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Foundations and interpretations of quantum mechanics

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The Foundations and Interpretations of Quantum Mechanics

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Abstract

The first famous thought experiment of Einstein gives rise to his theories of relativity, the bedrock of modern astrophysics and cosmology. His second famous thought experiment begins the investigation into the foundations of quantum mechanics. It leads to a paradox, inspiring various 'no-go' theorems proven by Bell, Kochen, and Specker. Physicists and philosophers worldwide become increasingly dissatisfied with the probabilistic complementarity interpretation (Born-Bohr) and eventually offer their own accounts of the theory. By the end of the 20^{th} century, two alternative approaches stand out as the best candidates: Both the hidden variables interpretation (de Broglie-Bohm) and the many worlds interpretation (Everett-DeWitt) give compelling descriptions of what the true nature of quantum reality could be. In this paper, a chronological overview of all these events is given, followed by a philosophical analysis of the three aforementioned interpretations. Ultimately, it is concluded that the many worlds interpretation should be adopted as the best understanding of the formalism of quantum mechanics and, therefore, should be used in the multiversity textbooks.

Acknowledgements

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Contents

1 Introduction

The turn of the 20^{th} century was not an average turn by any means. In the world of analytic philosophy, spearheaded by the likes of G. E. Moore, Bertrand Russell, and Ludwig Wittgenstein, the centurial turn was also a linguistic turn. In the parallel world of theoretical physics, men such as Max Planck, Werner Heisenberg, and Erwin Schrödinger made the quantum turn. Any good historian knows that this kind of parallelism is not merely coincidental: When physics and philosophy both begin to radically reform their respective disciplines there is definitely something in the air. It would be naïve here to think that physics and philosophy are fundamentally separate (their exact relationship will be discussed in §4.3); thus, similar progressions should not be all too surprising. However, a dynamic, *two-way* interplay between them is surely a telltale sign of not just a Kuhnian paradigm shift but a complete transformation of worldviews. The epitome of this kind of convergence was the coinciding of Newtonian physics with Cartesian philosophy. Isaac Newton showed, with beautiful mathematics, that the world is mechanized and governed by a few causal laws. Simultaneously, René Descartes laid down his mechanistic worldview and dualism, where minds and bodies are completely different, non-interacting substances. This allowed for the special status that the Newtonian observer needed. All of a sudden, the world was ordered and unified. The same laws that governed the falling of apples now applied to the heavens, and all motion was reduced to Cartesian coordinates in space and time. But, then, two hundred years passed, and, for the most part, physics and philosophy minded their own business, generally uninterested in the other.

1900-1913 saw the forming of what is typically called the "old quantum theory". At this stage the theory was strictly phenomenological: there was no underlying formalism bringing all the experimental results together into one framework. In 1900, Max Planck studied blackbody radiation, attempting to fix the problems associated with the ultraviolet catastrophe. In 1905, Albert Einstein investigated the photoelectric effect, seeing if the energy of the photoelectrons increased linearly with frequency. In 1913, Niels Bohr observed the spectral lines of hydrogen, trying to understand their discrete nature. The theoretical proposal given by all three physicists was the same: Energy is quantized (some sources say that Boltzmann suggested this in 1877, but apparently the idea was not taken seriously enough). This sort of idea was bizarre, but it was not unique to physics. At the same time, the philosophy community was digesting the idea that meaning was quantized. Russell was arguing that the smallest unit of meaning was the proposition (roughly, the sentence). And so it came to be that philosophers finally sympathized with the strict reductionism inherent to physics, so much that they allowed it into their own methodology and analysis. This mirrored movement in philosophy was called logical positivism and its headquarters was Vienna, the epicenter of 20^{th} century philosophical thought. The program of the Vienna Circle, as they were called, was taken to the extreme when Russell and Alfred North Whitehead set out on the colossal task of reducing Peano arithmetic (arithmetic of $\mathbb{N}$) to logic and a few axioms of set theory. Unfortunately for Russell and his co-author, their efforts were proven futile when Kurt Gödel published his ingenious incompleteness theorem in 1931, showing that no consistent axiomatic system (that is at least as complex as the arithmetic of $\mathbb{N}$) can prove all of its true statements. Only six years before Gödel 's theorem, Heisenberg was introducing his uncertainty principle, and with these two epistemically limitative

results the physics-philosophy reductionism spontaneously deteriorated. Finally, in 1951 logical positivism imploded when W. V. O. Quine dismantled the concepts of analyticity and reductionism. For the first time in the history of western philosophy, a philosophical movement developed so much logical weaponry that it was able to destroy itself. Simultaneously, physics was in its own process of rebuilding as subjectivity quickly permeated to all corners of the science. Thus, both in a state of shock and desperate for foreign aid, physics and philosophy needed each other in order to get back on firm ground. This marked only the beginning of the relationship between physics and philosophy in the 20^{th} century, for in the decades to come - the dawn of the digital age - these two disciplines would slowly merge into one intellectual endeavor in order to undertake their biggest collaboration in history.

The following paper attempts to describe this intimate and highly entangled relationship, giving unyielding respect to history and the reality of the slow but steady success that has happened. The immensity of manpower involved is sometimes daunting, and although the greatest care has been taken to give specific credit where its due, alas it is simply impossible to not omit someone here or there. There is so much literature written on this subject that organizing a century's worth of ideas is, in some sense, arbitrary. Even so, much deliberation has gone into how to organize such a body of knowledge in order to somewhat do justice to the vastness of the field. §2 describes the concrete foundations of quantum mechanics (hereafter QM): First the mathematical evolution of the theory is summarized and then the conceptual problems that immediately followed the completion of the formalism are outlined. These problems springboard into §3, which explains in detail the three major interpretations of QM. First is the Born-Bohr probabilistic complementarity interpretation (PCI), second is the de Broglie-Bohm hidden variables interpretation (HVI), and third is the Everett-DeWitt many worlds interpretation (MWI). Each subsection develops the key elements of the interpretation and then goes into the pertinent criticisms that have been made. §4 analyzes all three interpretations philosophically and weighs them against each other and against a checklist for subscription. §4 finishes on a more abstract level and asks a single, but incredibly important question: What is the role of philosophy in physics? Is it merely to assist in the testing of physical theory against the never-ending lists of intuitive metaphysical beliefs? Or is it to help the physicist realize the social aspects of her field and take creative risks where normally only the philosopher would? Should we even worry about an actual division of labor between physicist and philosopher? These and other relevant questions are entertained in order to hopefully gain a wider perspective on what we are actually trying to do when we interpret not just the data of physics, but the theories themselves. §5 concludes the paper, acknowledging that huge advances in this research are being made every year, but if we truly want a consistent and *comprehensible* theory of quantum gravity we must dig deeper.

2 The Foundations of Quantum Mechanics

The foundations of QM is a broad field, requiring the minds of professional physicists, card-carrying philosophers, and curious individuals alike. This is great in many ways, for any project that finds itself at the interface between two spheres of thought is definitely going to produce groundbreaking ideas and new ways to approach age-old problems. At the same time, however, there is a certain susceptibility for these ideas to copiously spread to all forms of popular media and to be adopted by all types of peoples. There are two main reasons why this occurs: (1) Interdisciplinary endeavors inevitably produce new-age, *avant-garde* ideas made for magazine covers and (2) the lack of complete authority over the ideas by a single discipline allows them to be taken less seriously, therefore allowing them to be distributed more freely with no risk of academic backlash. This being said, it must be prefaced that people academically involved in this subject must go about their research with a certain level of responsibility.

One example of the 'quantum hype' found in popular culture is *The Tao of Physics*, a book written by the particle physicist Fritjof Capra after he used psychedelic drugs. This book attempts to draw profound parallels between QM and eastern mysticism by abusing and unfairly exaggerating some of the irresponsible comments that the founding fathers of QM had made after trips to China late in their lives. Again, this is treacherous territory since many of the founding fathers made responsible use of eastern thought in their theories. Bohr was influenced by eastern thought so much that he actually added the yin yang symbol to his coat of arms when he was knighted in 1947. These influences can be seen in the ideas surrounding complementarity (§3.1). Also, Bohm's concept of wholeness stems from his experiences he had in the east (§3.2). Yet another example of hype can be seen in the film *What the Bleep Do We Know!?* This movie essentially is a piece of propaganda created in an effort to recruit people to the Oregon cult called Ramtha's School of Enlightenment and it uses QM to explain the notion that consciousness itself creates your world. The movie has a cast of scientists ranging from physicists to anesthesiologists along with mystics including Ramtha herself. Although the film does have some accurate information, it frequently inserts pseudoscientific or extremely speculative theories as if they were widely accepted. All in all, the foundations of QM is a very exciting and highly active area of research, but special care must be implemented if we want to make progress. At all times we must discriminate between 'quantum hype' and sound argumentation, although often it is quite difficult given the bizarre behavior of the quantum world.

2.1 Mathematical Construction

Louis de Broglie, the French Duke, initiated the mathematical construction of QM. In his 1924 PhD thesis he posited the de Broglie hypothesis, now referred to as wave-particle duality. Combining this hypothesis with Einstein's special relativity, de Broglie derived two relations. The first relation, often called the de Broglie wavelength, is

$$\lambda = \frac{h}{p} = \frac{h}{\gamma m v}$$

where λ is wavelength, h is Planck's constant, and γ is the Lorentz factor. The second relation reads

$$\nu = \frac{E}{h} = \frac{\gamma mc^2}{h}$$

where ν is the corresponding frequency of the object with the associated de Broglie wavelength. These equations are usually written, respectively, as

$$p = \hbar k \tag{1}$$

$$E = \hbar\omega. \tag{2}$$

In 1925, not long after de Broglie's revolutionary work, Werner Heisenberg and, working with him in Germany, Max Born formulated matrix mechanics, the first complete formulation of QM. The theory was the first to take the abstract entities of matrices - those strange arrays of numbers that had even stranger multiplications - and adopt them into the physical world. No longer were these mathematical objects just computational tools, for now they had physical significance. Matrices were chosen to represent the physical observables (position, momentum, etc.) of objects specifically due to their noncommutability. This is best summarized in the canonical commutation relation

$$[\mathsf{Q}, \mathsf{P}] = i\hbar\mathbf{1} \tag{3}$$

where Q and P are the matrix representations of position and momentum, respectively.

