷

Everett points out that because his theory doesn't make empirically testable predictions that differentiate it from other theories, acceptance of his theory is mostly a matter of interpretational preference. He himself was convinced that it was empirically correct but didn't believe that any one model was capable of fully describing physical reality:

"Once we have granted that any physical theory is essentially only a model for the world of experience, we must renounce all hope of finding anything like '*the* correct theory.' There is nothing which prevents any number of quite distinct models from being in correspondence with experience (i.e., all 'correct'), and furthermore, no way of ever verifying that any model is completely correct, simply because the totality of all experience is never accessible to us."²⁷⁸

In other words, it's up to the individual reader to determine for himself whether or not Everett's theory fits his understanding of physical reality.²⁷⁹ Contrary to the cries of many physicists who thought Everett's theory could not possibly be correct because we don't feel any splitting, Everett argued that the relative-state formulation of quantum mechanics is in accord with our experience of the world because it predicts that no observer would be aware of any branching of worlds.²⁸⁰ In a footnote to his paper, he wrote, "From the viewpoint of the theory, *all* elements of a superposition (all 'branches') are 'actual,' none any more 'real' than the rest. It is unnecessary to suppose that all but one are somehow destroyed."²⁸¹ We don't feel the branching

²⁷⁷ Barrett and Byrne, "Biographical Introduction," in *The Everett Interpretation*, 24.

²⁷⁸ Everett, "Long Thesis: Theory of the Universal Wave Function (1956), in *The Everett Interpretation*, 170.

²⁷⁹ Barrett and Byrne, "Biographical Introduction," in *The Everett Interpretation*, 25.

²⁸⁰ Ibid., "Conceptual Introduction," in *The Everett Interpretation*, 52.

²⁸¹ Quote attributed to Everett in Gribbin, *In Search of the Multiverse*, 28.

because no branch affects any other branch, and this implies that no observer would be aware of the splitting.²⁸²

Criticisms centering around the fact that we don't experience any of this branching so it can't possibly occur are along the same lines as criticisms of the Copernican theory that the Earth couldn't possibly be moving because we don't feel this motion. Both cases show that the criticisms fail because the theories themselves predict that our experience will be what it is, that is, unaware of the motion or splitting. In the case of the Copernican theory, it was the advent of Newtonian physics that explained why it makes sense that we don't feel Earth's motion. In the case of the MWI, we must understand that the universes are dynamically cut off from each other after the split and there is no way to communicate between them: they are separate states.²⁸³

Everett thought his theory could more appropriately be considered homomorphic (rather than isomorphic)²⁸⁴ to our world of experience for two main reasons, the first being that some elements of the theory don't directly correspond to experience and the second being that the theory doesn't try to explain all of experience. Pure wave mechanics is thus empirically faithful because actual

²⁸² Gribbin, *In Search of the Multiverse*, 27.

²⁸³ *Ibid.*, 27-29.

²⁸⁴ Where a homomorphism is a structure-preserving map between entities such that a function $f: G \rightarrow H$ from group G to group H is a homomorphism if $f(ab) = f(a)f(b)$ for all $a, b \in G$, while an isomorphism is a bijective homomorphism: "By isomorphism we mean a mapping of some elements of the model into elements of the perceived world which has the property that the model is faithful, that is, if in the model a symbol A implies a symbol B , and A corresponds to the happening of an event in the perceived world, then the event corresponding to B must also obtain. The word homomorphism would be technically more correct, since there may not be a one-one correspondence between the model and the external world." Everett, "Long Thesis: Theory of the Universal Wave Function (1956)," in *The Everett Interpretation*, 169.

experience is represented by relative measurement records on a branch, or world history line, that are associated with a probability measurement as determined by only pure wave mechanics.²⁸⁵ Although Everett advocated pure wave mechanics, he was open to various interpretations of quantum mechanics and of his own theory, as long as they were physical, not mental, emphasizing his stance as a realist.²⁸⁶