Only a year later, Erwin Schrödinger developed an entirely different formulation of QM called wave mechanics. This formulation was based on his wave equation

$$i\hbar\frac{\partial\Psi}{\partial t} = [-\frac{\hbar^2}{2m}\nabla^2 + V]\Psi = \hat{H}\Psi \tag{4}$$

in which Ψ represents the time-dependent wavefunction, V is the potential function, and $\hat{H}$ is the Hamiltonian operator. Schrödinger went on to prove the mathematical equivalence of matrix and wave mechanics, unifying QM under one formalism.

The last of the hallmark formulae of QM, the Heisenberg indeterminacy relation (hereafter IR) was derived in 1927 by Heisenberg. In its standard position-momentum form, the principle is

$$\Delta q_i \Delta p_i \geq \frac{\hbar}{2}. \tag{5}$$

Later that same year, Paul Dirac formulated QM using operator theory and invents the bracket notation, now the mostly widely-used QM notation (he also created the first relativistic QM in 1927). Using this notation, the state vector is written as

$$|\Psi\rangle = (c_0, c_1, c_2, ...)^T$$

and is called a "ket". Additionally, every ket has a "bra" in dual space and is represented by the row vector

$$\langle\Psi| = (c_0^*, c_1^*, c_2^*, ...)$$

with the coefficients complex conjugated. In 1930, the polymath John von Neumann expanded upon Dirac's work and gave QM a rigorous mathematical foundation as a linear

algebra theory of Hermitian operators living in an abstract, infinite-dimensional Hilbert space. Under this modern representation of QM, the eigenvalue equation becomes

$$A|a_n\rangle = a_n|a_n\rangle$$

and the orthonormality condition can be written as an inner product

$$\langle a_m|a_n\rangle = \delta_{mn}$$

where δ_{mn} is the Kronecker delta.

It is convenient now to mention that the generalized uncertainty relation can be expressed as

$$\Delta A \Delta B \geq \frac{1}{2}|\langle\Psi|[A,B]|\Psi\rangle| \tag{6}$$

for it will be referred to later in the paper [9]. It should be noted that the object 'sandwiched' between the bra and the ket will, from now on, be interpreted as a general Hermitian operator (which, of course, can be typographically expressed as a sans serif matrix, a differential operator with a hat, etc., whenever a specific mechanics is used) that always acts on the ket to its right. The Dirac notation will be universally used from this point on, unless otherwise stated.

Many textbooks like to 'axiomatize' QM. Here, axiomatize is used in a rough sense, for the authors of these books are not using the close to self-evident truths found in a formal system of rigorous mathematics. Furthermore, it is just incorrect to speak of axiomatic systems in physics: The formalism can be axiomatized, but that does not get one to the level of reality, the realm of interpretation. Therefore, when these authors speak of the axioms of QM they really mean the axioms of the *formalism of QM*, but this is just a technical note. From now on, 'axiomatize' will be used in the physicist's loose sense.

QM can be axiomatized as follows:

Axiom I:

$\forall$ *systems* $\exists$ an infinite dimensional Hilbert Space $\mathcal{H}$
whose vectors $|\alpha\rangle$ represent the *state* $\ni \langle\alpha|\alpha\rangle = 1$.

Axiom II:

$\forall$ *observables* $\exists$ A, a linear Hermitian operator, acting in $\mathcal{H} \ni A|\alpha\rangle = \alpha|\alpha\rangle$
where $|\alpha\rangle$ is an eigenstate of A and α is an eigenvalue of $|\alpha\rangle$.

Axiom III:

a *system* in *state* $|\alpha\rangle \implies P = |\langle\beta|\alpha\rangle|^2$
for the *system* being in *state* $|\beta\rangle$ where $0 \leq P \leq 1$.

Axiom IV:

$i\hbar\frac{d}{dt}|\Psi(t)\rangle = H|\Psi(t)\rangle$, where H is the unitary evolution operator.

Axiom V:

$$\langle\alpha|[q,p]|\alpha\rangle = i\hbar.$$

As can be seen, many of the founding equations of QM have honorary seats as axioms. Axioms I and II are generally known as the correspondence axioms because they make direct associations between the italicized 'extralogical terms' (to be discussed in §3) and mathematical quantities. Axiom I also expresses the orthonormality condition and axiom II uses the eigenvalue equation. Interpetations begin to diverge when they get to axiom III, which is sometimes called the axiom of quantum statics. Importantly, it is the only axiom which establishes a link between the mathematics and the data that relates to the physical theory. Axiom IV is the Schrödinger equation (4), albeit in its uninterpreted, abstract form. It is referred to as the axiom of quantum dynamics, for t is unavoidably interpreted as time even in the most extreme intepretations. Finally, axiom V, in its deceptive brevity, is nothing other than the canonical commutation relation (3), except that q, p, and $\hbar$ do not have instantiated physical significance. It should be noted that the indeterminacy relation (5) is not included in the axiom schema, which implies that it must either be derivable as a theorem or something altogether auxiliary to the formalism. This formal absence is the root cause of the problems now to be discussed [8].

2.2 Conceptual Problems

QM was not formally put on solid, theoretical grounds until the 1930s, and it was not long until its conceptual problems started to reveal themselves. They first manifested themselves in the form of thought experiments, or the german *gedankenexperimente*, in which many of the conceptual difficulties appeared irreconcilable. Decades passed until John Stuart Bell, followed by two mathematicians Simon Kochen and Ernst Specker, produced logical proofs that forced trade-offs between many of the philosophical preferences that all physicists carry over from the classical world. Amazingly, experimental techniques were developed to investigate which side of the proofs QM actually was on. The most notable (albeit not conclusive) experiment is the one conducted by Aspect and his team of researchers. This will be explained in §2.2.3.

2.2.1 Gedankenexperimente

The first *gedankenexperiment* to be discussed below was the culmination of a long series of proposed ideal experiments, many of which can be found in the correspondences between Einstein and Bohr. This Einstein-Bohr debate, as its called now, will serve as a centerpiece for us and it becomes the polarized platform that gives rise to the rift in philosophical preference amongst physicists of the time: Those wanting a more complete theory fell into Einstein's camp and generally subscribed to HVI (except, possibly, Einstein himself!) whereas those wanting to revise orthodox ideas stayed in Bohr's camp and subscribed to PCI. In addition to this immeasurably significant dialogue, Einstein received many of the essential ingredients of his argument from the thought experiment put forth by the philosopher Karl Popper. Popper's experiment was later shown to be flawed, but it was a big step towards the formulation of the EPR argument. Also, along with his foundational

work, von Neumann offered the first 'no-go' theorem for hidden variable theories, giving Einstein much of the logical force that he needed in order to convey his ideas [8].

EPR Argument In 1935, Albert Einstein, with the help of Boris Podolsky and Nathan Rosen, published a paper questioning the *completeness* of QM. Einstein's definition of completeness, however, differs from the word's more common usages seen in mathematical logic (Gödel) and also in linear algebra regarding the completeness of a set of eigenfunctions in a vector space. Einstein defines his completeness via a condition (C_1): "Every element of the physical reality must have a counterpart in the physical theory" [6]. This kind of injective mapping between ontology and theory was something Einstein firmly believed in and, thus, he demanded it of quantum mechanics. In addition to this condition, Einstein also proposed a condition of sufficient physical reality (C_2): "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 physical quantity". This added condition insures that physical reality is an a posteriori and empirical concept and not something grounded in a priori assumptions. With these two conditions in hand, it is then logically deduced that either (1) QM is incomplete or (2) two physical quantities whose operators do not commute cannot have simultaneous reality. Einstein and his co-authors first considered a system composed of two particles 1 and 2, with corresponding variables x_1 and x_2, that only interact during $0 \leq t \leq T$. It is also assumed that the initial states of the individual particles were known prior to their entanglement. This implies that the future state of the entangled system can be determined with the assistance of the Schrödinger equation (4) such that

$$|\Psi(x_1, x_2)\rangle = |\psi_a(x_2)\rangle |u_a(x_1)\rangle \tag{7}$$

where $u_a(x_1)$ is the eigenfunction of some operator corresponding to an observable. Next, employing his preferred wave mechanics, Einstein supposed that the wavefunction of the system was of the form

$$\Psi(x_1, x_2) = \int_{-\infty}^{\infty} e^{i\frac{(x_1 - x_2 + x_0)p}{\hbar}} dp \tag{8}$$

with x_0 being an arbitrary constant. Given this general form, equation (7) can be written in two different but mathematically equivalent ways:

$$\Psi(x_1, x_2) = \int e^{-i\frac{(x_2 - x_0)p}{\hbar}} e^{i\frac{x_1 p}{\hbar}} dp \tag{9}$$

or

$$\Psi(x_1, x_2) = h \int \delta(x - x_2 + x_0)\delta(x_1 - x)dx. \tag{10}$$

Now comparing (9) with (7), letting y = p, gives the eigenvalue p_1 = p for the u_p eigenfunction when acted on by the one-dimensional position-space momentum operator

$$\hat{p} = -i\hbar\nabla \tag{11}$$

where, in this case, $\nabla = \frac{\partial}{\partial x_1}$.

Likewise, the equation returns an eigenvalue of $p_2 = -p$ for the ψ_p eigenfunction when acted on by (11) with $x = x_2$. Thus, the system is entangled and any measurement of momentum of either particle 1 or 2 immediately implies the value of the other momentum. Comparing (10) with (7), letting $y = x$, gives the eigenvalues $x_1 = x$ and $x_1 = x_0 + x$ for the u_x eigenfunction when acted on by the position operators $\hat{q} = x_1$ and $\hat{q} = x_2$, respectively. Thus, as claimed by Einstein and his colloborators, both q_1 and p_1 can be obtained by measuring q_2 and p_2 [8].

Bohm Simplification David Bohm, in his 1951 textbook *Quantum Theory*, offered another version of the EPR *gedankenexperiment*. His version, using electron spins, was not only a mathematical simplification, but also put the core conceptual problem of *entanglement* right on the table.