Because pure wave mechanics is logically consistent insofar as it's modeled by the correlation structure given by the evolution of the universal wave function, Everett only needed to show that it's empirically faithful.²⁸⁷ If empirical faithfulness and consistency are enough to constitute an adequate physical theory, then Everett has shown that pure wave mechanics is sufficient and has the added bonus of being simple and comprehensive. We can understand Everett as having explained determinate measurement records and standard quantum statistics without convoluting it with metaphysical addendums, invoking only that which naturally emerges from pure wave mechanics itself, such as decoherence and branching histories. If Everett took his project to be finding a representation of our experience in a complete model of pure wave mechanics, then it seems that he succeeded without any help from further interpretations.²⁸⁸ He himself believed that his theory, as described in his theses, was complete, although it's possible that Everett was looking for something different from a physical theory than what those who came after him were looking for.²⁸⁹ The question is whether we now want more than Everett did, and if so, what is it that we're still seeking? It's unclear exactly how Everett wanted his

²⁸⁵ Barrett and Byrne, "Conceptual Introduction," in *The Everett Interpretation*, 52-53.

²⁸⁶ Ibid., "Biographical Introduction," in *The Everett Interpretation*, 22.

²⁸⁷ Ibid., "Conceptual Introduction," in *The Everett Interpretation*, 51.

²⁸⁸ Ibid., 53-54.

²⁸⁹ Ibid., 50.

relative-state formulation to be understood, but what is agreed upon is that his interpretation requires further interpretation.²⁹⁰

4.3 A TOPIC FOR FURTHER CONSIDERATION: A THEORY OF CONSCIOUSNESS

There are many questions that arise out of Everett's MWI, some of which may have profound implications for the way we understand the nature of the multiverse and our relationship to it. What I've accomplished in my thesis suggests to me several interesting avenues to explore, and in this section, I will focus on one of these possible routes for further consideration of Everett's MWI. I believe it is possible, based on metaphysical claims that Everett has made, including many that he shares with Bohr, to reframe the MWI in terms of a holistic reality in which the most fundamental unit is energy, or consciousness. Part of my motivation for this is to challenge the way that we currently relate to the world around us and to ask what would happen, especially with respect to the way we treat ourselves and others, if we understood ourselves as intimately interconnected with and fundamentally inseparable from everything around us. I believe that this argument follows directly from the metaphysical assertions made by both Bohr and Everett and is especially compatible with the MWI.

The launching point is a question about the causal relationship between observation and branching world histories. There is no claim of a causal relationship between observation and branching world histories; all worlds are assumed to exist externally with nothing bringing them about such that the taking place of observation

²⁹⁰ Ibid., "General Introduction," in *The Everett Interpretation*, 6.

is something that is part of these worlds but nothing actively creates them. This presents a picture of universes that have no efficient cause, which I find counterintuitive. If we live in a world where we experience causality every day, how could we experience a world of causes that itself has no cause? Instead of positing an "uncaused cause," I propose a two-part picture of causation: causes not as events but as processes and intra-actions, and causes not as particulars but as the power within the intrinsic nature of a particular.

Everett conceives of the multiverse as being in a state of superposition, where, at the most basal level, there is no particular state of affairs occurring, and instead, particular states of affairs only come about through intra-acting within the world, or making "observations" about the world. It follows from this that causes can be understood as processes and intra-actions, where nothing has a simple location (i.e. there is no definite instant at which all matter is simultaneously real), and instead, events are abstractions from processes, just as world branches are abstractions from the universal wave function. The most underlying part of reality is the universal wave function, or the processes, but what we perceive is the particular state of affairs contained within our world branch, or determinate events. What's really there is bunches of processes, but one might identify some portion of a process as an event. Everything is one continuous happening and we can't really speak of causes and effects as linking together separate events. Instead, everything is continually causing and continually being affected. We could think of the world as containing a causal field, like a magnetic field, without beginning or end, which is constantly modulating.

Just as Bohr discussed when illustrating the indeterminacy of what constitutes an entity, there are countless questions we could ask about the delineation of "events" that demonstrate the ambiguity of when one thing ends and another begins: when does the event of a human being coming into the world begin? At the moment of birth when the baby emerges from the mother? At the moment of conception? When the sperm is generated in the father or the egg in the mother? Couldn't we also say that a baby begins when its father or mother is born? Did WWI begin in 1914 and end in 1918? What about the things that led up to the war, long before 1914, or the repercussions of the war that lasted far beyond 1918? Everything is an activity (process and intra-action), not a thing (event). Events flow into each other and we can't say exactly where one ends and the other begins. There's an ordinary way in which we look at the world and see distinct events and entities, but this does not reflect the fundamental reality of the world. Causation as a process and intra-action is an attempt to get at what's truly fundamental, not to deny that we perceive distinct entities and events, just as quantum mechanics describes the fundamental physics of the world even though we perceive things classically.

Causes as powers reinforces the idea that our basic causal laws express natural necessities and that natural necessities are relative to the assumed truth of theories such that, within a specific worldview, the necessity of certain effects can be inferred from certain powers and the denial of statements describing the effects of these powers is inconsistent with the worldview.²⁹¹ This means that the causal claims of

²⁹¹ "Given some general theory specifying the fundamental causal powers and thereby laying down the general lineaments of a world, the necessity of certain effects can be inferred. Such effects are 'hypothetically necessary' in the sense that, given the specification of the causal powers of the things and substances in the world, the denial of statements describing these

science aren't reports of regularities, but rather, ascriptions of powers, where causal laws ascribe powers to particulars, and a power ascription holds in virtue of the very nature of the particular. This follows directly from the Everettian notion that there are many, even infinite, possible ways that facts about an individual world, such as the laws of nature, could be. Natural necessities are relative to the assumed truth of theories, such that, given the truth of the theory of gravity, it's necessary that a stone released from the top of a building will fall toward the ground. It isn't logically necessary that the stone fall, but in this world whose state is determined in part by gravitational attraction, the stone's fall is naturally necessary.

One important consequence of this notion is that certain causal powers are taken to be intrinsic in the sense that these powers are not explained by referencing the nature of some underlying particulars (e.g. gravitational attraction). In other words, certain causal powers, such as gravity, are intrinsic because they are themselves a power (unlike oranges, which have the causal power to prevent illness, but this power is not ultimate because it can be explained by referencing the power of vitamin C which can be explained by referencing the powers within the interactions between various molecules, etc.). The possibility is also open for certain causal powers to be intrinsically ultimate because not only are they themselves a power, but their power is everything that they are. Rom Harré and Edward Madden suggested that physical fields satisfy this requirement of identity in being intrinsically ultimate because a field has no nature apart from its powers. An electromagnetic field is

effects of those powers, when the environment allows them to be exercised, would be inconsistent with the nature of those things ascribed to them on the basis of the theory." John Losee, *Theories of Causality: From Antiquity to the Present* (New Brunswick, NJ: Transaction Publishers, 2011), 137-8.

nothing more than a distribution of potentials throughout space; if you were to subtract from the field the power to affect magnets and electric charges, there would be nothing left. Of course, a theory may one day be available to explain this distribution of potentials by referencing the nature of some underlying particulars, so even if physical fields are intrinsically powerful, they may not be ultimate.

Following from this is the question of whether there may be a viable theory of panpsychism in which "consciousness" is an intrinsically ultimate causal power. I put "consciousness" in quotes because consciousness here is not the capacity for self-reflection that we attribute to our human experience, but rather, the most minimal experience of there being *something it is like* to exist, or basic observational capacity. Consciousness in this sense can be understood as the primary building block from which all else emerges, including the more sophisticated patterns of consciousness that allow for self-reflection, which humans experience. Everett rejects the anthropogenic conception of observation, claiming that human observation is not the only kind of observation that can take place, and further developments of Everett's theory have shown that there are all kinds of "observational" processes, including those that involve only particles, which lead to branching.

If you were to take a microscope and look at my body, you would see trillions of cells within their own microscopic community: I am human, but I am also cells. If you were to take a microscope and look at those cells, you would see trillions of atoms: I am human, I am cells, I am also atoms. An even more powerful microscope would reveal smaller, subatomic particles, and if you magnified those, they would fade away and all you would see is energy: I am human, I am cells, atoms, subatomic

particles, and most fundamentally, I am energy. Physics tells us, based on Einstein's famous equation, $E = mc^2$, that matter is frozen energy and energy is matter in motion; energy and matter are, in essence, the same. This requires argumentation beyond the scope of this thesis, but I would like to develop a case for equating consciousness with energy, essentially claiming them to be synonymous with one another. If we view this "something it is like" to be consciousness, then, because we can strip away cognition and be left with only this phenomenological twinge, consciousness is the most basic component of our existence. We are physical bodies (matter), we are energy, and we are consciousness.