Bohm considered the decay of the neutral pi meson into an electron and a positron:

$$\pi^0 \rightarrow e^- + e^+.$$

Since the pion was at rest, in order to conserve linear momentum the electron and positron must have equal in magnitude, opposite in sign velocities. Also, the pion is a spin-0 particle, so in order to conserve angular momentum the electron-positron system must be in the singlet configuration of

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle_-|\downarrow\rangle_+ - |\downarrow\rangle_-|\uparrow\rangle_+). \tag{12}$$

Thus, if one of the particles is measured spin up, then the other particle is necessarily spin down. Furthermore, QM claims that although one can never know which combination one will get, on average one will get each pair half the time. The amazing attribute of Bohm's version is that this entanglement can exist over arbitrarily large distances: The electron and positron can go off and a measurement can be made when they are thousands of light years apart and still the 'unmeasured' particle will automatically choose the right orientation. The particles could even be on opposite sides of the universe (if such a phrase can be used) and the experiment would still give the same results. Einstein eventually called this behavior "spooky action at a distance" because it implied that there exists a superluminal influence that propagates through space instantaneously, relaying the needed information to the correlated particle. More so than anything, then, Einstein continued to fight the orthodox interpretation because it directly violated special relativity [7].

Schrödinger's Cat In response to the EPR *gedankenexperiment*, Schrödinger thought of one of his own. Wheras Bohm's version highlighted entanglement, Schrödinger's version highlights the mysterious act of measurement. In one version of the Schrödinger paradox, a cat is put into an opaque chamber along with a vile of cyanide. There is also a Geiger counter that has such a tiny amount of radioactive substance that probably only one atom decays in an hour. The whole apparatus is set-up in such a way that if the counter triggers after an atom decays then, through a relay, a hammer is activated which smashes open the cyanide, immediately killing the cat. If the probability of one atom decaying and one atom not decaying are equal, then the wavefunction of the cat is

$$|\chi\rangle = \frac{1}{\sqrt{2}}(|\chi_{alive}\rangle + |\chi_{dead}\rangle). \tag{13}$$

Now the cat is in a superposition of states, neither alive nor dead until observed by the experimenter. This idea was deemed absurd to Schrödinger: A macroscopic object like a cat cannot sensibly be in a linear combination of states. It is only microscopic objects that can exhibit superposition, he argued [7]. This did not attack Bohr's position, though, for Bohr would never allow a classical object like a cat to be represented by a single wavefunction. More will be said of these matters in §3, but for now we can say that the cat paradox is mostly relevant to objective collapse interpretations.

Wigner's Friend Even more relevant to objective collapse interpretations is Eugene Wigner's extension of Schrödinger's cat. Taking the thought experiment to its anthropocentric limit, Wigner took the exact same cat scenario but replaced the cat with his friend. This friend is not killed like the cat, but merely has the opportunity to witness whether an atom decays or not. The outside observer has a dilemma: The observer cannot decide whether her friend *collapses the wavefunction* (the belief in collapse, i.e. the belief that the wavefunction discontinuously attains a value upon observation, is one of the main topics of §3) herself or if her friend remains in a superposition, just like the cat had, until further inspection by the observer. Wigner argued that if anyone truly believed that only the outside observer can stop this state of suspended animation then they would be subscribing to solipsism. Solipsism is metaphysical idealism - where only minds exist such as in the work of the George Berkeley - taken to the extreme. Solipsism claims that the world is one mind and it is your mind. As empowering as it sounds, it is also logically irrefutable and not sympathetic with the plurality that physics tries to embrace [10].

2.2.2 Impossibility Theorems

From 1930-1950 virtually every textbook on QM mentioned these thought experiments in passing, stating them as curiosities that would eventually be sorted out after redefining a few terms here and there. However, these textbooks were in no way fair 'state of the union' addresses. There was a huge drive to formulate alternative approaches to the theory and the need for one was properly prioritized. And yet most physicists were content to work within the framework of the current paradigm, every once and a while Von Neumann's 'no-go' theorem being brought up in conversation. Bell, while working at CERN, became very intrigued by Von Neumann's proof after it was finally translated for him by his German colleague Franz Mandl. This lead to his paper on hidden variable theories (importantly, different from hidden variable *interpretations* - see §3.2). Soon after Bell's contribution, a paper was published by Kochen and Specker that complemented the conclusions of Bell.

Bell's Inequality In 1964, Bell wrote a paper entitled "On The Einstein Podolsky Rosen Paradox" which included a simple proof [1]. In it Bell used a Bohm-type setup of the EPR *gedankenexperiment* with a slight variation. In his version the detectors used to measure the spins of the electron and positron are not aligned in the same direction but freely rotating. The electron detector measures the component of the electron spin in the direction of a

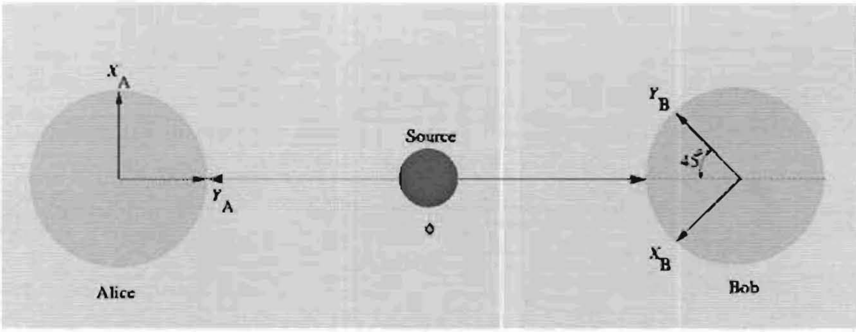

Figure 1: *Bell's setup for the EPR – Bohm thought experiment.* *en.wikipedia.org/wiki/EPRparadox*

unit vector **a** and the positron detector measures the component of the positron spin in the direction of a unit vector **b** as shown in Figure 1 below:

Each detector measures $\pm\frac{\hbar}{2}$ for spin up or spin down and a whole series of measurements can be made. Bell then introduced the expectation value (average) of the *product* of the spins. This product, C, is mathematically defined as

$$\langle S_a^{(1)} S_b^{(2)} \rangle \equiv C. \tag{14}$$

It is easily shown that, for arbitrary orientations of the detectors, the product is

$$C(\mathbf{a},\mathbf{b}) = -\frac{\hbar^2}{4}(\mathbf{a}\cdot\mathbf{b}). \tag{15}$$

Bell surmised that there exists functions,

$$A(\mathbf{a},\lambda) = \pm\frac{\hbar}{2} \qquad B(\mathbf{b},\lambda) = \pm\frac{\hbar}{2},$$

that give the result of the electron and positron measurements, respectively. Here λ represents the hidden variable or collective variables. Next, Bell defined C again, this time as an integral over a probability density:

$$C(\mathbf{a},\mathbf{b}) = \int \rho(\lambda) A(\mathbf{a},\lambda) B(\mathbf{b},\lambda) d\lambda. \tag{16}$$

The rest of his proof is simply mathematical manipulation and devoid of any additional assumptions. In fact, everything is completely general and the only real assumption is the existence of A and B, which is necessary for any tenable hidden variables theory. Bell introduces another unit vector **c** and makes use of the mathematical fact that

$$\left|\int \rho f(x) dx\right| \leq \int \rho |f(x)| dx,$$

which is the origin of the inequality sign. Finally, after some subtractions and substitutions and changing to units of $\hbar = 2$, we have

$$\boxed{|C(\mathbf{a},\mathbf{b}) - C(\mathbf{a},\mathbf{c})| \leq 1 + C(\mathbf{b},\mathbf{c})}. \tag{17}$$

Equation (17) is Bell's famous inequality [7]. Bell's conclusion was that (17) and the quantum-mechanical prediction of equation (15) are incompatible. Therefore, if we are to take QM as being *correct as far as it goes* then there cannot be a local hidden variables theory whatsoever. In contraposition, a radical conclusion is drawn: If there is a local hidden variables theory then QM is *utterly wrong*! To see this incompatibility we can take the special case of all three vectors lying in a plane, with **a** and **b** perpendicular to each other and **c** bisecting their right angle. This gives

$$C(\mathbf{a},\mathbf{b}) = 0, \quad C(\mathbf{a},\mathbf{c}) = C(\mathbf{b},\mathbf{c}) = -\frac{1}{\sqrt{2}},$$

which is demonstrably inconsistent with Bell's inequality:

$$\frac{1}{\sqrt{2}} \not\leq 1 - \frac{1}{\sqrt{2}}.$$

Ironically, Bell was the biggest proponent of the de Broglie-Bohm HVI, which is a *nonlocal* hidden variables intepretaton. Bell's result only showed that a certain class of hidden variable theories, namely the *local* ones were inconsistent with the predictions of QM. The assumption of locality referred to is essentially equivalent to Einstein's cosmic speed limit principle that grounds special relativity. Paraphrasing Einstein, locality is the idea that two objects, separated by a vast amount in space, do not have any influence on each other. This basic assumption allows us to approximate physical systems using quasienclosed, artificially isolated systems, a very important theoretical technique. In its most general analysis, Bell's theorem forces QM to abandon one of two fundamental assumptions found within all other physical theories: These two assumptions are *local realism* and *counterfactual definiteness*, both of which will be explored in detail in §3. It should be mentioned that Wigner later produced a probabilistic form of Bell's argument, something that was even more conducive to repeated measurements (talked about in §2.2.3).

The Kochen-Specker Proof Kochen and Specker, in 1967, showed that it is, within QM, impossible to assign definite values to every observable of a system that has noncommuting observables [8]. Whereas Bell's theorem is based on an assumption of locality, the Kochen-Specker (KS) theorem is based on an assumption of *noncontextuality*. Noncontextuality is another taken-for-granted presupposition of physics that must be forfeited if there is going to be any hidden variables theory that supplants QM. Noncontextuality states that if a quantum-mechanical system possesses a value of an observable then it does so independently of any measurement context. Once again, rejecting noncontextuality is not the only option in trying to maintain a hidden variable theory. Just like Bell's theorem, there exists a trade-off, this time between noncontextuality and the aforementioned value definiteness. The KS theorem is a geometrical argument that can be extended into many dimensions, and it strictly uses the formalism of QM. It is far too technical for the scope of this project, but its subtlety cannot let us overlook its enormous significance. Most of its significance comes from closing the two main loopholes of Bell's approach: (1) The charge that Bell assumes an infinite number of continuous observables is overcome because the KS theorem uses a finite number and (2) the KS theorem applies to one-particle systems as a trivial case and, therefore, targets noncontextuality without the added worry of nonlocality (which, obviously, only arises conceptually when there is more than one object).