Everett's theory states that the macroscopic state of everything is described by a wave function such that superposition is everywhere. Decoherence occurs causing the multiverse to branch into universes, and he explains that we aren't cognizant of other world histories because superposition is extended all the way to the mind. To take the SE seriously means to accept that the mind of a person observing a superposed process is itself in a state of superposition (i.e. the cat is both dead and alive and the mind observes the cat as both dead and alive). This is obviously not how we experience the world, so Everett explains that each of these superposed states is associated with a separate observer. As an observer makes a measurement or observation, multiple observers are produced, each corresponding to a determinate state of affairs, each observer experiencing a determinate world history. In other words, the state of a universe is relative to the measurements made by an observer, and the objective state of the multiverse is a superposition, as described by the universal wave function.

Perhaps, we could take the universal wave function to itself be an observer,²⁹² composed of superposed consciousness (aka "observational capacity"), which subjectively collapses the wave function into determinate, individual universes, just as my superposed observations produce corresponding versions of myself and the relevant results. Consciousness, as the minimal capacity for observation, could be the power that causes the superposed multiverse to subjectively collapse into individual universes that are in one eigenstate or another, with respect to all physically possible outcomes of an observation. If the multiverse is fundamentally composed of consciousness, then this consciousness would act as the observer and cause determinate worlds to be produced, each also being fundamentally composed of consciousness. In other words, consciousness as the power that causes the superposed multiverse to subjectively collapse into individual universes is a consequence of the holistic character of the multiverse: because decoherence is tied to observation and the only "outside" to the universe is the universal wave function, which contains all observers and describes the state of the multiverse, there is no unit smaller than the multiverse that can be considered a discrete observer sufficient to account for the complete system of branching.

Just as the multiverse is in a state of superposition, the consciousness within it is superposed, perceiving the infinite possible states of affairs. If consciousness, as an omnipresent observational power, is this core element of the multiverse, then universes could not possibly escape subjective wave function collapse, because they

²⁹² Everett's requirements for an observer is that it be physical and leave a mark on its environment, and the universal wave function can be understood as adhering to these two criteria by entailing physical universes and containing the information which causes subjective "collapse." The details of this are yet to be worked out.

are eternally engaging in observation. Therefore, consciousness is the observer within the multiverse, acting as the causal power that brings about the result of many worlds. Unless we are to assume that individual universes are created spontaneously, without cause, and just happen to correspond to determinate outcomes of probabilities, consciousness serves as the explanation for why any non-superposed world exists.

There are many possible objections to consciousness as an ultimate causal power, and although I do not have the space here to discuss in-depth potential solutions, I will list two objections. (1) Why do we need to believe that worlds are causally created, or, why credit an observation with something more than just a sequence of events? One potential answer is to apply to a weak version of the Principle of Sufficient Reason: our experience of the world and intuitive understanding of what we mean when we say "causality" implies that we actively perceive causes and don't merely infer them. (2) How can I make the jump of equating consciousness with energy? Doesn't this violate the commonsense understanding that there's a duality between the mental and physical? The simple answer would be that yes, it does. Equating consciousness with energy comes down to whether there is a duality between the mental and physical, and I deny this duality. My view as a whole underlies this jump: the entire theory is holistic, and I'm not claiming to have premises that would be acceptable to anyone who doesn't already believe in holism, but the argument follows from Everett's MWI and comes as a package deal with its own attractive features. Most people believe in dualisms, and, as this is merely an overview of one potential avenue for exploration, I don't yet have a knockdown argument apart from what I believe is in accordance with Everettian

metaphysics. We live in a society ingrained with dualisms such as "me" vs. "other," and this is largely my point: the causal inquiry regarding MWI is the catalyst for this argument, but the passion behind it comes from questioning the way we understand our relationship to the world.