2.2.3 Experimental Results

In 1982, Alain Aspect led an experimental physics group at the University of Paris to a remarkable discovery [10]. Using the orientations of photon polarizations instead of spins, Aspect and his team confirmed the predictions of QM and found Bell inequality violations. The team used calcium cascade sources that shot out different colored photons in opposite directions. Because the angular momentum of the initial excited calcium atom is zero, the final angular momentum (measured via the linear components of the photon polarizations) would have to be zero. In the experiment, each photon arrives at different detectors —say, one that measures polarizations of $\frac{\pi}{4}$ radians from the horizontal and one that measures $-\frac{\pi}{4}$ radians —that are placed on opposite sides of the laboratory. However, there is a switch that randomly changes the route of each photon so that they are redirected to the opposite detector. In their third and most celebrated experiment they arranged the experiment so that the setting of the switch, *and thus the subsequent path of each photon*, can be left until *just* before the photon arrives at the switch, long after (relatively speaking) the photons had been emitted. This was extremely important because it forbid the photons from 'communicating' in any way (such as 'telling' the other photon how the switch was set across the room) because no subluminal signal could be transmitted in the remaining time that would reach the other photon before it hit the detector. Many of the doubts about the conclusiveness of Aspect's experiments have been extinguished via the countless additional Bell test experiments that have been conducted over the past two decades by various groups throughout the world. It is so widely agreed, now, that quantum entanglement is a real feature of QM that it has given rise to a whole subfield of physics called quantum information theory. There is a tremendous amount of work being done in this area and its applications to quantum computing and cryptography are going to have revolutionary consequences on the future of information technology.

3 The Interpretations of Quantum Mechanics

The accomplishment of axiomatizing QM (conceptually analogous to Euclid's axiomatization of geometry) began with von Neumann, who had, in effect, partially solved one of Hilbert's 23 problems: Announced in 1900. the sixth Hilbert problem was to give a rigorous, axiomatic foundation for all known physical theories, and von Neumann. by 1930, had tackled the biggest beast of them all. Von Neumann's axiom schema for QM quickly became accepted by many philosophers of science of the early 20^{th} century including Rudolf Carnap and Ernest Nagel. The logical positivists (of which Carnap and Nagel were apart), as a whole, believed that a physical theory is composed of three parts: The mathematical formalism F, the set of epistemic relations R (physicists might call these 'rules of correspondence'), and the explanatory model M all fuse together to form the physical theory. Although these parts can be named separately, it does not mean it is possible to actually filter them out. It should be noted that the extralogical terms of system, state, and observable are not defined within the syntax of the formalism but are given semantic content through the use of the metalanguage of R (once again analogous to the implicit terms of Euclidean geometry such as point, line, and angle). One of the many unique aspects of QM is that F preceded any unified interpretation of the theory, which was the first time this

happened in the history of physics. Subsequent physical theories (e.g. quantum electrodynamics) evolved 'backwards' also, but QM remains the trendsetter. Combining F with R leads to what is normally called a *partially interpreted* theory, but for the logical positivists this is a full-fledged theory and all that one can expect to demand from nature. However, we are mostly concerned with the alignment of the combined F+R with M, the *process of interpretation* [8].

Upon the spread of the myriad incarnations of the EPR paradox, and the subsequent logical and experimental work, the need for 'the correct' interpretation became the holy grail. Philosophers were not shy to jump in (Popper already had) and the young physicist publishing her own fanciful reading of the QM formalism was no longer deemed career suicide as the subtle character of QM fully unveiled itself. Many philosophical concepts became the focus of debate, particularly the juxtaposed concepts of local realism and counterfactual definiteness (the trade-offs of Bell's theorem). Also, each interpretation gives a unique account of the measurement process, which is linked with each interpretation's own *interpretation of probability* (a primitive notion purposefully not defined explicitly in the axiom scheme of QM). Additional idiosyncrasies include each interpretation's view on the indeterminacy relation and the objectivity of the wavefunction, amongst others to be encountered. However, the two ionic columns of the scientific edifice, *reductionism* and *determinism*, came into question more so than any other philosophical beliefs. As working definitions we can think of reductionism as the proposition that *the phenomenon is the sum of its parts*, which takes the interactions between parts as 'parts themselves' (as seen in particle physics with force carrier bosons, for example); we can think of determinism as the proposition that *the world is causally closed*, which will be clarified later. The three major interpretations fundamentally differ in their stances on these two columns: the probabilistic complementarity interpretation (PCI) entirely dispenses with them, the hidden variables interpretation (HVI) somewhat welcomes them back, and the many worlds interpretation (MWI) redefines them in a shocking new way. It is these fundamentally different stances on reductionism and determinism that distinguish these interpretations as being the most profound of all interpretations yet to be expounded. By exploring these three candidates, a exhaustive survey of the spectrum of interpretation will be achieved. The minor, hybrid approaches cannot be ignored, but that discussion will be postponed for a later paper.

3.1 Born-Bohr Probabilistic Complementarity Interpretation

The paradoxes resulting from the *gedankenexperimente* of Einstein, Bohm, Schrödinger, and Wigner were made under the assumptions of the probabilistic complementarity interpretation. PCI is still what every undergraduate student of physics is indoctrinated with upon his or her first QM course: It is the orthodox, conventional, standard, traditional or, most commonly, the Copenhagen interpretation, all of these adjectives being used interchangeably throughout most of the literature. This ambiguity of name is appropriate, however, for the 'Copenhagen interpretation' itself is equally loosely packaged. Thus, it should be clarified from the start that PCI is the constellation of interpretational ideas advocated by Born and Bohr. The variations of PCI are endless, from Schrödinger's objective genre to Heisenberg's specific take (to be found in his *Physics and Philosophy*). Technically, though, all interpretations of QM are part of the same family, except maybe the philosopher's fa-

vorite, quantum logic. PCI just has the historical luxury of being first, but by no means does that give it extra merit or plausibility. In actual fact, both HVI (see §3.2) and the statistical ensemble interpretation, the interpretation that Einstein personally embraced, began around the same time that PCI was first being expounded by Bohr. Thus, it is mostly a matter of reputation that PCI was the first contestant to enter the race.

As alluded to earlier, the physical-theoretic structure of PCI is abnormal: PCI has a formalism F, epistemic relations R, but no explanatory model M. PCI took off in 1926, with Born's probabilistic interpretation of the wavefunction, which is highly responsible for the *ad hoc* appearance of Axiom III. Born posited that the wavefunction contained definite information — namely, probability densities — about the observables via the mathematical operation of the squared modulus of a complex function. This discovery led to amazingly accurate experimental findings and, therefore, became the interpretational starting block for many interpretations that followed.

3.1.1 Basic Principles

While working in conjunction with Heisenberg in Copenhagen, Bohr formed many of the PCI concepts, including complementarity, before the EPR paper was published. Bohr's complementarity is frequently called wave-particle duality, but Bohr himself would not approve of this nomenclature for it has a mystical connotation and, thus, it will be not be used. Also, this is the same name ascribed to the de Broglie hypothesis, which is not the same as complementarity. After the EPR argument was released, complementarity was still Bohr's weapon of choice, but his overall theory had coagulated into something much grander. In regards to Einstein's charge of incompleteness, Bohr wrote, "The apparent contradiction in fact discloses only an essential inadequacy of the customary viewpoint of natural philosophy for a rational account of physical phenomena of the type with which we are concerned in quantum mechanics" [4]. Bohr, in his article, systematically explained how the EPR slit setup is impossible, for there will always be a mechanical disturbance of the system. Complementarity runs much deeper, though, for Bohr continually mentioned one's 'freedom of choice' in his paper, and how one experimental arrangement forbids complementary *knowledge*. Thus, PCI is an epistemological theory. Bohr believed that we all possess a certain set of a priori, pre-scientific, common categories, not dissimilar from the views of the philosopher Immanuel Kant. This set includes the notions of change in position, duration of time, and the concepts of cause and effect, just to name a few. These categories serve as the necessary template, the 'mesh' through which all humans must understand the world. For Bohr, these Kantian categories are isomorphic to the classical concepts of the Newtonian world, and, thus, we can conveniently make use of the concepts of Newtonian physics when communicating our understanding of the physical theory.

Taking this as a foundation for all physical theories, Bohr asserted that QM has shown us, most pointedly, that these classical concepts are not all applicable simultaneously in the quantum realm. What is implied from this is that all physical observables are defined contextually, i.e. their value is dependent on the experimental setup. This is best captured in Bohr's words: "We are just concerned with a discrimination between different experimental procedures which allow of the unambiguous use of complementary classical concepts" [4]. Thus, complementarity requires that all observables are mutually exclusive,

but PCI argues that taken all together they exhaust all possible knowledge of the system. Only in the extreme limit where the quantum of action becomes negligible can we apply all of our classical concepts at the same time. This preceding statement represents Bohr's *correspondence principle* which explicitly states the limit as being the realm of classical mechanics. Mathematically, this is expressed in the QM formalism as the limit where the quantum numbers of a system become very large. The special feature of the measurement process, then, is that a microscopic system, which can only be described by one set of complementary properties, is measured by a macroscopic instrument that enables our use of classical concepts, which, once again, are the only concepts the human brain is able to comprehend. This idea is neo-Cartesian, for there is an inherent dualism in the idea that there are two distinct physical realms, although they asymptotically approach each other. Thus, the subject-object divide of Newtonian physics is artificially preserved.

3.1.2 Idiosyncratic Marks

As stated previously, each interpretation of QM has many idiosyncrasies which set it apart from the other interpretations. The first idiosyncrasy, then, would be the Bell trade-off: On what side of local realism versus counterfactual definiteness (CFD)does PCI fall? PCI forfeits local *realism* because it is nonrealistic in how unmeasured values are simply nonexistent. The position, momentum, or spin of a particle is indefinite until it becomes actualized via the act of measurement. PCI maintains CFD, though, for the idea of 'unique histories' remains intact. That is, if one had decided to measure the position of a particle then they would have measured the same value as when they actually measured the position. This leads in to the question of what the measurement process *is* under PCI. Bohr believed that measurement entails the interaction of a classical apparatus with a quantum-mechanical system. This interaction always involves an inevitable, uncontrollable, intrinsically random disturbance via the quantum of action. This immediately implies PCI's stance on axiom III. In interpreting axiom III, the Born rule is adopted, which is why the interpretation at hand is labeled as a Born-Bohr collaboration. The Born rule is to interpret P of axiom III as *physical probability*. Physical probability comes from the interpretation of probability called frequentism in which probability is the relative frequency that a given event tends to occur over a large number of trials. Physical systems which are given this form of probability must exhibit pure randomness, i.e. indeterministic behavior. Thus, from one of its first epistemic relations, PCI is shown to be fundamentally probabilistic.

Yet another idiosyncrasy is the view of the indeterminacy relation (IR). In the beginning of the section it was noted that PCI took off with Heisenberg working under the exasperatingly meticulous Bohr. Bohr, upon being introduced to Heisenberg's amazing theorem, equation (5), quickly adopted it as a logically prior "uncertainty principle". It was Bohr himself that made Heisenberg use the word 'uncertainty', for Heisenberg usually preferred *Ungenauigkeit*, the german for inexactness or imprecision, a much more epistemically neutral term [8]. The indeterminacy relation is the essence of complementarity and it demonstrates how we cannot simultaneously *know* the complete state of a system. Related to the state of the system is the wavefunction, which, in its probability carrying nature, represents a complete specification of the system. But that is strictly all it is; under PCI, the wavefunction (or state vector) Ψ is only an abstract mathematical tool used for calcu-

lations. It is has no objective reality. This agnosticism allows PCI to successfully avoid the problem of collapse, a problem that is not avoided in most other interpretations (including its objective collapse variants, such as the ones proposed by von Neumann and Penrose). However, avoiding problem usually results in more problems, which is the case for PCI, an interpretation that lacks any unified model of reality M.

The pillars of physics crumble under PCI. PCI makes QM indeterministic, claiming that the universe is fundamentally probabilistic. For Einstein, the sacrificing of this pillar was the main reason why he argued so vehemently against PCI: "I still work indefatigably at science but I have become an evil renegade who does not wish physics to be based on probabilities" [8]. Whether or not PCI preserves reductionism, though, is a little less clear. The fact that PCI does not supply a metaphysics, an M, or anything beyond the thick walls of positivism is the scapegoat for this ambiguity. What fairly can be said is that QM under PCI is quasi-reductionisitic: It is epistemologically reductionistic, but not ontologically reductionistic. We are forced to compartmentalize our thoughts when attaining knowledge of systems because of the inability to run single experimental procedures in order to exhaust the epistemic content of a system. Thus, in a way, this is a forced reductionism, one in which we can *only* attain fundamental truths of systems in piecemeal fashion. However, ontological reductionism is impossible because PCI refuses to posit anything unobservable and, thus, there is nothing to 'cut up'. In its broadest terms, PCI declares spacetime coordination and causality as complementary descriptions of reality, which is exactly why it cannot be couched in either of these philosophical pillars.

3.2 De Broglie-Bohm Hidden Variables Interpretation

The next candidate is the hidden variables interpretation. HVI actually began in parallel with PCI, starting with de Broglie's pilot wave model proposed in 1926. At the Fifth Solvay Congress in 1927, most of world's leading physicists gathered to discuss the conceptual difficulties surrounding the interpretation of their newfound theory of the microphysical world. Bohr discussed his complementarity and was met with much acceptance, Einstein staying somewhat quiet during the whole event. However, de Broglie got up and offered an entirely different approach, which was a truncation of his "theory of the double solution". His theory gave the wavefunction a twofold role: it is a probability wave, but it is also a *pilot wave* [*onde pilote*] [8]. Most people listened uncritically, but Wolfgang Pauli was intrigued enough to criticize the approach to see if it could become coherent to him. As the story goes, de Broglie hesitated in responding to Pauli's criticism (relating to inelastic collisions), and, thus, the theory was essentially abandoned.

That is, until 1952 when David Bohm resurrected de Broglie's ideas, putting them to the test. For our purposes, then, HVI will be seen as the constellation of ideas advocated by de Broglie and Bohm. This interpretation, as we will see, gives intuitive answers to the conceptual paradoxes above and is a highly classical theory. Its physical-theoretic structure is commonplace: it has a formalism F, a set of correspondence rules R, and an explanatory model M.

3.2.1 Basic Principles

The most basic principle of HVI is the presupposition of 'hidden' variables, λ. Both Bohm and Bell disliked the chosen word 'hidden', but it has historically stuck so we cannot dismiss its use; nevertheless, we can clarify what these dynamical variables are. They are either (1) experimentally inaccessible parameters that our current technology cannot probe or (2) fundamentally 'hidden' variables, a layer of reality that transcends our experience. It turns out both forms work fine within an interpretation of QM, but the former choice should be taken if any proponent of HVI hopes to leave room for a *hidden variables theory*, the kind addressed by Bell's theorem. The difference between an interpretation of λ and a theory of λ is that the former keeps the formalism F of QM invariant whereas the latter changes F, thereby constructing an entirely new theory. Thus, we will follow Bohm's approach and choose (1) in order to allow for the possibility of a deeper theory (although it is not necessary) while still maintaining an interpretation of QM. Since we have chosen (1), it must be decided what parameters λ physically signify. According to Bohm, λ are the exact positions of every particle in configuration space at any moment in time. With this in place, the notion of the classical trajectory is saved for now every subsystem is in a *precisely defined* state. But how do all of these classical intuitions infiltrate the quantum realm? Bohm managed to do this by cleverly manipulating the mathematics of QM. These techniques were not first employed by Bohm (attempts at hydrodynamic interpretations arrived at similar equations), but it is not an overstatement to say that he was the first to use them coherently within a unified interpretation.

By expressing the wavefunction in polar form,

$$\Psi = Re^{i\frac{S}{\hbar}} \qquad R(\mathbf{r},t),\, S(\mathbf{r},t) \in \mathbb{R},$$

the Schrödinger equation (4) can be split into two equations relating its real and imaginary parts. The imaginary part gives

$$\frac{\partial R^2}{\partial t} + \nabla \cdot (R^2 \frac{\nabla S}{m}) = 0 \tag{18}$$

and the real part produces

$$-\frac{\partial S}{\partial t} = \frac{(\nabla S)^2}{2m} + V - \frac{\hbar^2}{2m}\frac{\nabla^2 R}{R}. \tag{19}$$

Next, although S was an arbitrarily chosen variable (that was dimensionally equivalent to angular momentum or action), three relations can be stated that reveal analogues to the quantities of non-relativistic momentum, energy, and probability density:

$$\nabla S \equiv \mathbf{p} \tag{20}$$

$$-\frac{\partial S}{\partial t} \equiv E \tag{21}$$

$$R^2 \equiv \rho. \tag{22}$$

Then, the mysterious third term of equation (19) is defined to be

$$U = -\frac{\hbar^2}{2m}\frac{\nabla^2 R}{R}, \tag{23}$$

which Bohm calls the "quantum potential". Substituting into equations (18) and (19) for the equivalents found in equations (20)-(22) and adopting the definition of (23) reveals two very familiar equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \tag{24}$$

and

$$E = \frac{p^2}{2m} + [V + U]. \tag{25}$$

Equation (24) asserts the conservation of probability (specifically, its the continuity equation for probability density) and equation (25) asserts the conservation of energy (formally, its a modified Hamilton-Jacobi equation).

It is, of course, very comforting to see these equations come out of the woodwork. What is uncomfortable is the introduction of U, a grossly nonlinear potential term. This quantum potential modifies the classical force formula, making it

$$\mathbf{F} = -\nabla V - \nabla U, \tag{26}$$

where the second term is the force exerted on the particles of the system by *the wave*. Under HVI, the wave is a guiding wave, the same choreographic *onde pilote* of de Broglie's original model. However, it is also a 3N-dimensional field, where N is the number of particles in the subsystem (thus, 3N represents the degrees of freedom). By using the equivalence (20), we can extract the velocity equation from the gradient of S:

$$\mathbf{v} = \frac{i\hbar}{2m} \nabla ln \left(\frac{\Psi^*}{\Psi} \right). \tag{27}$$

It is quickly seen that these velocities depend on the distant positions λ — the Ψ-field is a function of the hidden variables. Thus, the intrinsic nonlocality of the theory is revealed.

3.2.2 Idiosyncratic Marks

HVI lies on the same side of the Bell trade-off as PCI, but for a different reason: HVI divorces itself from *local* realism because the interpretation is inherently nonlocal. The quantum potential is an instantaneous (superluminal) casual influence that acts on the positions of particles via the Ψ-field. This idea is closely linked to the measurement theory that Bohm offers [2]. What a measurement entails under HVI is a violent fluctuation of the Ψ-field, especially where R is found to be very small. It is this ultra-sensitivity that forces us to resort to statistical description. Nonetheless, every particle has definite values of its 'observables' at all times, and, hence, realism is maintained. The real, unambiguous, physically meaningful observables, Bohm points out, are the hidden variables and velocities of the particles, but this information is built into the Ψ-field and we cannot, in practice, obtain this quantum information via our classical measurement devices. In theory, though, we may eventually be able to ascertain the exact values of the real observables, but this presupposes significant technological advancements.

In interpreting P of axiom III, HVI uses *evidential probability* which comes from the Bayesian school of thought. This probability interpretation is different from the physical probability of PCI, for with evidential probability intrinsic randomness is not required. It

is simply a 'degree of belief' or a 'plausibility gauge'. There is nothing fundamental about the truth of axiom III in HVI — it is comparable to the mean kinetic energy of an ensemble found with the equipartition theorem of thermodynamics. Accordingly, since P has been demoted somewhat, it logically follows that the indeterminacy relation in HVI will have a less profound role also. Indeed, this is the case, as Bohm writes that HVI "contains Heisenberg's relations as a limiting case. valid approximately for fields averaged over a certain level of intervals of space and time" [3]. Therefore, the IR under HVI is not an epistemic limitation but a practical limitation, one that can be overcome by probing deeper levels of space and time. Finally, it should be reiterated that the wavefunction of HVI is an objective, multidimensional Ψ-field that obeys the Schrödinger equation.