There are also many possible advantages to consciousness as an ultimate causal power in addition to problems it may solve for MWI, and although I do not have the space here to discuss them in-depth, I will list four of the potential advantages. (1) This theory of consciousness contains the potential for us to understand more about the world than other theories of causation allow for. I realize that at first this will sound like a vacuous statement, but everything causes everything. If the multiverse is completely full such that no body can move without affecting all surrounding bodies, and those bodies can't move without affecting all surrounding bodies, and so on, then communication extends indefinitely. Therefore, there is the possibility, in principle, to read off from each body what is happening everywhere, what has happened everywhere, and what will happen everywhere.²⁹³ (2) It is more intuitive, better describes what we mean when we talk about "causality," and is more in accordance with our experience of physical reality. It isn't necessary to sift through details to find sufficient causes or figure out how to appropriately restrict the relevant

²⁹³ "...everything is *full*, which means that all matter is interlinked. If there were empty space, a body might move in it without affecting any other body; but that is not how things stand. In a plenum [world that is full], any movement must have an effect on distant bodies, the greater the distance the smaller the effect, but always *some* effect... Each body is affected by the bodies that touch it, and feels some effects of everything that happens to them; but also through them it also feels the effects of all the bodies that touch them, and so on, so that such communication extends indefinitely. *As a result, each body feels the effects of everything that happens in the universe, so that he who sees everything could read off from each body what is happening everywhere; and, indeed, because he could see in its present state what is distance both in space and in time, he could read also what has happened and what will happen...*" Leibniz, *The Monadology*, §61.

conditions, and these tactics don't often lead to a universally agreed upon identification of causality. We don't have to sort through questions like, "what exactly was the cause of my taking a step?" "Was it my legs?" "What is the fact that the ground was beneath my feet?" "Was it the event of putting my foot on the ground?" These options suggest that objects, facts, and events are the relata of causal relations, but I'm claiming that it's the powers within particulars that are responsible for causality. Objects, facts, and events can all be involved in causation, but they're involved by virtue of containing powerful properties. There is *something about* a substance that causes. Properties are powers because a fire being hot would mean nothing if it didn't have the power to heat; water being wet would mean nothing if it didn't have the power to hydrate. We would be fools to sit by a fire hoping that, by chance, it'll happen to warm us up.

(3) It has the potential to explain phenomena that are generally considered inexplicable but that most people would claim to have experienced. Empathy, for example, can be seen as a real intra-action within a physical field of consciousness rather than merely a deluded form of sympathy. Premonitions, too, can be seen as real intra-actions within this physical field where an individual is engaging in a kind of "reading" of the movements among bodies. Other such examples include "a mother's intuition," telepathic communication between twins, or that feeling of just having a hunch. (4) If we can truly engage with this theory, it has the potential to make us happier, more moral citizens of the multiverse. Just as we observe the conservation of mass and energy, if consciousness is equal to energy, there must also be conservation of consciousness, meaning that, at least in universes where our laws of physics

function, the world is a place of no end and no beginning, no birth and no death. Our human bodies are temporary manifestations of our consciousness, but we existed before this form and will continue to exist after this form. If we could see the entire world as our body, we wouldn't have to be so attached to and concerned with our temporary, human bodies, and maybe we could more fully enjoy our experiences. Additionally, how would the world be different if we all understood that we are interconnected and fundamentally inseparable? As noted by Bohr, the distinctions we draw between entities has more to do with the way we engage (or intra-act) with and within the world than what we're composed of. What would happen if we understood all suffering, grief, and joy as our own? We could let go of individual survival and flourishing, instead understanding that the entire world is our body and the experiences of others is also our own. Would we no longer inflict suffering upon others or destroy our environment for personal benefit if we understood this as being the same as harming ourselves? If everyone could make sense of themselves as belonging to one large, interdependent body, I believe we would be happier. When you let go of individual survival, all of your priorities change because you see the entire world as your body and the suffering and joy of others as your own. What kind of power could we have to benefit the world if we put the interest of the whole in front of ourselves, even if that meant we had to sacrifice ourselves in the process? I doubt many people would be willing to do that right now, but what if seven billion of us did it? I think one thing that both causes problems in the world and keeps us from solving problems is this flawed notion that we are separate from the world, and maybe it's time we change our minds.

"If people sat outside and looked at the stars each night, I'll bet they'd live a lot differently... when you look into infinity, you realize that there are more important things than what people do all day."
– Calvin & Hobbes

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