The pillars of physics are half-way saved in HVI. The world is deterministic: The Ψ-field evolves continuously and the hidden variables λ form classical trajectories. However, this comes at the price of losing reductionism altogether. QM under HVI is essentially antireductionistic, or *holistic*, as the inherent nonlocality interconnects particles over vast distances. Importantly, though, this does not destroy the apparent reductionism seen at higher levels of observation, e.g. in the classical realm. Subsystems can exist in the statistical sense, and thus the results of reductionistic physics survive. This eerie compatibility of reductionism and holism is embraced by many modern notions such as fractal geometries, holographic images, and recursive patterns. and thus it is slightly easier to swallow than the complete dismantling of the deterministic picture.

3.3 Everett-DeWitt Many Worlds Interpretation

In 1957, the first American-made heavyweight interpretation was proposed by Hugh Everett III under John Wheeler. The interpretation was a radical response to the absurdly magical quality of the measurement. Everett's Princeton doctoral thesis was called the "relative state formulation" and it involved the states of subsystems being defined relative to one another. The interpretation was motivated by relativity theorists and cosmologists like Wheeler who were still displeased with the jarring differences between QM and the large-scale universe and so it seems only natural that another form of relativity be introduced. However, even though the sequence of events in GR are relative to an observer, there still remains an absolute spacetime. But what remains absolute in QM under Everett's approach? It is the *universal wavefunction* of which all subsystems are composed.

Everett's paper was largely ignored by the physics community, but Everett was not taking no for an answer. He decided to personally explain his stance to Bohr and he flew to Europe. Bohr basically saw Hugh Everett III as some *enfant terrible* and severely criticized his work for taking the QM formalism too literally. Everett became awfully depressed and resigned to working for the defense department for the rest of his life. Decades passed until his work finally began to garner some attention. It was Bryce DeWitt who eventually popularized Everett's interpretation under the name of the many worlds interpretation and initiated the conceptual unpacking of an otherwise dormant idea. Thus, we will refer to MWI as the constellation of ideas advocated by DeWitt and Everett. Its physical-theoretic structure is atypical: it has a formalism F, an explanatory model M, but lacks epistemic relations R.

3.3.1 Basic Principles

The main principle of MWI has already been introduced: The universal wavefunction exists for all time and governs all the dynamics of the world. An immediate consequence of this proposition is that there cannot be an external observer of the universal wavefunction — there is nothing external. Implied from this fact is the renunciation of any collapse mechanism. Thus, under MWI wavefunction collapse is illusory, and yet it still needs to explain how the appearance of collapse is brought about. This is where MWI uses the theory of *decoherence*. Generally speaking, decoherence involves successive environment-system interactions that lead to stable, non-overlapping 'worlds'. In a theory of decoherence, the environment is constantly monitoring the system, performing miniature measurement-like acts which leads to the phenomenon of interference suppression. There exists a certain preferred set of states — a *basis* in linear algebra terms — that the environment will tend to couple to, thus causing suppression of interference. Microsystems that manage to decohere have a high probability to significantly overlap in their states, thus keeping the environment entangled. However, the key to decoherence is that as systems become sufficiently complex the chance of this kind of perfect overlapping — every particle of a 'world' aligned with every particle of another 'world' — is very slim. Macroscopic systems of this kind exhibit thermodynamic irreversibility and become mutually unobservable 'worlds'. Mathematically, the universal wavefunction, then, is expressed as

$$|\Psi\rangle = \sum_{i=1}^{m} \left(\prod_{j,k=1}^{n} |\psi\rangle_j |\phi\rangle_k \right)_i , \tag{28}$$

where m is the total number of current branches (see equation (29) below) and n is an arbitrary number that counts the number of subsystems of each branch. Each additive term of this equation, then, corresponds to a separate 'world'. Each world is seen as a product of subsystems, which remain coupled until decoherence decouples the constituent subsystems into mutually orthogonal, brand-new worlds.

For historical accuracy, it needs to be remarked that Everett never used the terminology of 'worlds', and that is why it has thus far been simply a quoted term. However, DeWitt's introduction of the term is appropriate, for it is quickly realized that if the observer is truly coupled to the environment and part of the universal wavefunction then the recording devices — the memories stored in the human brain — undergo the same splitting or branching of worlds that everything else does. DeWitt's first impression of this notion is notably captured in his article on MWI, where he gives his personal first meeting: "I still recall vividly the shock I experienced on first encountering this multiworld concept. The idea of 10^{100+} slightly imperfect copies of oneself all constantly splitting into further copies, which ultimately become unrecognizable, is not easy to reconcile with common sense. Here is schizophrenia with a vengeance" [5]. In many ways, it is the utter bizarreness and unbelievable quality of this idea that helped MWI to gain such a comprehensive audience.

As DeWitt mentions in the quote above, there is a vast number of splittings occurring at every moment and the total number of branches only increases with the direction of time. Naturally, then, the notion of entropy is used to count these branches. Specifically,

information entropy is used, compactly written as

$$H = -\sum_{i=1}^{n} P_i \, log_2 P_i. \tag{29}$$

Equation (29) makes use of the Born probabilities associated with each splitting. The idea is, instead of getting an arbitrary value that follows some probability distribution, every possible value associated with a physical observable is realized. These, then are, in a sense, the sites of the splittings, each world branching off with a definite value. In order to account for the truthfulness of the Born probabilities, Everett extends one of modern cosmology's favorite *ad hoc*, pseudoscientific principles, the anthropic principle. In Everett's extension, it is assumed that systems of our complexity — systems with minds — exist on a typical branch. This leaves room for 'maverick worlds', ones in which the Born rule is violated. However, Everett proves (using decision theory) that there is a low measure (probability) of existing in one of these worlds, and thus we can safely assume we are not in one.

3.3.2 Idiosyncratic Marks

As foreshadowed in §2, MWI forfeits counterfactual definiteness (CFD). This arises because of the non-uniqueness of histories inherent to MWI — when one hypothetically makes a measurement every possibility is realized in a separate branch. As a result, local realism is saved, and MWI allows QM to be both a local theory and a realistic one. What this means for measurement theory is that there is nothing at all special about the measurement process. More precisely, the concept of measurement itself becomes ambiguous, for all systems of sufficient complexity, be it a geiger counter or a laptop computer, are constantly taking 'measurements' of their coupled systems. When entanglement becomes negligible worlds split and pretty much forever remain parallel and mutually unobservable (to the same extent that projectile eggs that have splattered reassemble themselves and jump off the ground).

The probability interpretation of the axiom of quantum statics for MWI is neither that of relative frequencies or degrees of belief. P of axiom III is defined to be the branching ratios of the splitting worlds. Recent work by David Deutsch and colleagues has shown that via decision-theoretic and information-theoretic techniques, the Born rule directly emerges from these ratios (see "Parallel Universes Make Quantum Sense" *New Scientist*, 2007). This not only gives the Born rule a greater theoretical indispensability, but it equates it to a higher *measure* that exists for single trials. That is, the 'measures' of worlds are coefficients that deterministically evolve as the multiworld tree grows exponentially; they do not arise from any intrinsic randomness or notion of plausibility. This does not affect the role of the indeterinacy relation, which is taken as an 'uncertainty principle' just like it is under PCI. The difference is that the IR in MWI is not a logically prior priniciple, but a derivable theorem from the formalism of the theory. Lastly, the wavefunction is objectively real under MWI, and it represents the state of the entire multiworld.

MWI salvages both pillars of physics, but in doing so it severely redefines their meanings. QM under MWI can be called neo-deterministic, for every universe is causally closed yet there is a multiplicity of noninteracting worlds. All of the sudden there is much more freedom within a deterministic framework — every possibility is actualized, obeying all

laws of physics upon its inception. Also, because locality holds under MWI, reductionism is kept in full, the subsystem-apparatus divide surviving, albeit in a relativized form.

4 Philosophical Analysis

By definition, there are no experiments that will decide which interpretation is right or, more precisely, closer to reality. Every interpretation attempts to fully account for all of the predictions of QM and every interpretation is superimposed on the same, *identical* formalism, the only semantic difference being that of how the extralogical terms are interpreted. This being the case, we are left with two philosophical tools — the use of history and careful application of our intuitions — in order to weigh each interpretation. In applying these tools, neutrality is necessary, for otherwise blinding biases prevent us from seeing the greater implications of the approaches. Ernst Mach, the founder of positivism who had a tremendous influence on Einstein, once proclaimed, "The philosophical point of view of the average man has a claim to the highest consideration." To take these words sincerely we must be open minded when it comes to deciding what actually count as strengths and weaknesses of interpretations of physical theories.

4.1 Comparison of Major Interpretations

In choosing our candidate interpretations, we implicitly made each one identical in its formalism F. This is done because F is the essence of the physical theory; in other words, a physical theory composed of just R and M is just a collection of discrete facts that cannot generate anything novel. Conversely, a physical theory with only F is a mathematical theory that does not attempt to map to reality — the theory is syntax sans semantics. Thus, the three discussed interpretations represent the *only* fundamentally distinct views of QM, for each one is one of the three possible combinations of R and M. PCI only has R, HVT has R and M, and MWI only has M. From this argument alone it is shown that all other interpretations of QM are minor, hybrid attempts that only find originality in their confusing conflations of the three major stances.

4.1.1 Criteria

Now that we have justified the importance of these interpretations historically and logically, it is time to compare them side-by-side. Our intuitions point us to three established criteria, which we can employ in a systematic comparison.

The first criterion is that of **scope**. How fertile is the explanatory model M? This question is what we mean by scope, because it is much more about the potential for growth and *incorporation* into grander contexts than it is about covering all the phenomena of the current framework. This second part is important, but it was tacitly assumed that each interpretation accounts for the same range of phenomena to begin with. The difference, then, comes from the language which the interpretation utilizes in order to gain insight into broader worldviews.

The second criterion is that of **economy**. How efficient is the set of correspondence rules R? In the philosophy of science, there is a certain method for navigating between the

observation language of a theory to the theoretical language of a theory.

The third criterion is **elegance**. Elegance is traditionally a hallmark of powerful mathematical theories, but with the advent of axiomatic systems of physics, it has entered into the judgement process of the formalism of a physical theory. *Prima facie*, this criterion seems out of place due to the fact that earlier we had said that all of the interpretations were identical in F. However, it was also spoken of earlier how difficult it can be to rightly disentangle F, R, and M. By invoking elegance as a criterion for judgement we are firmly acknowledging the malleability of F in reaction to R and M. In actual fact, the correspondence rules and model of a physical theory that put stress on F are usually signs of a tenable theory, or at least one to be seriously entertained. Thus, our question is this: How (potentially) compact is the formalism F?

4.1.2 Judgement

Judging the interpretations with these criteria takes further exploration of each approach. Consequently, we will now explore deeper levels of of PCI, HVI, and MWI, viewing them comparatively and contextually.

Scope The scope of PCI is essentially nonexistent. PCI has no unified M to speak of because it refuses to posit any unobservable metaphysical entities [8]. This is Mach's positivism taking to its logical apex, an ontologically vacuous theory that lead to a scientifically impotent. apathetically agnostic attitude that permeated throughout the Copenhagenist (Bohr and Heisenberg) channels. Bohr and other adherents made use of this fact — that PCI is not an unambiguously defined set of ideas — and proceeded to unfairly apply its ideas to other areas of thought. As seen in §3.1, Bohr basically was grabbing at straws when trying to form the philosophical foundations of QM — he made significant use of two philosophical heavyweights, Descartes and Kant, both who were responsible for reinforcing the two previous paradigm shift physical theories of classical mechanics and relativity theory, respectively. He was ideologically inspired by many eastern ideas, particularly the yin yang symbol which was later put on his family coat of arms. In reading the *Tao Te Ching*, Bohr viewed the binaries of life as being ubiquitous examples of complementarity pervading all forms of human understanding. In the early 1930s, physicists like Pascual Jordan claimed that vitalism and physicalism were complementary aspects within the sphere of biology. In the following decades, complementarity was applied to linguistics, ethics, ethnography (by Bohr himself), and psychology [8]. It was even applied to theology at one point, some arguing that science and religion are in fact complementary to each other. The lesson to learn here, then, is that vagueness cannot be confused as generality: PCI has no M, and, hence, is completely infertile to conforming to and incorporating frameworks beyond itself. It is a loose set of epistemological principles that, because they do weave themselves into a metaphysical worldview, lie at the disposal of any intellectual endeavor looking for additional justification. This should not be taken as a strength of a physical theory in any way and is, ultimately, the biggest disadvantage of adopting PCI. One of the leading logical positivists, Rudolf Carnap, even said, "Description *and* explanation, rightly understood, are essential aspects of science" [8]. The positivistic interpretation of QM, unfortunately, did not take these words to heart, for PCI only speaks of complementary modes of descrip-

tion, refraining from any explanation whatsoever. This attitude discourages the progress of science and should definitely be reevaluated, especially in light of the implosion of logical positivism.

On the contrary, the scope of HVI is quite expansive. HVI has a very modern M, one that conforms well to the field-theoretic approach found in many modern-day physical theories, from general relativity to quantum electrodynamics. The first drawback, though, is that the field itself is an objectively real wavefunction that exists in a higher-dimensional configuration space. To many critics, this is very problematic, and it takes away from the classical feel of the approach. Having 4-dimensional manifolds was tough enough to handle, but how are we to digest 3N-dimensional fields that can act on particles instantaneously? Proponents argue that this is just what is needed. The biggest advantage of HVI is that it can be embedded in a larger *holographic theory*. Just like Bohr, Bohm was highly influenced by eastern ideas, specifically the concept of 'undivided wholeness' found in the immanent Tao and other eastern concepts. His attraction to this idea allowed him to work past the nasty nonlocality and mathematically messy nonlinearity of his theory and catch a glimpse of what he called 'a new order'. Bohm asked, "Is there an instrument that can help give a certain immediate perceptual insight into what can be meant by undivided wholeness, as the lens did for what can be meant by analysis of a system into parts?" [3]. The answer, surprisingly, is yes. The instrument is the *hologram* which, unlike the simple lens that barely preserves an isomorphism between the parts of an object and the parts of its image, contains all the information of the object in a single part of its image.

The hologram has been applied to many aspects of the universe outside of QM. For example, it was discovered by Stephen Hawking and collaborators that the entropy of a black hole is proportional to its surface area:

$$S_{BH} = \frac{kA}{4\ell_p^2}, \tag{30}$$

where k is Boltzmann's constant and $\ell_p = \sqrt{\frac{G\hbar}{c^3}}$ is the Planck length (entirely defined by fundamental constants of nature). This is merely one example of what has been called the 'holographic principle', which hypothesizes that the information contained within any closed volume can be encoded on the boundary of the region. The idea has even tickled the curiosity of many cosmologists, who play with the concept that the holographic principle may apply to the entire universe. Many arguments claiming M-theory — 11-dimensional superstring theory — as the ultimate theory of everything (quantum gravity) stem from extensive use of the holographic principle to account for unseen and higher dimensions of the universe. Thus, HVI is extremely fertile, for it sits within a broader theory that has the potential to connect many different areas of research into a holistic picture.

The scope of MWI is grand. Its first striking feature is that it can be applied to quantum cosmology, taking the universe to be a single quantum system that evolves via the universal wavefunction. This was a predestined outcome, of course, for Everett, being taught by the relativist Wheeler, intentionally set out to devise an interpretation that conforms to the needs of cosmology. The sacrifice made for this ability to do quantum cosmology is the extravagance of the many worlds themselves. Here, many critics of MWI attack with full force, declaring that Occam's razor surely cuts the plurality of the many worlds. Occam's

razor is a standard tool used to filter out unnecessarily complex theories. In essence, the principle states that "entities should not be multiplied beyond neccesity" [*entia non sunt multiplicanda praeter necessitatem*]. Superficially, these critics sound correct, but, for a subtle reason, they are indeed wrong. The problem lies in the equivocation of vastness with complexity — MWI adds vastness but does not add complexity [5]. DeWitt's choice of introducing the term 'world' may have a lot do with this misunderstanding, its common connotation inducing visions of fully concretized lands. However, if we use the term 'history' instead of 'world' this vision seems to mostly vanish and the simplicity of MWI comes to the forefront.

The great strength of MWI, just like HVI, is that it is able to be embedded in a larger theoretical framework. In the case of MWI the broader theory is the *multiverse theory*, popularized by Max Tegmark of MIT and others (see "Parallel Universes" *Scientific American*, 2003). In this theory there are many 'levels' of universes. In level I of the multiverse, we have the universe beyond the observable horizon, objects emitting light that will tragically never reach our eyes. In level II of the multiverse, we have bubbles of level I multiverses existing between vast regions of space that constantly undergo cosmological inflation. The level III multiverse is the many worlds of MWI, existing 'parallel' to other level II multiverses. Lastly, there is a level IV multiverse in which the laws of physics themselves are different and give rise to different mathematical structures. This grand theory is extremely powerful in that it leaves no room for theological inquiries about the special or designed state of specific universes.

Economy The epistemic relations of PCI are not extremely economical. For example, in conducting the single slit experiment we must preemptively discard the wave picture and observe the results via our correspondence rules that pertain to the corpuscular mode of description. However, in changing our apparatus to the double slit diaphragm, we must remember to switch modes to the undulatory set of rules and disregard any description of particle behavior. Thus, PCI is inefficient with its R for they are all contextualized and experiment-dependent.

Historically, as Carnap points out, theoretical concepts have served effectively as umbrella terms for a vast array of observables. For instance, the concept of intensity of electric current can be measured in a myriad of ways, and yet physicists choose to hold onto one concept of current. This kind of injective mapping is essential for the progress of physics and allows for conceptual flexibility. All of the most basic theoretical concepts of physics — e.g. mass, space, time — can be measured in a multitude of ways, creating interconnections and coherence within a certain physical theory (e.g. gravitational mass and inertial mass in relativity). PCI takes the first steps in preventing this mapping, for it systematically maps to different theoretical terms for different observable terms — dots go to particles, interference patterns go to waves, etc. Unless there is strong evidence for believing that this trend is necessary for the future of physics, this methodology should definitely be thrown away.

HVI has correspondence rules which are, in a way, estimative. The real, classical observables have been literally hidden away, pushed into the experimentally inaccessible scales. As a result, the 'observables' of states and expectation values are exactly what their statistical character say. The 'systems' of HVI are ill-defined, too, so not only are the rules themselves

estimative but also the observational terms are approximations.

The R of MWI is infinitely efficient insofar that it is entirely absent. The downside of this is the philosophical converse of the downside that PCI has for having no M: Where PCI lacks ontology, MWI lacks epistemology. Here it is clearly visible how reactionary MWI is to the positivism of PCI, but we must not be quick to count this as beneficial. Surely, MWI avoids all the messy work that comes along with building a set of epistemic relations, but in return it puts mathematics itself on an even higher pedestal than it has ever been before. Everett, in his paper, argued that his formulation is actually a *metatheory*, one that proves that the QM formalism can bring about its own interpretation, unadulterated by human invention. This has enchanting promise, but is it plausible? By subscribing to this kind of theory-building, mathematics becomes more than a descriptive framework: Now, mathematics *is* the structure of the multiverse, a layer that we humans are lucky to be able to tap into. Of course, mathematics as it is expressed can never be purged of its anthropocentrism (using radix 10, for example), but its underlying form can be viewed (by some realists) as existing on its own. There have been many dreams about this reality, such as Wigner's article "On The Unreasonable Effectiveness of Mathematics In The Natural Sciences", in which mathematics literally is the foundation of everything. If this hypothesis turns out to be true, then MWI is the first step on our way to fully fathoming nature.

Elegance PCI is not very elegant. Its F maintains all five axioms, but its conceptual difficulties give rise to a huge temptation to add in a sixth, 'collapse axiom'. This approach, followed by Von Neumann and others, makes the act of measurement a fundamentally different process than the unitary evolution of the otherwise undisturbed wavefunction [5]. The only reason why PCI (and not Von Neumann's version) avoids this added axiom is because it avoids the construction of M instead. By omitting M, PCI cannot comment on the objectivity of the wavefunction and takes that as justification for pushing the collapse problem aside. It is seen quickly, then, that when the positivistic stubbornness leaves PCI it is forced to expand its F, not a telltale sign of a successful interpretation. Thus, PCI has a maximal F, i.e. it is the least compact.

HVI is slightly more flexible than PCI due to the richness of its physical-theoretic structure (having F, R, and M). Bohm explains that his approach involves three presuppositions that make HVI a proper interpretation of QM and not an interpretation of a deeper theory (i.e. QM with a modified formalism). These three assumptions include (1) the Ψ-field satisfies the Schrödinger equation, (2) the particle momentum is restricted to $\mathbf{p} = \nabla S$, and (3) we have a statistical ensemble of particle positions, with probability density $\rho = |\Psi|^2$. Thus, simple modifications of these three restrictions yield inhomogeneities in the field, which would be a strong similarity to electromagnetic field theory. Furthermore, these restrictions will still exist as limiting cases and preserve the operational features of QM as its used in practice. Thus, HVI stays within the five axiom schema and under mild manipulations a deeper theory may be found. It is more potentially compact than PCI, but not as compact as MWI.

MWI has a minimal F because the axiom of quantum statics is shown to be redundant. It arises from purely mathematical reasoning involving decision theory as it relates to the branching histories of the multiverse. Proofs of the equivalence of the branching measures with the Born probabilities are beyond the technical reach of this paper and they are still

in their preliminary stages. Nevertheless, current work has indeed established a definite correlation between the apparent probability densities of the Born rule and the measure of each branch and this result is immensely important for the reputation of MWI. The ability for the explanatory model M of MWI — which, as Everett argues, derived isomorphically from F to begin with — to act back on the formalism, simplifying its most *ad hoc* axiom out of the schema is a token of just how internally consistent, coherent, and elegant MWI truly is.

4.2 The Role of Philosophy in Physics

Once again, it is not a coincidence of history that the fall of logical positivism as a philosophy was quickly followed by some of the most ontologically 'heavy' interpretations physics has ever seen. Quine's *Two Dogmas of Empiricism* allowed the anti-metaphysical program to come to a screeching halt. With Everett's dissertation five years after Quine's revolutionary paper, metaphysics had officially returned home to philosophy, serving as a refreshing, much needed, assistant to quantum physics. Here we reflect on the real impact of philosophy within the hard science of the modern world. Now that physics has been revitalized, has philosophy done its temporary job, no longer relevant to the advance of physics? Does philosophy of science go back to clarifying language puzzles buried in the cracks of the history of science, or does it have a permanent task of constantly running checks and balances on rival interpretations of increasingly abstract physical theories? My hope is that the reader sees these as the *wrong* questions, questions that presuppose a certain division labor between philosophers and physicists. This division, although it exists on universities campuses all across the world with separated buildings, usually decorated with completely different motifs (physics buildings resemble hospitals, philosophy buildings resemble the Parthenon), is entirely artificial. Both endeavors should feel free to invade the realm of the other because they are interdependent modes of discovery, relying on each other for insight, advice, criticism. But the reader, in replacement, should be left with another question: Is there not a job of the philosopher that the physicist simply *cannot* do? Shockingly, the answer is yes. Before getting into this specialized job, however, we will discuss a depressing world in which physics has no philosophy. This is no hypothetical dystopia: It was the real world of physics that existed in the past century in the interim of these all too important interpretations.

4.2.1 Instrumentalism

There is a famous saying in physics classrooms that goes as the following: Shut up and calculate. It is attributed to David Mermin (and sometimes Paul Dirac). This dictum perfectly encapsulates the lack of philosophical inquiry within the physics classroom of even today. Yes, luckily philosophical discourse in physics class has increased somewhat over the past couple decades, but that is probably only because of textbook authors feeling pressured to do justice to historical continuity and put in appendices mentioning minor philosophical implications; it is probably not because professors have felt it their duty to raise the consciousness off their typically robot-like physics students. The saying is emblematic of *instrumentalism*, a pragmatic approach to physics half-heartedly embraced by the physicists above along with a plethora of other science educators of the 20^{th} century.

An instrumentalist interpretation of QM involves the minimal interpretational machinery needed to make useful predictions. All metaphysical and epistemological baggage is deemed irrelevant if it attempts to do more than supply interpretation on a practical level. Under instrumentalism, then, the idea of theories being better and better approximations of truth is meaningless. A theory either works well in describing phenomena or it does not; it is not more or less 'true'. This view is not quite the view of relativism — where truth-values themselves are only culturally or linguistically relative — but it creates the same apathetic attitude.

The first place philosophy should always step into, then, is a scientific drought like the ones found during these instrumentalist times. Every professional scientist knows that speculative, far-fetched, epiphanic interpretations are (normally) irresponsible, but this should not hinder the working scientist from constantly trying to immerse her theory in a philosophical framework. The criteria used in our comparisons of the candidate interpretations are admittedly mostly due to accidental trends and aesthetic appeal, and so the rational scientist will save her time and, more times than not, choose not to spend futile efforts participating in metaphysical hogwash. Looking at other trends, though, we can see that our physical theories are only going to become more and more abstract, as new mathematical technology is produced at an exponential rate. This being so, the instrumentalist apathy that is ubiquitous in many scientific communities must dissipate quickly if we ever want to *comprehend* our theories and not just write down equations. Richard Feynman is misattributed for the aforementioned dictum because he was one of the most outspoken anti-philosophers of his time. He would refer to philosophy as wordplay, utterly useless activity that only clutters the mind. And yet, as can be discovered from any of his biographies, his classes where teeming with his philosophical positions on everything from the nature of the electron to what science is. An enigma he notoriously was, but the public disapproval of philosophical work by physicists is the greatest of all contradictions.

4.2.2 The Sociology of Science

In 1996, the NYU physicist Alan Sokal published a paper in the postmodernist cultural studies journal *Social Text* entitled "Transgressing the Boundaries: Towards a Transformative Hermeneutics of Quantum Gravity" [11]. It was a complete hoax, full of ridiculous jargon and fringe theories loosely strung together by quotes and postmodernist ideas. The decade of debate that followed was enlightening for many reasons, but most importantly because it made the world recognize how much of a gap exists between the natural sciences and the social sciences. Sokal won, fair and square, and his point was well taken by many academics on the 'cultural side' but it in no way confirmed the supposed intellectual authority of the natural sciences. What has fully materialized now is a new discipline — the sociology of science. This kind of meta-science does what 'the other side' should be doing. That is, sociologists of science treat working scientists as 'lab rats' and research them in their natural habitat, noting their social behavior and methods of communication amongst each other. This then, is the eternal occupation of the philosopher-outsider, if the line has to be drawn at all. It is to keep scientists in check, letting them know when new theories are becoming unscientifically cultic (e.g. string theory) or when prominence has unjustly overshadowed poor theorizing (Bohr with PCI). Reputation is hugely advantageous, even

within the seemingly dull world of science. The was best captured in the anecdote of de Broglie, first offering his pilot wave theory bravely in front of all the leading physicists of the time, only to be shot down by one critic. His approach, now a mainstream and promising area of research, was entirely forgotten for almost 30 years.

5 Conclusion

In conclusion, we can see that the function of the philosophy of science is multifaceted. Also, philosophy must continually stay involved in the mathematically complicated world of physics, clarifying concepts at all times. The philosophical project within physics is unfinished and will remain unfinished even after we discover a theory of everything (assuming there is one, of course).

Nonetheless, our analysis has been thorough and exhaustive, applying appropriate weighting coefficients to philosophical preferences and pre-established, intuitive criteria. Ultimately, it is concluded that MWI should be adopted by university textbooks as the *default* context in which QM is meant to be first interpreted. This is not too much of a hassle, either, for the calculations of QM remain unchanged under MWI — textbooks simply have to be expanded (and not just given appendices that students will never read). We have shown that MWI has the widest scope of the three candidates, conducive to being incorporated into an impressive multiverse theory and showing seamless compatibility with subdisciplines such as thermodynamics and quantum information theory. It also has sprouted new subdisciplines, most notably that of quantum cosmology, a prerequisite area of study for any successful inquiry into the big bang and the first moments of our universe(s). Additionally, it has an idealized economy of correspondence rules, putting the semantic pressure on the mathematical terms themselves. And it is by far the most elegant of the three major interpretations, reducing the formalism by an axiom and accounting for it within model of the theory.

Also, MWI maintains both of the philosophic pillars of physics — determinism and reductionism both survive under MWI. This is more of a comfort than anything else, giving us more room to theoretically breathe, so to speak. PCI loses both of the pillars and HVI remains deterministic at the price of introducing holism, a powerful but scientifically foreign idea (for now). Most importantly, MWI is the *least anthropocentric* of the three approaches. PCI, in its epistemological measurement process, keeps us in a defined role as special observers in the universe. HVI, although not discussed specifically, keeps *consciousness* in a special place, a philosophical preference of Bohm that gives humans a distinct role in the cosmos. MWI, though, in taking the formalism literally, takes a Copernican leap and smears our identities across an infinitude of possible worlds. The direction of purging physics of its anthropocentrism is the path history has taken and should continue to take, and MWI does well it pushing forward.

Ultimately, didactic reasons should not prevent physics students from getting an early introduction to the philosophy of science, especially in light of how relevant it has become. Being aware of the history, of the conceptual transformations, of the tendency of physics to get ahead of itself cannot be underrated. It has become commonplace now for great physicists to proclaim during the peak of their lives that physics is 'almost over'. Way back in the second half of the 19^{th} century, James Clerk Maxwell, after stunning himself with

the elegance of his electromagnetic theory, boldly foretold that "In a few years, all great physical constants will have been approximately estimated, and that the only occupation that will be left for men of science will be to carry these measurements to another place of decimals" [8]. This, of course, a century and a half later, is not the case. Still, though, physicists have fashionably made statements about the 'end of physics' more and more frequently, especially in light of the possibility of unification of QM with gravitation theory. Although they are surely meant to be inspiring, they have let us overlook the philosophical problems of which plague this so-called finale of the enterprise of physics. MWI is definitely not the end of the story, but it should help physics break free of the theoretical stalemate it has undergone in the past 50 years, eventually leading to more profound insights and a deeper understanding of reality.

In terms of inspiring the work of the generation to come, there are no better words than John Stuart Bell's: "The theoretical physicist differs from the novelist in that he believes the story to be true" [1]. It is exactly this kind of faith that inspires the imagination and allows the physicist to tell the greatest story of them all.

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